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VISUALIZATION OF SIMULATION RESULTS BASED ON MOBILE AUGMENTED REALITY

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Abstract. *The convergence of engineering and information technology has brought many changes and innovations to the industry as well as academic research. In particular, computer simulation technology has evolved from the level of replacing existing physical experiments to a level that can accurately simulate actual physical phenomena and analyze them in real time. In this paper, we describe the Computational Fluid Dynamics (CFD) technology, which is mainly used in industry, and the post-processor that uses Augmented Reality (AR), which is emerging as a latest visualization technology. Active research is underway to visualize CFD simulation results using AR technology, but it is only used to visualize data in a desktop environment due to the large size of the result data and the use of AR technology in CFD simulation that needs to be reviewed in real space is limited. To solve these problems in this study, we analyze the CFD results in the post-processing process, and then perform data optimization to support operation in the mobile environment. In the visualization process, lightweight data is used to perform real-time tracking using cloud computing, and the analysis result is matched to the screen and visualized. This allows the user to review and analyze the CFD analysis results in an efficient and immersive manner in various spaces where the simulation is performed. Finally, we show the usefulness of the proposed method for indoor air cleaning analysis results.*
Keywords: Computation fluid dynamics, Augmented reality, Mobile environment, Lightweight data

1. **Introduction.** In general, design in the product development process takes the highest time and cost because the product performance must be repeatedly evaluated and verified. Manufacturers must reduce the time to market by saving the design time and cost, and the Computer Aided Engineering (CAE) technology using high-performance computers is applied to this end. The CAE used by manufacturers can be largely divided into structural analysis and fluid analysis. The structural analysis is a procedure or method of finding and measuring the effects of external forces on physical objects, and is used to predict the behaviors of structures according to the load acting on the structures. By contrast Computational Fluid Dynamics (CFD) is used to analyze the flowing method

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of gas or liquid and to predict the effects of gas or liquid on flowing objects using mathematics, physics and computational software. CFD is based on the Navier-Stokes equation which predicts how the speed, pressure, temperature, and density of a moving fluid on the flow of the fluid. Many CFD-related studies have been conducted on the accuracy and convergence of numerical analysis techniques, but research on the visualization of simulation results is relatively insufficient. The research on visualization of large-scale CFD simulation results using supercomputers has been often conducted, but Virtual Reality (VR) or Augmented Reality (AR) visualization of simulation results based on the mobile is still in an early stage.

This paper describes a method of visualizing fluid analysis simulation results based on AR technology. Indoor flow and contaminant convection-diffusion analysis is performed using the analysis results of commercial solvers such as OpenFOAM and Fluent, which are the most widely used CFD open source solvers. The analysis results are realistically visualized on mobile devices using AR technology, and a cloud computing environment is used for real-time visualization. In other words, the cloud computing environment is used to process the CFD simulation results and environmental tracking in AR environment which require large computing resources.

This paper is organized as follows. Section 2 describes notable studies that used AR technology in the engineering simulation field and discusses their limitations. Section 3 and Section 4 describe the method of lightweight data and representation data generation through post-processing of the analysis result calculated using commercial and open-source solvers and the visualization method for AR environment tracking and analysis results using parallel cloud computing. Finally, Section 5 summarizes conclusions and presents future research directions.

2. **Related Works.** Traditionally, various numerical analysis methods have been used to solve engineering problems. Owing to the dramatic development of computing technology since the early 20th century, powerful analysis and simulation software tools such as ANSYS, Abaqus, and COMSOL have been developed. However, the user interfaces such as menus, dialogs and toolbars of these analysis and simulation software tools take long time for users to learn and it is difficult to intuitively examine the simulation results.

As part of solutions to these problems, engineering analysis VR studies have been actively conducted using immersive virtual environments. Through them, an environment for more intuitive and efficient examination of the simulation results has been prepared. However, due to the nature of the engineering field that is closely related to the physical elements of the real world, the utilization of VR is low because it is difficult to clearly recognize physical influences. Furthermore, VR systems require high cost due to the expensive equipment and it is inconvenient to attach heavy equipment.

AR has been researched for several decades as an efficient and complementary tool to improve the quality of engineering analysis by complementing the limitations of VR. AR-based visualization helps users recognize and understand the analysis results more accurately by visualizing and representing numerical analysis results in a real physical space [1]. Users can verify in real time the parameters that influence products and technologies and efficiently analyze problems by updating numerical analysis results in real time in the real world. Therefore, AR can be used as the best tool for engineering analysis and simulation [1]. AR technology has been studied in various engineering simulations. In the biomedical field, the visualization of Computed Tomogrfaphy (CT) and Magnetic Resonance Imaging (MRI) data in AR has been mainly researched [2]. However, AR has been mainly used as an educational tool due to the accuracy issue of the current research results and the difficulty of configuring the related system environment.

In the machinery and manufacturing fields, studies have been conducted on AR visualization of 3D shape models and structural analysis results for intuitive examination and discussion of 3D design data such as Computer-Aided Design (CAD) [3-6]. The AR utilization research in the machinery and manufacturing fields focused on limited areas such as structural analysis and mechanical equipment, which have limitations because accurate matching with physical models is difficult. Furthermore, in the electric and electronic fields, research has been carried out to express the electromagnetic analysis results in AR and to intuitively review the results.

With respect to CFD simulation, the visualizations of analysis results in machinery, civil engineering and urban engineering fields have been researched. Civil engineers and urban designers can analyze and improve indoor and outdoor environments using the visualization of design results in AR. However, existing studies on AR based on CFD simulation focused on the design of entire cities or architectural engineering, and it is difficult to apply them to CFD simulations in a wide variety of fields.

These studies adopted various visualization methods such as Java3D, OpenGL, Paraview, and VRML to visualize CFD simulation results using AR technology. However, most studies only support specific CFD simulations or desktop-based visualization, limiting the review and utilization in various spaces. Therefore, this study proposes a method of using various forms of data in the software industry and the explosively growing simulation information in low-specification devices such as mobile devices in AR environment.

3. **Design of the Mobile AR-Based Post-Processor.** In this section, we describe the structure of the mobile AR-based CFD simulation post-processor using various types of the commercial and open source CFD analysis results. The proposed mobile AR-based CFD simulation post-processor is composed of AR Post-Processing and AR Visualization as shown in Figure 1.

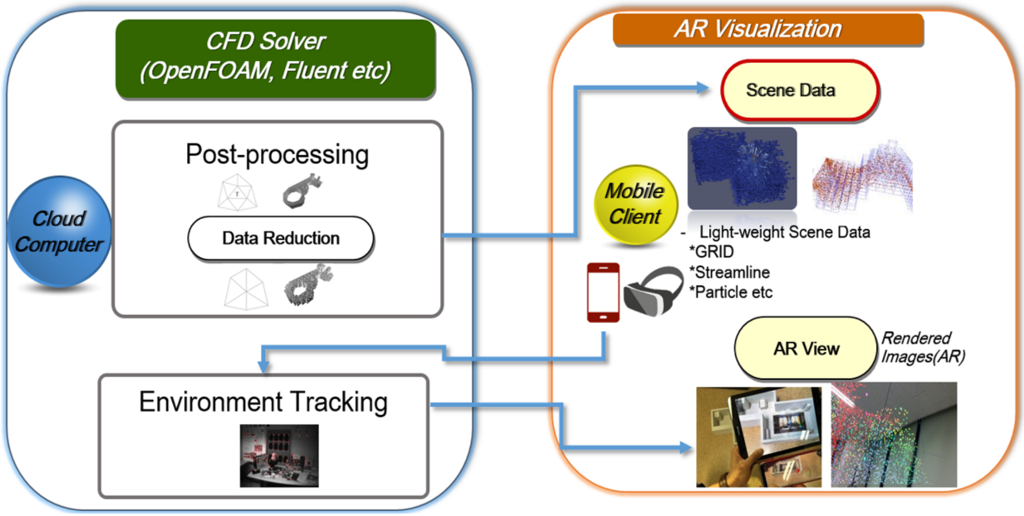

FIGURE 1. The concept of the mobile AR-based CFD simulation post-processor

First, the CFD analysis result uses important information such as indoor flow and pollutant convection-diffusion calculated by commercial solvers such as OpenFOAM and Fluent, which are most widely used among CFD open-source solvers. In the AR Post-Processing step, representation data are generated for smooth operation using the calculated CFD analysis result in the mobile environment. The CFD analysis results with large data are quickly analyzed to produce lightweight data.

In the AR Visualization step, visualization is performed for real-time positioning and analysis results. The elements are generated using the lightweight representation data generated from the cloud, and these generated visualization elements are mapped to the tracked positions to visualize them in the AR environment. For fast performance of real-time tracking for the entire environment space, complex computations are processed in the cloud environment.

4. **Post-Processor for Visualization of CFD Simulation Results.** In the CFD analysis result, the space in which fluids move has a very large number of elements because it is represented as a form with surface data and filled inside. Therefore, for effective visualization of the CFD analysis result in a mobile environment, the visualization elements extracted from the analysis result need to be lightweight. To that end, this study performs the lightweight conversion process of the visualization elements as shown in Figure 2 to support the effective operation in the mobile environment.

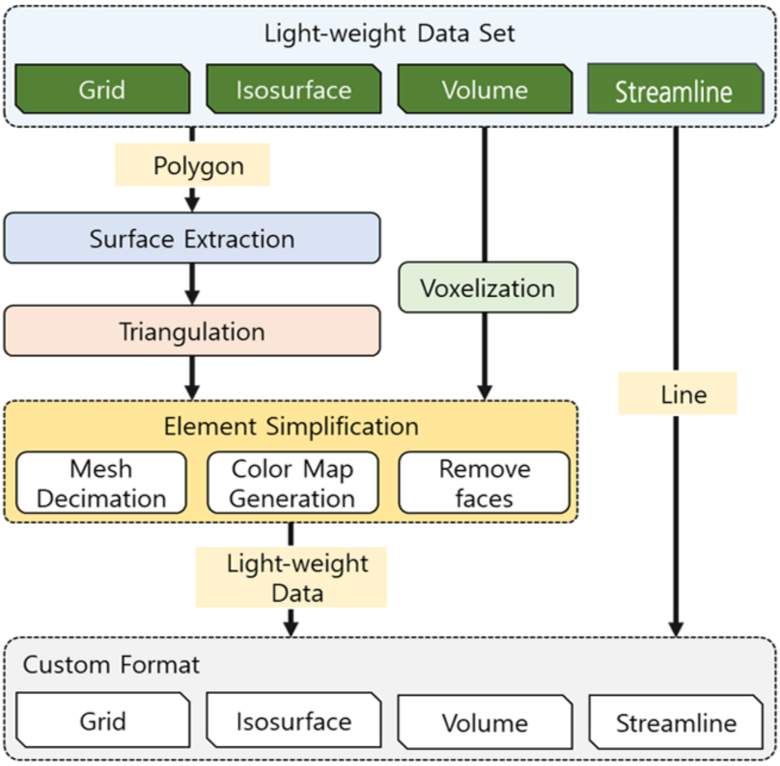

FIGURE 2. Optimization of the CFD result

When the visualization elements for the CFD analysis result are extracted, they are converted to lightweight data according to their attributes. Since grids, isosurfaces and volumes occupy the largest part of rendering in the analysis result visualization, the light conversion is performed around them. Unity3D used in this study supports triangle meshes only for the representation of a 3D mesh model. Therefore, after triangulation [7] is performed for the grids and isosurfaces which can have various forms of meshes (e.g., triangle, rectangle, and hexagon), element simplification [8] is performed to reduce the number of nodes that have been subdivided by triangulation. The mesh simplification method generally removes the color information as well because each node in the CFD analysis result contains color information. Therefore, mapping images are generated from the color information of the analysis result before simplification before simplifying meshes and applying mapping images to the simplified meshes. In the case of volumes, voxels were generated from the adjacent relationships of nodes and the duplicate elements were removed by simplification method that removes the shared faces to enable effective visualization in the mobile environment. These lightweight data are stored in a proprietary format and used for visualization in the mobile environment.

As described above, this study performed post-processing to extract the analysis and visualization elements of the CFD analysis result. This can be useful not only for extracting the initial analysis result analysis and visualization elements, but also for controlling the visualization elements required by users in the mobile environment depending on the situation. Therefore, detailed review and analysis of the simulation results were enabled by composing functional control features such as the change of streamline seed point or the change of the color expression (legend) range for each element. In the process of reviewing and analyzing the CFD simulation result, when a user control event for visualization elements occurs, the parameters of the event are delivered to the control script in the server. Then the result is modified and the modified result is processed and returned to the user, and this process is repeated. This control method can be effective for collaboration systems using the analysis result.

The visualization elements of the CFD analysis results that have been analyzed and simplified through post-processing are stored in simple formats defined to be directly compatible with Unity3D rendering elements and are delivered to the mobile device. Thus, rendering can be performed quickly by simple syntax analysis only without complicated computations through the predefined and produced rendering elements. The generation of rendering elements is composed of Create Mesh, which produces grids, isosurfaces, and volume elements, Create Curve Mesh, which generates streamlines, and Create Particle, which generates fluid flow elements, as shown in Figure 3. The elements produced in each process are rendered through the Unity Rendering Pipeline.

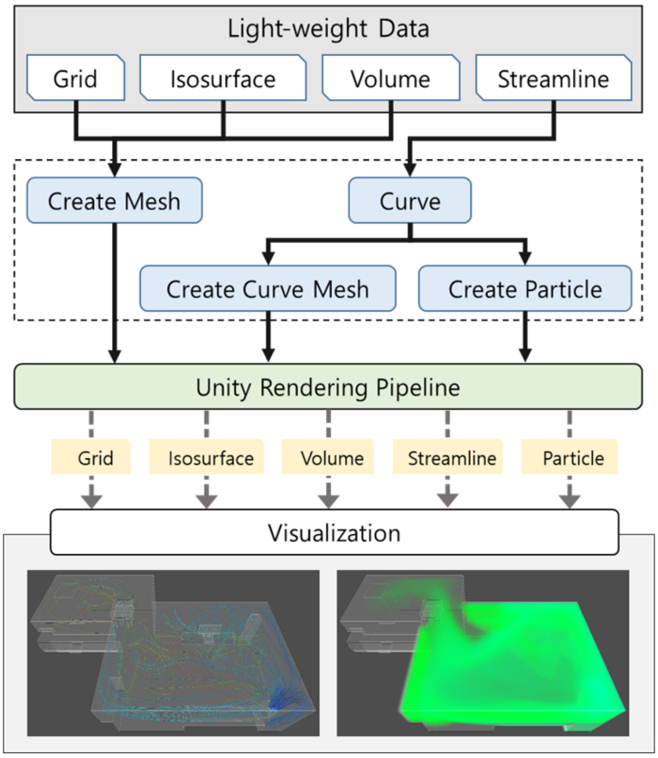

Figure 3. Generation visualization data

5. **Conclusions.** In this paper, we proposed a CFD simulation post-processor using mobile AR technology. This method allows users to examine and analyze CFD simulation results in various simulated spaces effectively and immersively. In the future, we plan to apply various types of CFD simulation results besides indoor air cleaner and perform usability tests.

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