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Research Article

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Posted Date: February 19th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-3941650/v1

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Augmented reality to visualize a finite element analysis for assessing clamping concepts

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Abstract
This paper presents the development of an innovative augmented reality application for evaluating clamping concepts through visualizing the finite element analysis. The focus is on transforming the traditional simulation results into immersive, holographic displays, enabling users to experience and assess finite element analysis in three dimensions. The development process involves visualization in the software Unity, data processing by MATLAB, and the use of Microsoft’s Hololens2 for displaying the holograms. The most important advancements include the ability to visualize complex clamping situations, enhancing understanding and engagement in engineering education. The application was tested in a real machining environment, revealing significant performance improvements with help of an external PC and offering an immersive learning experience. This work not only demonstrates the technical feasibility of such applications but also opens new avenues for interactive and engaging learning in engineering education.

Keywords: education, augmented reality, machining, clamping fixture, finite element analysis

1 Introduction
As the calculations in classic finite element analysis (FEA) programs are usually carried out in 3D, it seems natural if it would be possible to look at them in three dimensions. However, this is impossible with classic output devices like screens, projectors, or even paper printouts. There is always only a two-dimensional image of a 3D calculation, even though it can be seen from different sides and various directions. Thus, essential possibilities are only available to the user to a limited extent. The results and the related information are not presented very excitatingly any more, even though they are colourfully animated, as they represent the state of the art and are sufficiently well-known as well as used in the engineering world.

In this work, an augmented reality (AR) application was developed to evaluate the characteristics of clamping situations using FEA simulations. The presented development shows possibilities for visualizing FE calculations with the help of holograms via a head-mounted display (HMD). The focus of the development was to convert a simulation of a clamping situation with
the finite element method into a holographic image, in order to be able to assess the quality of the clamping situation for a selected machining task. The visualization was performed with the HMD. Since the HoloLens2, Microsoft’s mixed reality headset, was used in this application, the terms “HMD”, “smart glasses” and “headset” are used in this paper to describe the AR end device.

The paper is structured as follows: the state of the art is presented in Section 2. Section 3 describes the approach and methodology, focusing on the technical process of converting FEA simulations into holographic displays using Unity. It also covers data processing between ANSYS Mechanical and Unity using MATLAB. Section 4 details the development and features of the augmented reality application, including the user interface, menu navigation, and scene-specific interactions within the application. In Section 5, the developed AR application was tested in a real research environment. The performance improvements achieved by integrating an external PC and the immersive experience provided by the HoloLens2 are highlighted. The last section concludes this research work, points out the limitations of the AR application, and discusses the research interest in engineering education.

2 State of the art and previous research

In 1994, Milgram et al. were the first to differentiate between the terms of AR, virtual reality (VR) and mixed reality (MR) within the reality-virtuality continuum [1]. The virtual environment describes a synthetic world in which physical laws, such as gravity, time and material properties, no longer apply. The real environment, on the other hand, is clearly limited by the laws of physics. These two concepts are seen as opposite ends of the reality-virtuality continuum.

Due to an ever-increasing number of interesting and more powerful HMDs, not only the number of uses but also of developed applications is growing in the scientific field. In the following, developments relating to education and engineering are presented in particular.

An overview of AR and VR publications on developments in the field of education was presented by Abdullah et al. 2023 [2]. Criteria such as the number of publications by source, keyword or subject area were analysed from selected sources of database (Scopus). Regarding the subject area, engineering ranked third with 15.2%, ahead of medicine in fourth place with 14.5%. Computer science was in first place with 22.5%, and social science came in second place with 15.6%. Over the last several years, the number of publications in the context of AR and VR has increased exponentially.

A further overview of augmented reality and virtual reality in the context of work, research and teaching was presented by Knoll and Stieglitz in the Springer journal “HMD Praxis der Wirtschaftsinformatik” in 2022 [3]. In this German publication, they discussed the opportunities and risks of open source projects, along with various industries and key areas of development.

In 2015, Huang et al. [4] developed a special application involving FEA with AR features, in which the stresses acting on the real objects were visually superimposed. In the case of a stepladder, force sensors were used to determine the acting loads. In the Springer Handbook of Augmented Reality, Huang et al. presented a detailed description of the development of an AR application integrated with FEA [5]. This comprehensive description illustrates a marker-based system that superimposes virtual FEA objects onto a real environment. The system, developed since 2015 [4], has been tested in various scenarios with different inputs and result options. The focus is on the calculation and interaction with a stepladder. This system includes features such as sensor integration, selection of objects using marker-based pointers, and the display of calculation results in the real environment. In contrast to the application developed in this work, the FE calculations or the FE mesh are presented on a 2D screen, not through an HMD device. The HMD device enables realistic 3D display with eye-tracking capabilities. Moreover, the FE mesh used in this application was of a coarse resolution.

The visualization of 3D objects in space with mobile devices was carried out by Passas-Burgos et al. in [6]. The study described the development of an open access tool for mobile devices that allowed the visualization of 3D objects through augmented reality. Visualizing 3D objects in space is both a challenge and a developable skill
for engineering students, which the application presented in this paper aims to facilitate.

Another mobile application in engineering based on augmented reality technology was presented by Zhylenko et al. in [7]. The described form of education about the information transfer in a virtual environment is useful for avoiding the perception difficulties of graphic information by visualizing complex objects.

In 2022, Coronado et al. [8] provided an analysis of current augmented reality technologies and a review of the state of the art regarding augmented reality in teaching, focusing especially on engineering at the undergraduate level. The augmented reality simulation, presented as an app for mobile devices, allowed a three-dimensional representation of planar mechanisms as well as several possible interactions, plots and calculations.

Jo et al. wrote and published a patent [9] proposing a system for training, education, and/or advertising of complex machinery in MR using the metaverse. The system included a simulation performance unit, configured to carry out three-dimensional simulations by providing a digital twin to perform simulations of a specific visual component for maintenance training, education and/or advertising by means of smart glasses, as well as a training unit configured to provide artificial intelligence (AI).

As part of this project, two additional research works were conducted in cooperation with the IFE (Institute of Educational Science) at the University of Stuttgart and have been presented to the public. An AR development without HMD was described in [10] in 2021. Instructions for operating a complex turning/milling centre were displayed here to the user on a smartphone or tablet. In the context of learning and teaching, a further publication [11] in 2022 presented explanations of the structure and individual components of the same turning/milling centre, an Index R200, by means of the very realistic hologram with many individual components. The developed application was validated with selected users and analysed for further development.

3 Approach and methodology

In order to be able to display a three-dimensional simulation movement of the FEA in the form of a hologram on smart glasses, various calculation steps were necessary as the glasses can only reproduce 3D models of particular file formats. Various tools for format conversion were used as intermediate steps. The goal was to transform the known postprocessing results from classic, conventional FEA programs into immersive and interesting moving 3D holograms, which can be experienced through smart glasses. Fig. 1 shows the processing steps including the software programs used for this purpose.

The 3D model was prepared in the preprocessing and solver group. The Creo Parametric CAD tool was used to engineer the clamping situation. The simulation tasks were calculated using the FEA program ANSYS Mechanical. In addition to the use of the ANSYS solver, the postprocessing of the program including its manipulation tools served as a design model for the subsequent presentation of the simulation results. In order to be able to display a three-dimensional and continuously changing representation in the form of moving holograms on the HMD, additional steps had to be carried out involving the development of tools and the programming of scripts.

In the interface between ANSYS Mechanical and the Unity development platform, MATLAB was utilized for data processing. With its object-orientated numerical calculation of matrices, the MATLAB platform is a widely used tool in the field of science and offers the ideal aid for the necessary processing of the numerical data from ANSYS Mechanical.

The developed application was then processed for the Hololens2 HMD in the Unity real-time development environment. Unity is one of the world’s leading platforms for the creation and execution of interactive RT3D content. According to the manufacturer’s information, 70% of the 1000 most popular games for mobile devices were developed with Unity [12]. In addition to the classic operation of a program via a graphical user interface, Unity also offers the use of scripts in the C# programming language. The Microsoft Mixed Reality Toolkit offers further options, which can be used, for example, to control the behaviour of game objects and the interaction between them.

After creating an AR application in Unity, two options were chosen for transferring the data to the Hololens2 HMD. This app can
directly be created using Microsoft’s Visual Studio development environment and be installed into the Hololens2 headset. Alternatively, the data could also be transferred via the Holographic Remoting Player on the smart glasses. The holographic content were streamed from there to the HMD in real time. Both options were tested and used in the end. Further details on the individual development steps are explained in the following sections.

3.1 Use case: clamping and machining task

For the application example, the clamping and machining situation was selected as shown in Fig. 2. The clamping task was carried out in the framework of another project aimed at investigating the nonlinear, dynamic contact behaviour between the workpiece and the clamping elements (Feng et al. [13] and [14]). The details of the clamping situation are not discussed in this paper, as it is focussed on the implementation of the holographic application for a complex use case and the tools developed for displaying FEA calculations on smart glasses (HMD).

A drilling operation in a corner of the workpiece was selected as the machining task. A deep pocket had already been milled into the aluminium workpiece, resulting in larger deformations and thus a more attractive representation of the calculation results. The drill had a diameter of D = 12 mm. The feed rate was f = 0.3 mm. The calculation according to the Victor-Kienzle formula [15] resulted in a feed force of 1,136 N, which was used as a boundary condition in the FEA calculation.

3.2 Data processing and modelling in Unity

In general, the models in Unity contain information about meshes, materials and textures, defining their shape and appearance.
The representation of 3D models in Unity can generally be divided into two approaches.

The first option is to create models outside Unity and then import them. This can be carried out with the graphics file formats of .fbx, .dae, .dxf and .obj. However, these formats were unsuitable for our intended application. The alternative is manually creating a mesh and assigning materials to define its appearance. This method provides a wide range of visual options offered by the Unity development environment. For this application, we utilized the mesh class, which can be accessed via C# scripts.

The manual creation of a mesh is illustrated in Fig. 3 using the example of a rectangle consisting of two triangles. The nodes in the index array must be arranged in a clockwise direction to render a visible surface. Unity distinguishes between visible surfaces facing forwards (front-facing) and invisible surfaces facing backwards (back-facing) from the perspective of the viewer. The vertices 3D vector array lists the coordinates of the vertices, and the triangles integer array presents the nodes.
in a clockwise direction. Finally, the two arrays are assigned to the corresponding attributes of the mesh class.

Each node of the mesh can take on its own color. The color value is assigned depending on the deformation state of the model and is determined by a color gradient. Consequently, models can be displayed similarly to the FE model in ANSYS.

3.3 Data processing in MATLAB

Models in Unity are represented as an envelope by a surface mesh. It was sufficient here to model the envelope in Unity instead of modelling the entire body. This saves computing time on the HoloLens 2 HMD by ignoring irrelevant information inside the model. The visible nodes on the surface of the model contain all relevant information for the representation.

The solids used in the simulation were tetrahedral elements with ten nodes (tet10) and hexahedral elements with 20 nodes (hex20). These could each be described by a characteristic element with a specified structure of nodal points. The characteristic elements for tetrahedra and hexahedra are shown in Fig. 4. In the simulation, a surface ID defines each side of the solid so that the position and orientation could always be seen together with the nodes. The data described here was read into a MATLAB and prepared for processing in Unity.

4 Development and presentation of the features of the augmented reality application

The following section describes the structure and menu navigation as well as the interaction options available to the user when operating the application with the HoloLens 2 HMD. The menu navigation in the application is characterized by calling up an extra scene for each menu. Fig. 5 shows the conceptual design of the application, providing a brief overview of its operation across six scenes. The individual scenes are described below, detailing what the user sees and the interaction options available in each scene.

4.1 Scene 1: start the application

The application can be selected and started from the start menu of the MR headset using the classic two-hand gesture on the wrist.

4.2 Scene 2: set up of virtual model

In this scene, the user is instructed to spatially position the model for further viewing. To do this, the user has to grip the model by hand as shown in Fig. 6 and move it to a position that allows enough space around the model for viewing. Upon gripping the model, a feedback sound is emitted, and the colour of the model changes to a light shade of grey. These functions are intended to provide the user with an intuitive operability of the model and an initial feeling for handling it.

Furthermore, an arrow that is faded in as soon as the user looks away from the model makes operation easier. This arrow always points in the direction of the model. Once the user has finally positioned the model, he has to confirm this by pushing the Next button. The position is then maintained for the entire application, but can be changed at any time by returning to this menu. The user can also use this function later to place the model in the desired position in the real machine tool.

4.3 Scene 3: main menu and information about the model

In this scene, the user can gain an overview of the clamping device. He has the option here to display the designations of the individual components. These designations always orientate themselves to the viewing direction of the user, allowing the model to be seen from different positions (Fig. 7).

Fading in the drill shows which machining task is to be carried out. Then the drill carries out an animated stroke movement to indicate that a hole will be drilled at this point. The next scene is called up by tapping the FE Analysis button.

4.4 Scene 4: the main menu of FE analysis

The main menu of FE analysis (Fig. 8) presents a simplified model for the simulation. The user can fade in information describing and explaining
Fig. 4: Left: tetrahedral element with ten nodes (tet10); Right: hexahedral element with 20 nodes (hex20); orange arrows indicate the surface ID respectively [16]

Fig. 5: A brief overview of individual scenes in the augmented reality application

these simplifications. They were made to save computing power and thus reduce display errors.

The other buttons in the menu are based on the structure of FE simulation software. The user can choose between preprocessing and various postprocessing options. The following options are available for the holographic visualization of the results:

- total deformation
- equivalent stress
- modal analysis

From these submenus, the user can always return to this FE main menu via a back button.

4.5 Scene 5: preprocessing

The MR headset is responsible solely for the postprocessing of the simulation model, while the
Fig. 6: Spatial positioning of the model by gripping it with the hand

Fig. 7: Upper: main menu for Scene 3; Lower: exemplary designations of the components in the model and illustration of the machining process

preprocessing and the solver process are executed using ANSYS. In this scene, key components of the preprocessing are visualized to give the user essential background information about the simulation. As depicted in Fig. 9, this visualization includes the mesh utilized in the simulation. Additionally, boundary conditions such as the clamping, bearing, and the force applied by the machining operation are also displayed.

4.6 Scene 6a: postprocessing - total deformation

This scene, along with the subsequent ones, encompasses the core elements of the task, namely,
the postprocessing of the FE simulation. The results of the simulation are fully duplicated into the AR headset. In these final stages of the developed application, users can independently assess the quality of the clamping situation based on the simulation results they have reviewed.

As shown on the left side of Fig. 10, the control panel is divided into the following areas: buttons, slide controls, and a scale. The Play and Stop buttons are located on the left side of the menu. Pressing "Play" causes the model to alternate between its undeformed and deformed states. The color of the bodies is also changing continuously. Pressing "Stop" halts this movement, and the model is then displayed in its deformed state again. When the "Maximum" button is pressed, a label indicating the point of maximum deformation appears. This label always aligns itself with the user’s viewing direction.

The exaggerated displacement and the movement speed can be adjusted using both slide controls, which must be operated between the thumb and index finger. Once the scene is activated, the color scale values are displayed. The model’s deformation is represented by an equidistant distribution in millimeters, with coloring based on the degree of deformation.

4.7 Scene 6b: postprocessing - equivalent stress

The equivalent stress in the clamping fixture can be inspected similarly to the total deformation (Sec. 4.6). The values of the equivalent stress are given in MPa. The scalar values for exaggeration, speed or the colour scale are adjusted accordingly. The model changes its coloration based on the level of equivalent stress and deforms based on the data of the total deformation as well.

4.8 Scene 6c: postprocessing - modal analysis

To inspect the modal analysis, the menu shown on the left in Fig. 11 is enhanced with new buttons for selecting eigenmodes. Here, the third natural frequency is selected, and the corresponding
displacement is displayed on the right side of Fig. 11. However, other eigenmodes can be shifted using the additional buttons. Similar to the total deformation (Sec. 4.6), when the “Play” button is pressed, the model deforms according to the selected eigenmode.

5 Testing the augmented reality application in a real research environment

During extensive testing of the new AR application for assessing clamping concepts, it was found that the application on the Hololens2 crashed after a certain period of use, especially when viewing the scenes that assess the simulation results involving movements. The reason was identified as the Hololens2’s memory of 4 GB, which was filled rapidly by the AR application.

By incorporating an additional external PC, the application’s usability period was extended indefinitely. The PC or notebook was connected to the Hololens2 via Unity, using the Holographic Remoting Player app. The remote PC, with its 32 GB of main memory and internal hard disk, was used to temporarily swap data. With a robust Wi-Fi connection and a suitable PC (i7 with GeForce GTX 1650, 32 GB Ram), the frame rate (FPS) on the Hololens2 increased from 25 to 33. If the movements of the vibrations or deformations
are operated exclusively on the PC, achieving 50 FPS is feasible.

To demonstrate how users could perceive calculated results in a real-world setting, an image shows the clamping situation in the Grob 550 machining center, which is available at the Institute for Machine Tools. This machine was also utilized for the cutting tests with the previously mentioned clamping situation [13, 14]. Fig. 12 illustrates that the user can view the results in the form of a hologram on the milling machine table, accurately reflecting the exaggerated deformation or natural modes of the clamping fixtures.

In the example presented, the user can select the desired calculated natural frequency and adjust the exaggeration or the colour gradient. Unlike the PC representation, the result is a three-dimensional moving hologram with a changing color gradient, closely resembling real-life scenarios. Moreover, the observer can view the workpiece and clamping elements from various angles and positions. This visualization aids engineering students in more effectively understanding the cutting process and the workpiece clamping technology.

6 Summary and outlook

The aim of this research work was to develop an AR application that expands the capabilities of evaluating FE simulation results by means of AR technology. Using a clamping scenario with a specific machining task as an example, this application enables users, students, or technicians to immersively experience and independently assess the quality of the clamping. The representation of simulation results and the interaction with the model within the augmented application was analogous to established FEA software.

MATLAB scripts served as an interface between FEA and the Unity development environment for processing the exported simulation data. This data interface could be applied to any simulation model composed of tetrahedral and/or hexahedral elements. Hence, the postprocessing with the HMD can be easily adapted for other models and be expanded for other engineering scenarios.

Operating the AR application via the Holographic Remoting Player proved reliable and achieved a sufficient frame rate. During the
development, it became clear that the Unity development environment is not designed for handling tabular data typically encountered in engineering problems. While the software can manage such data, it lacks integrated structures for organization, particularly for the import of CSV files that store data in arrays. Furthermore, there is no overview of the currently existing variables in Unity, meaning that these values can only be retrieved by manual debugging with the console.

Testing and using the application on the Hololens2 created a remarkable immersive effect. Both experienced users familiar with Hololens2 applications and first-time users considered this research-derived use case as an intriguing FEA scenario, allowing them to immerse themselves in a novel world of learning and experience.

Funding. This paper was written as part of the LEBUS2 project (Teacher Training at Vocational Schools 2 in the framework of the quality initiative for teacher training), funded by the Federal Ministry of Education and Research (BMBF), Germany with the grant number: 01JA1902.

Conflicts of interest/Competing interests. The authors declare that they have no conflict of interest.

Availability of data and material. Materials, datasets, and software used in the study are available from the corresponding author upon reasonable request.

Code availability. The code used in this study is available from the corresponding author upon reasonable request.

Ethics approval. Not applicable.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

Authors’ contributions. Walther Maier conceived of the presented idea and led the project. Walther Maier, Qi Feng and Richard Wunderle contributed to the implementation of the research. Prof. Hans-Christian Möhring provided invaluable advice, offered critical feedback and guided the direction of the research project. Walther Maier and Qi Feng contributed to the final manuscript.

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for educative use. International Journal on Interactive Design and Manufacturing (IJIDeM) 16(2), 643–656 (2022) https://doi.org/10.1007/978-3-030-79168-1_33


