3D-Model-Based Augmented Reality for Enhancing Physical Architectural Models

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In the presentation of architectural projects, physical models are still commonly used as a powerful and effective representation for building design and construction. On the other hand, Augmented Reality (AR) promises a wide range of possibilities in visualizing and interacting with 3D physical models, enhancing the modeling process. To benefit both, we present a novel medium for architectural representation: a marker-less AR powered physical architectural model that employs dynamic digital features. With AR enhancement, physical capabilities of a model could be extended without sacrificing its tangibility. We developed a framework to investigate the potential uses of 3D-model-based AR registration method and its augmentation on physical architectural models. To explore and demonstrate integration of physical and virtual models in AR, we designed this framework providing physical and virtual model interaction: a user can manipulate the physical model parts or control the visibility and dynamics of the virtual parts in AR. The framework consists of a LEGO model and an AR application on a hand-held device which was developed for this framework. The AR application utilizes a marker-less AR registration method and employs a 3D-model-based AR registration. A LEGO model was proposed as the physical 3D model in this registration process and machine learning training using Vuforia was utilized for the AR application to recognize the LEGO model from any point of view to register the virtual models in AR. The AR application also employs a user interface that allows user interaction with the virtual parts augmented on the physical ones. The working application was tested over its registration, physical and virtual interactions. Overall, the adoption of AR and its combination with physical models, and 3D-model-based AR registration allow for many advantages, which are discussed in the paper.

Keywords: *Augmented Reality, AR, 3D-model based AR, Architectural Representation, Architectural Modeling.*

INTRODUCTION

In architectural representation, physical architectural modeling, also known as scale modeling, has been one of the most powerful methods that convey an architectural idea from an architect's mind to a tangible reality before the final outcome is built. However, physical architectural models are not only reductive and sometimes abstract representations of real buildings but also, are limited in conveying architectural ideas in an architect's mind into a physical realm. Moreover, the static nature of physical models lacks features that include motion and dynamism. However, virtual 3D models can offer these, such as realistically rendering materials and texture or adopting animation for the dynamic part of a design. For instance, representing a dynamic façade that responds to climatic conditions or displaying different design options that change with parameters would be challenging with a physical model both in terms of constructing and controlling. Although it is possible to integrate dynamic features into a physical model by using mechanical or electrical systems and parts, it usually takes more time, effort, and cost and in addition, it requires knowledge in those areas. Similarly, bringing graphics, data, or animation features into a physical model would be burdensome by using tangible additions. For instance, employing agents to show the usage of the building or pedestrian and vehicle traffic in a site plan with animation would be self-explanatory while representing agent motion in a physical model even with electrical systems would be arduous. However, these physical limitations could be overcome in an easier, efficient, and faster way by integrating virtual features into a physical model. Augmented Reality (AR) can enable this integration and present a new way of utilizing physical models by extending the capabilities of physical models while bringing them closer to the more accurate representation of ideas in architect's mind. To demonstrate and investigate physical and virtual model integration in AR, we created an AR prototype, which is an App for a hand-held device. For AR registration, we used a 3D model-based registration method and trained our prototype to recognize and track the physical model in order to align virtual model components with the physical model. A user interface was developed for visualizing the integrated physical and virtual model interactively. The integration of physical and virtual models presents both tangible and virtual interactions. The prototype demonstrates how design options and dynamics of the model are enabled and visualized in AR.

LITERATURE REVIEW

Throughout architectural history, the popularity of physical architectural modeling significantly varied based on the variety of approaches to the design and design process. For instance, in ancient Egypt, the oldest surviving examples of models found in tombs were used as a symbol of an afterlife, while in ancient Greek, models were not that significant due to the restricted proportions defined based on architectural temple style (Stavrić, Šiđanin and Tepavčević, 2013). In the Roman era when architecture and engineering merged, models were useful in testing concepts and persuading the public about the validity of projects, and then, models were used to get the support of the patrons and examine geometrical ideas during the Renaissance (Mills, 2011; Stavrić, Šiđanin and Tepavčević, 2013). One of the notable experimental modeling was done by Antoni Gaudi (1852–1926) for inquiring about truth and perfection about God's natural forms; he made structural form explorations for the Sagrada Familia church with the help of hanging ropes, weights, and a mirror (Smith, 2004). In modern architecture, physical modeling became a design tool for examining and experiencing space through movement that perspective and orthographic drawings cannot provide (Mills, 2011).

Physical architectural models can be categorized into two levels: scale and use. According to scale, models can vary from urban models, site plans, building models, interior models to detail models. According to use, models can be a conceptual model, a working model, or a finished presentation model (Knoll and Hechinger, 2008). Conceptual models and working models would be crucial in the design process since they solidify architectural ideas and concepts and invite feedback on architectural forms and relationships of building elements among themselves and their surroundings. In addition, working models are beneficial for running building energy performance simulations and their design could be modified based on their performance. For instance, putting a working model into a heliodon would simulate its lighting performance whereas putting it into a wind tunnel would simulate its wind distribution and airflow. On the other hand, presentation models showcase an accurate and realistic form that would be as close as to the final building design so they are widely preferred in marketing. To conclude, architectural models provide a tangible form in a physical space that offers interaction and can be developed or modified based on its purpose.

With the introduction of Computer-Aided Design (CAD), virtual modeling promised an easier, faster, and more precise way of 3D visualization as an alternative method to architectural physical modeling. CAD tools enable designing complex architectural forms. Using NURBS (Non-uniform rational b-spline) gives more control on the design form. Moreover, these CAD tools lead to new concepts and architecture such as topological architecture, isomorphic architecture, animate architecture, metamorphic architecture, parametric design, and evolutionary architecture that use genetic algorithms (Kolarevic, 2001). Computational modeling not only makes designing intricate forms possible but also facilitates coworking with Computer-Aided Manufacturing (CAM), or digital fabrication. Computer Numerical Control (CNC) enables the cutting of curvilinear forms precisely and it is aided both in construction and creating physical models. Recent development in 3D printing makes it more affordable and accessible to architects while contributing to the process and the quality. CAD modeling allows running and visualizing building performance simulation and optimization, especially when paired with parametric modeling. Lately Building Information Modeling (BIM) has created an information enriched platform for architectural, engineering, construction, and maintenance processes to collaborate.

In our research, we aimed to integrate the tangible properties of physical modeling with the possibilities that digital tools offer. Augmented Reality (AR) presents an effective medium for this integration to work. AR can display virtual objects in physical environments (Milgram and Kishino, 1994)(Azuma et al., 2001). AR runs in real-time, allows interaction, and aligns physical objects and virtual ones (Azuma et al., 2001). Besides working with 3D objects, AR can add 2D graphical or text content to the environment. Bridging the gap between the virtual world and the physical world, both spatially and cognitively (Schmalstieg and Höllerer, 2016), AR promises a wide range of possibilities that would enhance architecture, both in the design and presentation processes. Besides Architectural, Engineering, and Construction (AEC), AR has been employed in several fields such as manufacturing, education, medicine, tourism, military, and art. For instance, AR becomes useful to cut the cost and improve efficiency in human-involved operations in manufacturing (Caudell and Mizell, 1992). Knowledge-based AR was developed for assisting maintenance by explaining maintenance and repair tasks (Feiner, Macintyre and Seligmann, 1993). 3D-model based interaction in AR provides spatial understanding improvement by visualizing abstract concepts (Kaufmann and Schmalstieg, 2003), simulating objects and environments that cannot be experienced in real life, creating a collaborative learning environment, and bridging the formal and informal learning (Wu et al., 2013). By engaging gaming, AR has become attractive for touristic experiences in visits to museums (Gimeno et al., 2017) and with the integration of GPS, visits to heritage sites (Han and Jung, 2018).

AEC industry has employed AR for assisting construction processes, especially with complex geometry or material assemblies by providing visuals and instructions (Chen, Liao and Chu, 2018; Jahn et al., 2018; Hahm et al., 2019; Kwiatek et al., 2019; Qian, 2019; Yan, 2022) that can reduce errors and training periods of the staff. Instead of a fully automated construction process with robotic arms, drones, CNC machines, and automatic-operation construction machines, a hybrid system between machine and AR-powered human is the most practical one and giving the most accurate results (Abe et al., 2017). Presenting the material choices and applications on construction sites in AR helps decision-making (Sangiorgio et al., 2021). Similarly, IKEA's application allows customers to locate and visualize furniture at full scale in their homes to make their decisions appropriately and quickly (*Say hej to IKEA Place*, n.d.). Furthermore, AR could be employed to visualize building performance simulations and their animations, such as computational fluid dynamics (CFD) in real space (Zhu, Fukuda and Yabuki, 2020) or a physical model. In the intersection of architectural presentation, preservation, and exhibition, AR could enhance the architectural model by enriching visualization and audio storytelling such as in BAMPFA AR Project (Caldas, 2019). In this exhibition, AR media is projected onto a large-scale model of the UC Berkeley Art Museum and Pacific Film Archive (BAMPFA) building, where visitors walk around the model and interact with the model through hand-held devices that visualize AR, and learn about the history of the building.

Although with Head-Mounted Displays (HMD) such as HoloLens or Magic Leap One or table-top systems, which enable users to experience AR in an immersive and hands-free mode, mobile phones and tablets are getting more popular for AR because of their accessibility and affordability. Hand-held options can be lightweight and can be employed outdoors with GPS-based AR. As a marker-less AR registration (alignment) method, GPS-based AR is adopted by outdoor mobile AR applications such as Pokémon Go; however, GPS-based AR doesn't work properly indoors and requires manual adjustments for a more accurate alignment (Ashour and Yan, 2020). Besides GPS-based registration, point clouds or 3D models can be used for marker-less AR registration.

Through the literature review, although there are examples for AR powered architectural models, tangible interaction with AR powered architectural models and marker-less AR registration methodology employment are not considered individually or together, but integrating them in this research brings novelty to the framework.

PROTOTYPING

A prototype was created using the Unity game engine to demonstrate the adoption of AR with a 3D model-based registration and the applications of integrating physical and virtual models in AR. The prototype consists of a physical model and virtual components; the virtual parts can be visualized on the screen of a hand-held device, i.e. an AR-enabled mobile phone. A mobile phone App was built which registers with a 3D model and enables the virtual parts to be mounted on the physical model so that the physical and the virtual parts could be perceived together on the screen.

As an example of physical models, LEGO® Architecture London was chosen, which was 5" high, 11" wide, and 3" deep (Figure 1). In our experiment, the LEGO physical model was not built completely but with the London Eye missing on purpose (Figure 2).

The aim was to demonstrate integrating virtual model components into the physical model in AR and examine the registration performance and potential applications, e.g., visualizing the dynamics of the model by animating the rotation of London Eye. In addition, another virtual component of LEGO Buckingham Palace, was added into the model to visualize different design options.

Besides, two different user interactions with (1) the London Eye virtual model (rotation start and stop), and (2) the Buckingham Palace virtual model (visibility on and off), respectively, were created and demonstrated. The AR App was built in Unity on Windows and deployed as an application through Apple's XCode to an AR-enabled iOS device (iPhone).

Registration

The 3D model-based AR registration is implemented using Vuforia's Model Target method (Vuforia, 2020). Using machine learning in the Model Target Generator (MTG), the Vuforia Engine is able to train an AR registration model with a 3D CAD model for recognition of the corresponding physical model in AR. The user is asked to specify a guide view for a 3D object for the training and then at the end of the

Figure 1
LEGO Architecture London (*LEGO Architecture London*, n.d.)

Figure 2
LEGO Architecture London without the London Eye as preparation for AR experiments

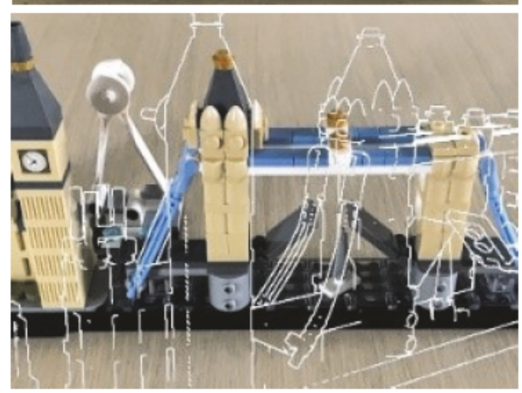

Figure 3
Model Target registration using guidelines

training process, MTG generates border edges of the 3D model as guidelines for the AR registration. During the registration process, the user is required to move the AR device to overlap these borders displayed on the mobile phone's screen with the physical model (Figure 3).

As a more advanced registration method, Advanced Model Target Database could be created by deep learning training process with the Vuforia Engine where recognition ranges can be defined up to 360 degrees (Vuforia 2020). In this training, 2D images of the CAD model with different backgrounds are automatically populated and augmented inside Vuforia Engine and deep learning is applied on these images to learn from them and detect their edges. Since the process is complex, it requires more time and leads to the advantage of AR registration without the necessity of guidelines, i.e., the model target could be recognized from any point of view (Figure 4). In our prototype, we implemented the first method and then switched to generating a database to overcome the limitations of aligning guidelines with the object in the registration.

The virtual model (obj format) of the LEGO Architecture London excluding the London Eye was used in the training of the Model Target. An adaptive mode of registration was selected in Vuforia engine enabling the AR content to robustly adhere to the physical model in case of any movement (translation and rotation) of the physical model.

In a Unity project, a virtual model of the London Eye was mounted on its physical location in the LEGO model. The virtual model (fbx) provides a realistic rendering of the London Eye in AR. Similarly, the virtual model of LEGO Buckingham Palace (fbx) was added to the scene on the left side of the skyline, next to the National Gallery (Figure 5).

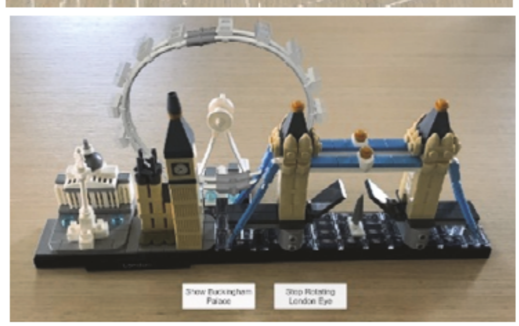

Figure 4
Advanced Model Target Database registration without using guidelines (the London Eye is a virtual model)

Figure 5
London Eye and Buckingham Palace were inserted into the physical model in AR automatically

Occlusion

When working in AR, physical objects and virtual contents should align in the perspective view and blend in terms of scale, occlusion, and rendering to create a realistic scene. Appropriate occlusion makes objects (either physical or virtual) in the front, blocking the view of the objects (either physical or virtual) behind or the background according to the physical reality. Occlusion in AR can happen in two ways: virtual blocking the physical or vice versa (Schmalstieg and Höllerer, 2016). Physical objects such as hands occluding virtual objects should be considered especially if an interaction is involved (Yan, 2022). Another occlusion challenge lies where virtual contents occlude physical objects by default but the opposite is desired. To overcome this issue phantom rendering is introduced using a 3D virtual model of a physical object aligned with the physical object and rendered invisibly in AR (Breen et al., 1996; Kalkofen et al., 2011; Yan, 2022).

In the front view of our prototype, the virtual London Eye is located behind the physical London's skyline LEGO pieces. Therefore, we had to phantom render the registered London's skyline virtual model to enable the physical model to occlude the virtual London Eye appropriately. Phantom rendering was implemented using a C# script to create a corresponding shader material.

User Interface (UI)

There are many ways to interact with AR such as using gestures, body posture tracking, hand and finger tracking (Schmalstieg and Höllerer, 2016), the movement of the head for HMDs, and the movement of a hand-held device. For demonstrating the major functions of visualization, we utilized the simple touchscreen UI (buttons) for the two interactions designed for this prototype: rotation and visibility of virtual model components.

For the first interaction, the dynamic part of the AR, London Eye was chosen to rotate around Y-axis (in Unity) through its central point. The rotation control enables specifying the speed of the rotation in Unity's C# programming (Figure 6). The fbx model of London's skyline (including the London Eye) was a collection of individual meshes of LEGO pieces. For the second interaction, the visibility of the virtual Buckingham Palace can be controlled, which is also programmed in C# (Figure 7). To better illustrate the discussion here we prepared a demonstration video of the framework and we highly recommend to check it at the following URL (YouTube Video): https://www.youtube.com/watch?v=PmzfWTz5rDQ

DEMONSTRATION

It is important to manipulate a physical model from different angles in order to examine it. The aim was to demonstrate how the created, new functions of integrating physical and virtual models work for visualizing design alternatives and dynamics with a physical model, by manipulating the model. To do that, we defined eight individual test cases and explored the performance and potential uses of the prototype. The eight cases were created by a combination of using three parameters with two different states (on and off) for each case. The parameters were animation of the rotation of a digital model, visibility of additional building, and manipulation of the physical model. The authors tested the prototype for on and off state of each parameter for all possible combinations. With an initiation of the App, registration worked instantly independent from the angle approached to the physical model. After the registration, the virtual London Eye appeared and aligned with the physical model, and it could start and stop rotation. The virtual Buckingham Palace's visibility could be turned on and off. The physical model was manipulated and changed its position and orientation (Figure 8). Although the movements of the physical model were quick, the prototype provided robust and accurate AR tracking and registration, and realistic occlusion in all test cases. Right in the user's hand, the animation of the London Eye and the visibility of Buckingham Palace can be examined freely from different viewing angles following the motion of the hand.

Figure 6
The sequential photos were taken from the animation while virtual London Eye is rotating in the counterclockwise direction at 0º, 30º, 60º, and 90º respectively

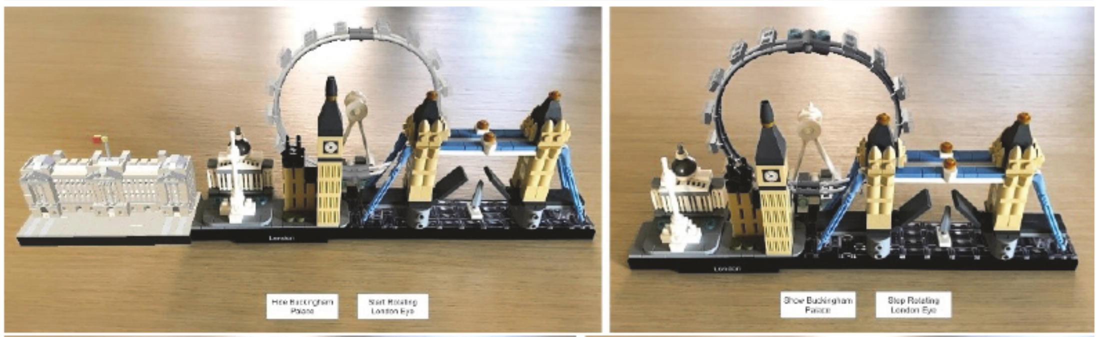

Figure 7
The virtual Buckingham Palace's visibility is changing (on and off)

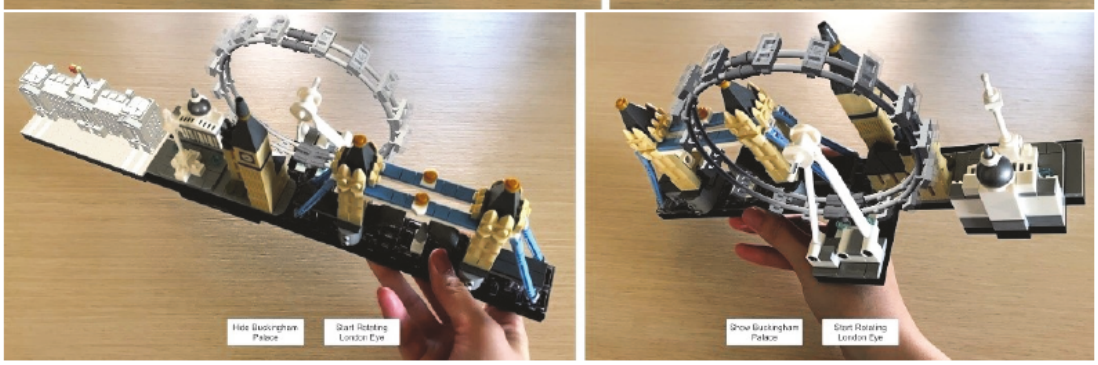

Figure 8
Manipulation of the physical model and the viewing angle

CONCLUSION AND FUTURE WORK

The AR-powered physical models introduce a new way of architectural representation which goes far beyond a simple representation. Although the physical models are known as reductive representations of architectural projects, AR integration not only may add a realistic touch up (e.g., adding up material, texture, and lighting effects or details on the surface of a physical model) but also can scale up the representational capability and tackle the physical limitations of a model. This extension could be observed on many levels: 1) adding a realistic rendered look on a model, 2) displaying building information with numbers, tables, graphics, and visuals, therefore providing substantial data to further demonstrate a project, 3) exhibiting 2D architectural drawings including plans, sections, elevations, orthographic/perspective drawings and details, 4) illustrating site plan, future development plans in 3D, surroundings and environmental elements, and 5) employing animation to demonstrate:

- the usage of the building and its surroundings with agents and vehicles, such as movements of users and vehicles in an airport project,

- various building performance simulation results, such as visualized simulation results changing in a period of time or for the exact dates and time,
- dynamic parts of the buildings' mass, envelope or structure, such as climate responsive envelope behaviors or rotating or
- moving parts of towers or high-rise buildings, and
- exhibiting parametric design options with the help of UI, so that a user can control the parameters and project the changing design options on top of a physical model.

With our prototype, we presented an AR animation on a physical LEGO model which is an example of a dynamic feature. At the same time, we elaborated the physical LEGO skyline model by adding a 3D virtual building model in AR which can be an example of contextual surroundings or a future development scenario. Utilizing AR for extending the capabilities of a physical model for the aforementioned utility would be easier, faster, and low-cost, or sometimes the only possible way compared to adding those features using other medium, such as electrical or mechanical systems.

This association of AR with physical models adds significant value to the utilization of physical modeling in design and education. As previously demonstrated in our prototype, right in the user's hand, the animation and visibility of building components in AR can be examined freely from different viewing angles following the motion of the hand. This is expected to strongly enhance the tangible and general user interfaces between designers and the designed artifacts. Real-time tangible interaction is especially crucial in (architectural) education for understanding and building spatial relationships with enhanced eye-hand coordination in AR. With the integration of physical and virtual models in AR, the real-time tangible interaction would be preserved. The user can freely interact with the physical model while maintaining the AR parts robustly adhered to the physical parts during manipulation. In other registration methods, where AR is registered by a marker or a planar surface, the user either has to keep the marker visible to the AR camera all the time or the AR model needs to stay on a surface and cannot be transformed and examined in 6 degrees of freedom (DoF). Employing the 3D-model-based AR registration method in our prototype allows AR parts to move alongside the physical model so that the user can freely manipulate the physical model with its AR parts. The AR registration works robustly in various backgrounds with reflection and noise, which eliminates the need of a uniform background. In addition, the user can interact with the AR-powered model both tangibly and through the use of UI on the AR device screen. The UI interaction would present a useful and quick control of the AR parts.

The limitations of the research include that the AR registration model needs to be updated when the physical model is changed. The use of the LEGO model was for experimenting as a simple yet representative physical model example in the early stage of the research, and future work will include more types of physical scale models with different materials and constructions used in the architectural workflow. Also, although being more accessible, AR in mobile device may not be practical while handling the physical model and may interrupt the user experience and can be distractive; so, a tripod may be needed during the experience.

Future work will also include user studies for the effectiveness of the developed AR system for architectural design. Moreover, different AR devices, e.g., AR glasses, with different UI designs can be investigated in the future for how they can support architectural design and education.

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