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A MIXED REALITY APPLICATION FOR HOLOGRAPHIC STRUCTURAL ANALYSIS EXPERIMENTS

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Abstract

Digitalization in higher education has become an unprecedented demand in recent years, especially under exigent circumstances, such as the recent COVID-19 pandemic. New formats and platforms for learning objects must be devised to conform with decentralized learning demands. Parametric modeling and mixed reality (MR) technology provide a sound basis for designing virtual learning environments. This paper presents a MR application to experience (immersive) virtual learning environments for structural engineering students by visualizing structural analysis results as interactive holograms. Different experiment phases and modes are explained in detail, followed by a discussion on further extension possibilities to the MR application.

Introduction

In recent decades, with advances in information and communications technology, new learning concepts such as E-learning and blended learning have been introduced and spread across several education institutes and disciplines (Tlili et al., 2021). A learning object is a digital or nondigital entity, which is devised for learning, education or training. Learning objectives and frameworks play a key role in selecting the most suitable learning objects (IEEE Standard for Learning Object Metadata, 2020). Conventional learning objects are progressively transformed into digitized formats, while digitalization in education has founded new formats for learning objects, such as computer-generated models, virtual classrooms, and holographic teaching (Paredes & Vázquez, 2020). Technology-enhanced learning environments offer several benefits, namely in terms of interoperability of course materials, re-usability and modifications, and decentralized learning experiences. However, accessibility, whether in terms of open-/closed-source means or platform/device dependency, poses challenges for both educators and students (Sandanayake, 2019). Yet another drawback when considering modern learning objects is the complexity, which is perceived with respect to workload (skills and time) required for preparing a learning object.

Virtual, augmented, and mixed reality (VAMR) applications, as a subset of computer-generated learning objects, have been widely implemented in various educational fields (Matišák et al., 2020). For example, various applications have been employed in healthcare education and medical treatments, which are proven as effective tools for interactive and immersive trainings (Gerup et al., 2020). Moreover, similar research efforts on VAMR applications have been conducted in diverse research fields, such as aviation, robotics, and industrial engineering, with the sole objective to evaluate effectiveness and quality of immersive experiences, both in training and in practice (Bartik et al., 2019). In the architecture, engineering, and construction (AEC) industry, the VARM applications can offer a wide range of implementations in different operational phases, from design and planning to fabrications and maintenance management. However, VARM applications are not yet employed as a common tool in practice (Cheng et al., 2020; Tayeh & Issa, 2020). In recent years, several implementations of VARM applications for AEC education and training have been conducted and reported (Wang et al., 2018).

In a previous work, existing guidelines for designing educational multimedia environments have been reviewed to derive categories of design principles suitable to transform to MR learning environments (Yepes et al., 2020). Later, learning scenarios from the field of structural mechanics were implemented for engineering education use and the examined motivational and cognitive parameters resulting from user studies were evaluated by means of success control (Krischler et al., 2021). Building up on this application, further developments to investigate the learning behavior and corresponding control variables in an experimental setting for the target group of civil engineering students, have been conducted within the *AuCity2* project. Turkan et al. (2017) have developed an iOS-based AR application for mobile devices that can be used for teaching structural analysis concepts leveraging holographic 3D models. Another notable example is the use of audiovisual learning objects in the *PARFORCE* research project, where 360-degree and 180-degree 3D footages from lab experiments are exhibited on virtual reality (VR) glasses and smartphone devices (Abrahamczyk, 2022). The project aims to develop an open-access VR environment to be used for collaborative and interactive virtual experiments in the field of civil engineering. Similar use cases, distinctively in AEC teaching, confirm the applicability and effectiveness of VARM applications leveraged for virtual learning environments (Torres et al., 2021).

This paper presents an immersive virtual experiment designed for structural engineering students. Within the scope of our main project, we aim to explore the utilization of VARM technologies in engineering education as a complementary tool to the usual curriculum and to investigate the effects attributed to incorporating enhanced learning environments in comparison to traditional learning methods. By developing VARM applications and conducting user studies with the desired target groups, we hope to gain insights into the motivational and cognitive parameters to further improve the use of such technologies within the realm of educational institutions. In this experiment, students can randomly define virtual structural elements that overlap with real world objects, can manipulate geometrical and structural parameters, and can select the desired structural analysis results to be visualized. Parametric modeling and mixed reality tools are used to develop a holographic view of structural analysis results based on user inputs. For visualizing holograms, the Fologram application is used on smartphones and Microsoft's HoloLens AR glasses. The objective of the current application is to enable the user to experiment with different structures by defining the number of nodes and elements, the loads as well as the degrees of freedom. Through the instantaneous overlay of the forces and deflection curves as holograms, the user can see and compare results of different models. The MR application is defined using the parametric design plugin of the Rhinoceros 3D software, the Grasshopper plugin. Background information on concepts and tools used for developing the MR application is briefly discussed in the following section. The rest of the paper demonstrates the parametric model forming the virtual experiment in detail, discusses experiment results from student trials and experiment limitations, followed by conclusions on the MR application and potential future improvements.

Theoretical background on parametric modeling

Parametric modeling in computer-aided design (CAD) refers to models, in which design features and constraints are adaptive and can be modified. Unlike direct modeling, geometrical and analytical parameters in a parametric model can be adjusted, either through random assignments or by pre-defined list of values. Thus, the parametric design approach can offer vast flexibility through automatic updates to the model, while averting the need for starting a model design from scratch (Harries et al., 2019). In addition to design iteration and automation, parametric modeling can facilitate platform design for a family of products, while integrating processes that reduce the production time. However, when compared to direct modeling, parametric modeling has few drawbacks, such as lack of interoperability (platform-dependent designs) and ease of use (higher design effort) (Chang, 2015). Fu (2018) has listed methods, software tools, advantages, and challenges of parametric modeling in CAD for complex structures.

The use of parametric modeling in engineering and architectural education can enable students to explore multiple design alternatives in early stages of learning, which in turn can lead to a deeper understanding of design outcomes, i.e., the impact each variable may have on a model design as well as relationships between parameters. Internalizing relationships between variables and outcomes has been proven effective for understanding design processes in a case study by Agirbas (2018). The difference in thinking in terms of parametric design and the cognitive impact through the parametric design adoption have been identified in the work by Oxman (2017). Yu & Gero (2016) have analyzed the cognitive behavior of architects at different design stages in an empirical study by comparing their use of parametric design to geometric modeling in similar tasks. The findings were further evaluated in terms of produced outcomes and performance in a later work, which outlines the many benefits of using parametric design (Yu et al., 2018).

There are several software tools that can be used for parametric modeling. For example, Solidworks is a powerful tool for parametric design in mechanical engineering, or Creo Parametric is a very well-known 3D modeling software for industrial designs. Rhinoceros 3D is a modeling tool used in various industries for both direct and parametric modeling. The Grasshopper plugin in Rhinoceros 3D is a visual programming language used for parametric modeling. Grasshopper offers various components for describing geometries, generative algorithms, and integrated scripts, thus, provides a user-friendly, flexible, and efficient environment to parametric designers. There are several add-ons already developed for Grasshopper, which can integrate more functionalities and components for desired use cases. For example, the Kangaroo2 add-on is used for simulating, optimizing, and constraint-solving lightweight structures (e.g., membranes) and the ShapeDiver is used for exporting and visualizing adaptive models on web applications.

In mixed reality, parametric modeling can be used to design an adaptive virtual experience. Through user interactions, virtual objects may be (re-)placed in different positions or may be later modified. However, there are currently limited practical tools that can visualize structural parametric models on AR/VR wearables. For example, Coppens et al. (2019) have developed software components to connect parametric models to VR headsets, and have showcased an immersive virtual environment for a building model that can be modified through pre-defined list values. Fologram is a toolkit that can instantly visualize Rhinoceros and Grasshopper models on HoloLens AR headsets or smartphones. Model geometries, layers, and material parameters can be synchronized with the Fologram application on the connected device (Fologram toolkit, 2022). Various applications of Fologram toolkit have been reported in research projects. For instance, Belesky et al. (2020) have used Fologram for holographic visualization of AR information on a live sandbox landscape in real time. Also in practice, many successful implementations of Fologram can be found, e.g., the MR application for construction of curved benches and the Steampunk installation (Albajar, 2019; Jahn, 2020). The Fologram add-on facilitates connection of multiple devices at the same time and offers various Track components for hand gestures (only on HoloLens glasses), pointers, scans, and device states. Parameters, material, and geometries may be synchronized with all connected devices through *Sync* components. Any changes to the synchronized parameters, material, and geometries on connected devices are in turn reflected on the Grasshopper model in real time. Details on Fologram components and use cases are well-documented and can be found on Fologram community online (Fologram Community, 2022).

Karamba3D is a powerful Grasshopper plug-in for parametric finite element calculations in structural analysis and coupled optimization algorithms. Components for defining structural elements, such as supports, beams, and shells, along with components for describing load cases, materials, cross section properties are included in the Karamba3D plug-in. Algorithms, such as linear and nonlinear structural response, cross section optimization, buckling and internal forces evaluations are already available as analysis components. However, when desired, Grasshopper *Script* components can be used to integrate further finite element functionalities of interest. In Karamba3D, structural analysis results are defined through various components with meshes, curves, and vector outputs, e.g., the *Beam View* component can return meshes of the rendered beam element and sectional forces as curves. Fologram *Sync* components can be used to visualize holographic view of geometries and analysis results generated by Karamba3D plug-in (Karamba3D parametric engineering, 2022).

MR application for holographic experiments

This section describes the Grasshopper parametric model designed for the MR application for structural analysis experiments in detail.

The MR application comprises four sequential phases, i.e., spatial mapping, point selection, model definitions, and model analysis phases, which are explained in the following subsections. An overview of the MR application phases and their respective order is schematically depicted in Figure 1. It is worth noting that HoloLens1 and HoloLens2 AR glasses are considered as main devices for testing the MR application; however, the MR application can also be used on smartphones.

Spatial mapping

The first phase in the application is set for 3D reconstruction of the surrounding real environment, i.e., registering geometries in form of meshes or point clouds. This process in AR/MR applications is called spatial mapping. Through meshes, all surfaces are scanned and collected as a set of triangles with registered vertices and planes. As the user equipped with a pair of HoloLens glasses starts the mapping phase, holographic meshes appear spreading over the scanned space. For accurate scans, it is advised to slowly move around the environment, looking in all directions while going over areas of interest multiple times. Spatial mapping is of great importance for an immersive MR experience, in which occlusion of virtual and physical objects are to be set correctly.

In the parametric model, the Fologram component *Track Scan* collects meshes scanned by HoloLens glasses. As the user moves around in the real world and more meshes are registered, the number of meshes as the output of *Track Scan* component increases. As soon as the spatial mapping of areas of interest is completed, the user can change the model phase from a list value. Using the *Sync Parameter* component, a list value containing application phases is defined.

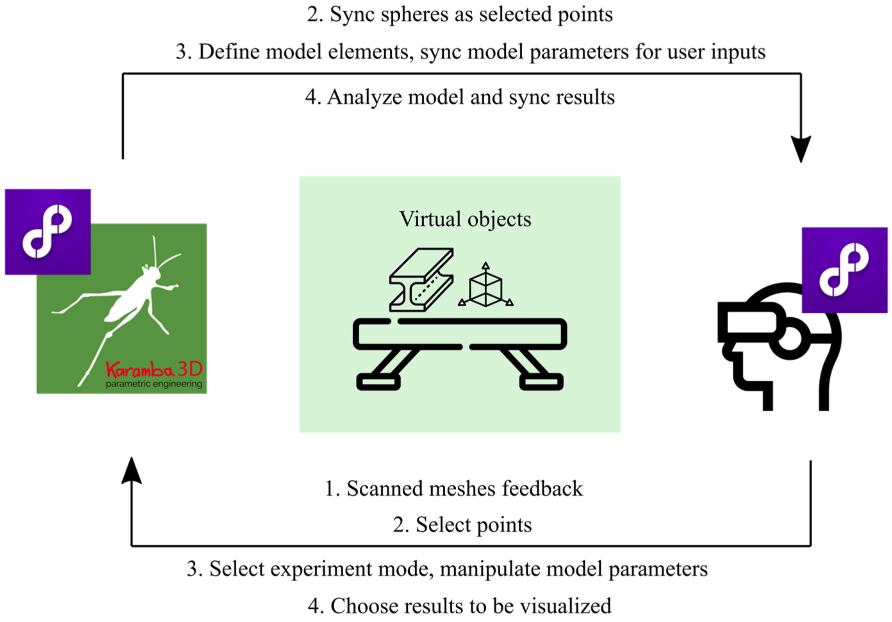


Figure 1: Overview of the MR application

The list value appears as a holographic drop-down menu under the parameters tab on the Fologram application on HoloLens. Figure 2 showcases a spatial map, which was tracked by Fologram plug-in on Grasshopper and was visualized in Rhinoceros in real time.

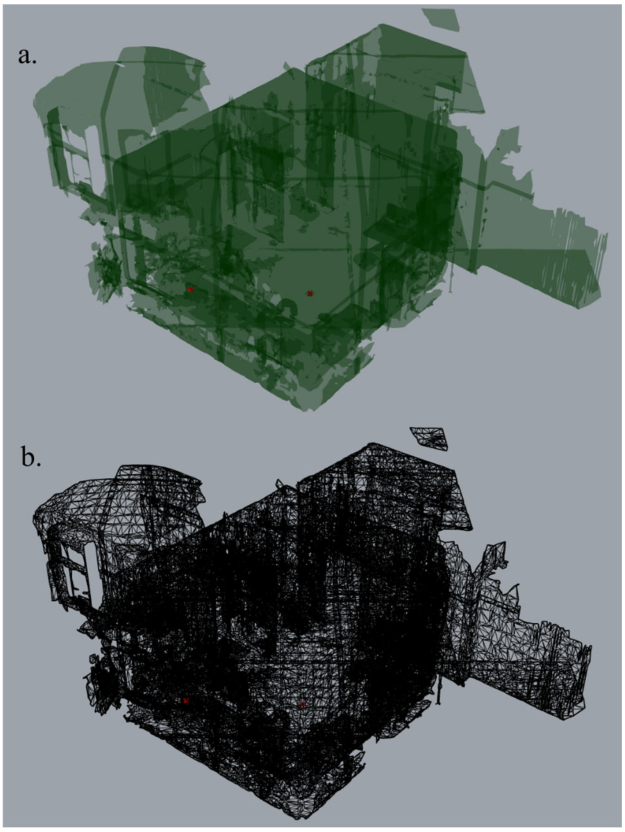


Figure 2: A spatial map of scanned surfaces and objects (a.) and the respective wireframes (b.) in Rhinoceros3D

Point selection

Following the spatial mapping phase, the user must select reference points for defining structural elements. Points are selected either within the scanned space or are aligned to surfaces and objects, i.e., are snapped to scanned meshes. For the latter, mesh outputs of the *Track Scan* component are jointed as one mesh entity. Using Fologram *Track Pointer* component, users index finger is being tracked as pointer rays. The *Mesh Closest Point* Grasshopper component is used to find the closest pointer ray to the scanned mesh entity. On press or by tapping, a point can be registered. Each selected point is set as a base plane for a sphere geometry with a given radius and is visualized on any connected device using the *Sync Object* component. Figure 3 displays an example hologram of points snapped on the mesh surfaces.

So far, there are two experiment modes defined in the MR application: Beam and frame analyses. For the beam analysis, the user must select at least two points. Respectively, for the frame analysis four points must be registered. Extra points selected are automatically eliminated as soon as point selection phase is completed. A reset button is defined within point selection phase for erasing registered points; hence, in case of wrong selections or alignments, users can restart point selection phase easily.

Figure 3: Random points selected by snapping to scanned surfaces (a.) and sphere alignment on the surface (b.)

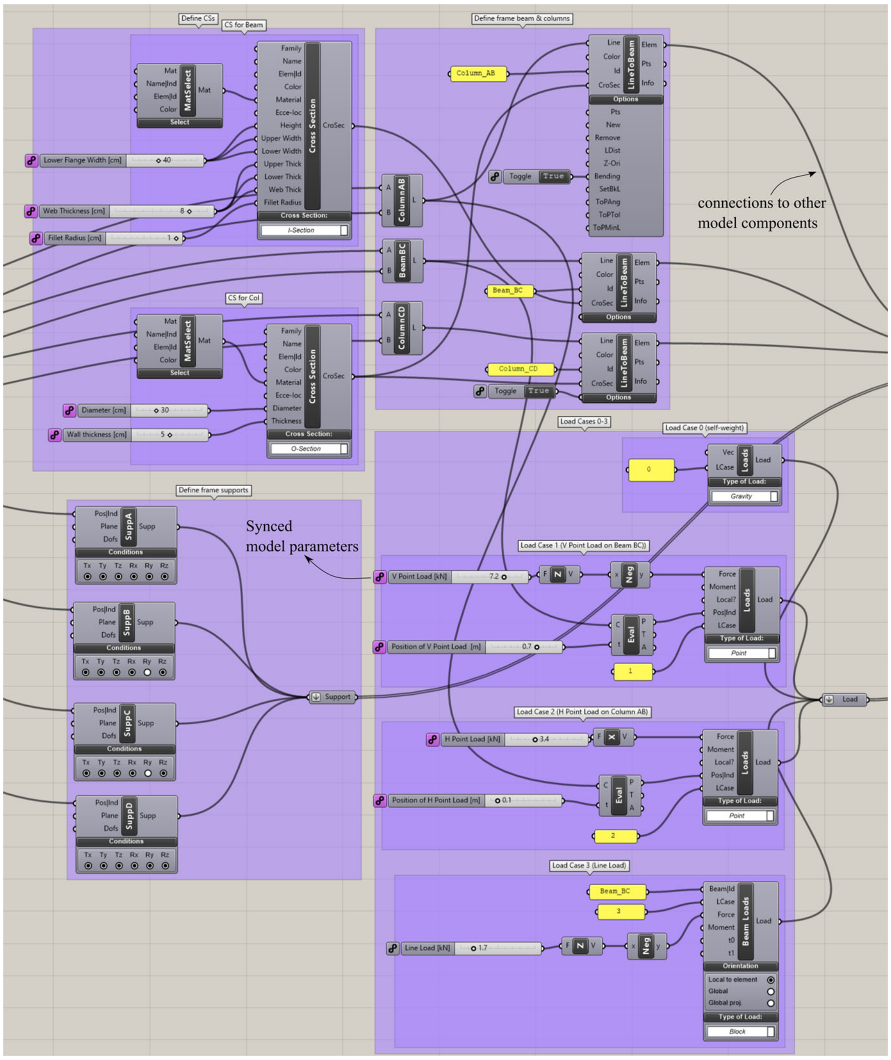
Model definitions

In this phase, Karamba3D components are used for defining model elements, such as beams, cross sections, material properties, supports conditions, and load cases. Reference points collected from the last phase are used here for defining line segments among each pair of points. Then, the Karamba3D *Line To Beam* component transforms line segments into beams. It is worth mentioning that line segments when meeting at a common point are automatically connected. Through the *Cross Section Range Selector* component, a cross section shape and type according to international codes can be adjusted. Analogously, the *Material Selection* component specifies material types and classes.

A support can be defined using the Karamba3D *Support* component, which is defined by position index (i.e., point), orientation plane, and integers indexing degrees of freedom to be fixed. By synchronizing indexes using Fologram *Sync Parameter* component, users can manipulate support conditions. Karamba3D can define various load types and combinations, such as gravity, point, and distributed loads, as well as initial strains and prescribed displacements. In the MR application, users can toggle between different load cases using pre-defined list values. Figure 4 partially illustrates model definitions used for the frame analysis mode.

Model Analysis

After defining and assembling model elements mentioned above, the model is ready for structural analysis. Karamba3D contains algorithm components, such as small deflections, large deformations, Eigenmodes and buckling modes analyses. To date, the MR application has been tested for performing first and second order small deflections analyses. Karamba3D components listed under *Results* tab are categorized in general model, beam-specific and shell-specific components. The *Mode View* component is used to review current state of each model and can transfer deformed meshes, curves and displacements to a *Beam View* component for visualizing purposes. Legends and tags can be assigned to analysis results, which are represented using curve and mesh components. Further adjustments to analysis results, such as defining section force ranges, boundary conditions and maximum (absolute) values are conducted using Grasshopper components. Figure 5 presents an instance of



connections to other model components

Synced model parameters

Figure 4: Partial view of model definitions for an instance of the frame analysis mode

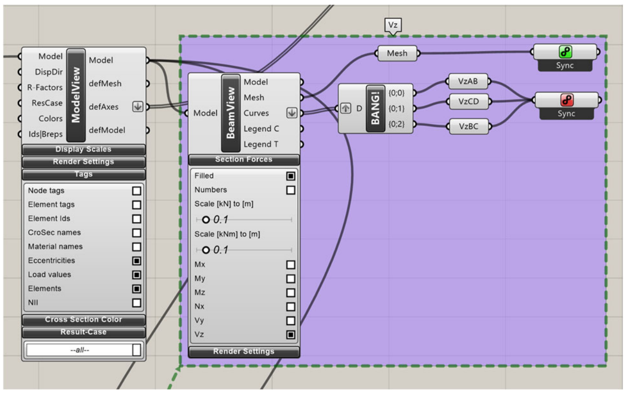


Figure 5: An instance of beam view settings for analysis results using Karamba3D and Fologram components

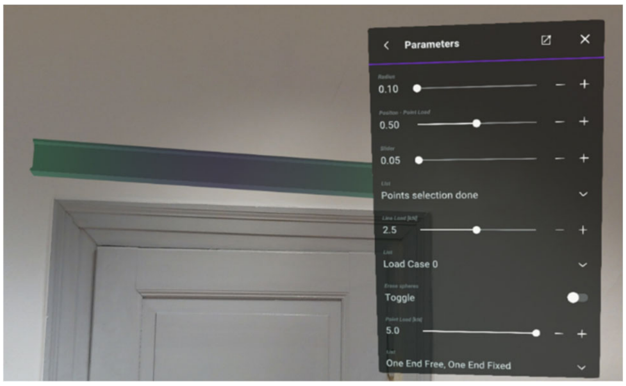
component settings for model analysis results defined for the frame analysis mode. In this Figure, the *Beam View* component is set to show results for shear forces (*Vz*) with *Filled* settings for all load cases. Thus, the output *Curves* produces corresponding lines representing the *Vz*-diagram, and output *Mesh* is producing the mesh area under the *Vz*-diagram. Each output is in turn visualized using the *Sync Object* component with different colors.

Results and discussion

To evaluate the MR application, several experiments have been conducted using HoloLens AR glasses and smartphones. In the following paragraphs, a set of test results is highlighted.

A hologram of a beam element and respective model definition parameters are shown in Figure 6. Users were asked to change model definitions using synchronized cross section, material, load and support parameters. A list of values, appearing as a drop-down parameter on the Fologram application under parameters menu, helps users navigate through different material and cross section definitions. Load magnitudes can be altered using number sliders and for support conditions, a value list together with the *State Gate* component is used to provide five support combination scenarios.

In the beam analysis mode, there are four load cases defined. For the desired load case, users can select the results to be viewed as deformed curves and meshes with color legends and can retrieve maximum section forces and deformation values as text tags. For example, Figure 7 shows bending moment results with respect to a point load applied in the middle of the beam element and Figure 8 depicts shear force results due to a combination of distributed load (cases) and the applied point load.



Parameters

Radius 0.10

Position - Point Load 0.50

Slider 0.05

List: Points selection done

Line Load [kN] 2.5

List: Load Case 0

Erase spheres: Toggle

Point Load [kN] 5.0

List: One End Free, One End Fixed

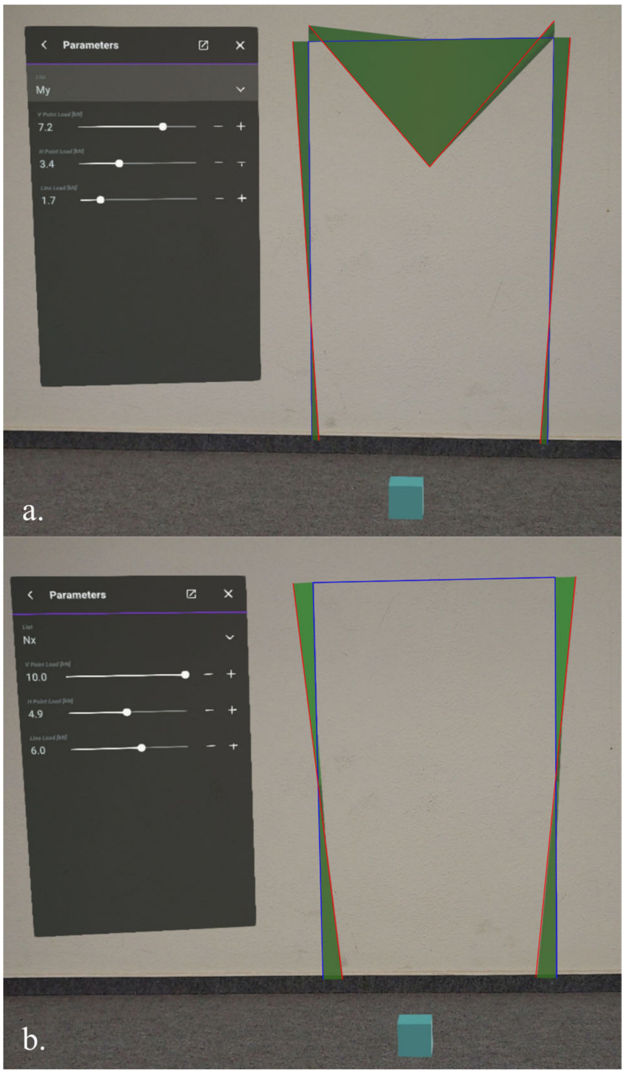
Figure 6: Hologram of a beam element and synchronized model parameters on the Fologram application

Figure 7: Holographic view of analysis results for bending moments in a beam element with the maximum value

Figure 8: Holographic view of analysis results for shear forces in a beam element with the maximum value

Another group of students, who had tested the MR application for the frame mode, have submitted screenshots from the holograms on HoloLens AR glasses, as depicted in Figure 9. For better visualizations, the students have only exported the resulting curves with respect to section forces and the undeformed fixed frame.

According to the feedback received from students, who have participated in testing the MR application, the virtual experiment featured in this project can offer the intended interactive experience to students. However, due to limited number of HoloLens AR glasses available at the laboratory and restricted lab access during the pandemic, some students could only test the MR experiment on their smartphones. Due to the higher quality of spatial mapping and possibility to use various hand gestures associated with more functionalities than on a smartphone, the MR application can be used with its full capacity on the HoloLens AR glasses. There are, however, two restrictions when using the MR application, i.e., device dependency and software license costs, which limit users' access in practice. While collecting users' feedback, the focus was put on testing the application integrity in producing holograms from model elements and analysis results, rather than on users' comfort. Some students have reported problems when interacting with the parameter menu and navigating through synchronized parameters. This matter is to be addressed in the future to improve the robustness of the MR application.



Parameters

List: My

V Point Load [kN] 7.2

H Point Load [kN] 3.4

Line Load [kN] 1.7

Parameters

List: Nx

V Point Load [kN] 10.0

H Point Load [kN] 4.9

Line Load [kN] 6.0

Figure 9: Holographic view of analysis results for bending moments (a.) and axial forces (b.) in a fixed frame

Conclusions

A mixed reality application as an interactive and immersive virtual experiment for structural analysis has been presented in this paper. Background information on decentralized learning, new formats and platforms for learning objects suitable for a virtual learning environment, and few examples of VARM applications implemented for virtual experiments in AEC teaching has been presented. Later, parametric modeling tools and software packages implemented for developing the MR application have been elaborated in detail. The MR application has been designed using the Grasshopper plug-in for Rhinoceros 3D software as a parametric model, which is based on vital components from Fologram and Karamba3D add-ons for Grasshopper. Spatial mapping, point selection, model definitions, and model analysis have been discussed in detail as the MR application phases. Structural engineering students have conducted several tests on the MR application using HoloLens AR glasses and smartphones. The feedback from tests has shown that the MR application could correctly reconstruct the real environment, register user input parameters, perform analysis algorithms based on user-defined criteria, and visualize holographic view of analysis results in form of meshes, curves, and text tags. Shifting from the focus of this work of implementing an initial experimental setup with multiple modes for structural analysis visualization and testing the usability of such application, the next steps of development are intended to concentrate on the learning outcomes and cognitive load and behavior of users. In addition to the expansion of the structural analysis in the background in form of additional experiment modes, integration of extra algorithms and the use of control keys for higher user comfort, users should be enabled to interact with the created structural systems by changing the materials, geometry, degrees of freedom and loads to observe and learn the effects of these parameters. Empirical user studies must be conducted to explore the application's full potential and later to compare resulted learning outcomes with traditional learning methods. Furthermore, the empirical studies could provide insights into the additional information needed to be presented in virtual environments and suitable learning objects with potential merit.

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