INTEGRATING BUILDING INFORMATION MODELING, MIXED REALITY AND COMPUTATIONAL FLUID DYNAMICS FOR BUILDING ENVIRONMENT STUDY

○Yuehan ZHU＊1　Tomohiro FUKUDA＊2　Nobuyoshi YABUKI＊3

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1. Introduction

In the housing construction field, the thermal environment design is a significant process for sustainable development issues while the health considerations of occupants have also been increasingly appearing. For the daily life of mankind, a qualified thermal environment design not only makes human life more comfortable but also reduces the incidence of most the chronic ailments.

In order to evaluate the thermal environment, Fanger (1970) proposed an index called Predicted Mean Vote (PMV) which includes two environmental factors and four personal factors. However, it takes lots of time to conclude those six factors and reduces the efficiency of design feedback. Feedback is the most important element of any design process. A highly efficient feedback system would make the discussion target clearer to understand (Fukuda et al., 2015). Moreover, only with these six data, it is still not intuitively enough to express the thermal environment. The integration of building performance feedback in the design process is increasingly considered as a key aspect of the decision support framework that drives current high-performance architecture, from early conception to fabrication (Angelos et al., 2017). However, the building design process usually follows the waterfall model which is a sequential and non-iterative design process. Facilities are important elements that affect the thermal environment. Therefore, in the waterfall approach, the thermal design belongs to the latter process (Phillip and Colin, 2004). The waterfall approach is an inefficient process because it is a one-way approach that affects the feedback efficiency and discourages stakeholders to collaborate in a synchronized manner. Integrated project delivery (IPD) has been proposed by (Reza and Burcin, 2011) in order to bring together stakeholders, and involve them in the decision-making process from the very beginning of the design project. The thermal design process should be synchronized with the building information modeling (BIM) process, which contains the lifecycle data of a structure and is essential for realizing IPD. However, the challenge is to integrate BIM with the computational fluid dynamics (CFD) software, which is widely used to perform advanced thermal environment analysis. The CFD analysis produces a large amount of numerical data that can be used to generate 2D image data or 3D model data by using post-processing software such as ANSYS and ParaView. However, watching those CFD result without building information on the display, there is difficulty in building a relationship between the 3D model and the 3D virtual space. In the process of consensus building, the more intuitive the information, the more smoothly the building design progresses. For that purpose, an interactive visualization system using a marker-based augment reality (AR) was proposed by Yokoi et al. (2017) to comprehend this relationship. Although the system can display CFD results on a video see-through head-mounted display (HMD), it can only display the thermal environment at discrete points in time. Moreover, the range of activity is restricted owing to the AR marker, which diminish the user experience.

This research proposes simultaneous localization and mapping (SLAM) technology, a more precise way for registration. Compared with past methods, SLAM fixes many problems, such as hand-arm vibration, distance constraint from the marker and susceptible lighting conditions.

A case study was conducted to assess the proposed system which integrates BIM, CFD, mixed reality (MR) to visualize the indoor thermal environment of a full-scale building and to make the process more scientific. Users can experience the indoor thermal environment from any viewpoint, and this helps them understand design alternatives and consensus building more accurately.

2. Proposed Method

2.1. SUMMARY

The proposed system visualizes the indoor temperature conditions and the room ventilation. Users can observe the thermal environment and experience the situation in the building. Moreover, the visualized CFD calculation data can be replaced at any time. Stakeholders could compare different thermal design and adjust CFD parameters such as physical properties, building components and room design to figure out the optimal design. Afterward, the stakeholders would be more understanding of each other and the discussion would be more smoothly. Designers would focus on considering a new and better design rather than consume unnecessary effort on communication like before. The SLAM-based MR system used a wireless optical see-through HMD that allowed the user to walk around and observe the thermal environment.

This system consists of 4 steps: BIM Creation, Mesh Generation, CFD Analyzation and MR Visualization (Figure 1).

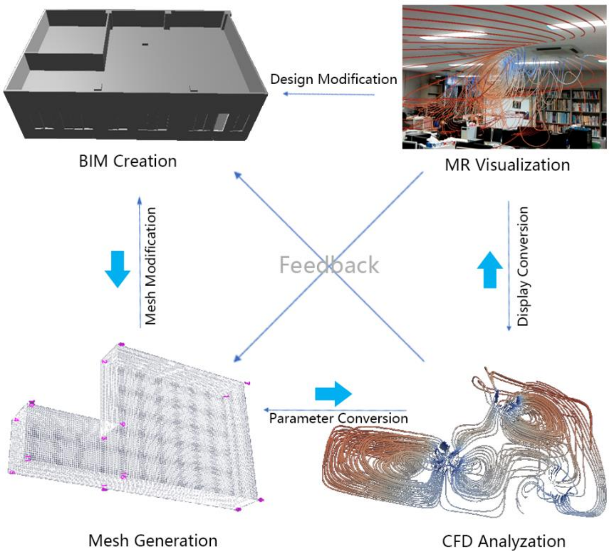

Figure 1. System flow.

2.2. BIM CREATION

The software used to create BIM model is Autodesk Revit Architecture. As a feedback system, the BIM model can manage the life cycle of the whole project. Meanwhile, it can also provide the block mesh that is needed during CFD processing.

2.3. MESH GENERATION

The method to generate mesh is by using the BIM model. The more complex the BIM model, the more time it takes. It is a full-scale simulation in this research. Thus, the unit grid should be one cubic meter.

2.4. CFD ANALYZATION

Set the block mesh and the boundary conditions according to the BIM information. Then progress those data onto CFD processing. OpenFOAM is an open-source CFD toolkit that can simulate the thermal environment. For using a steady-state solver, users are required to choose a Reynolds-averaged model. This study assumes that the thermal environment of the building was in a stable state so that the Reynolds-averaged simulation can be set to the standard k-ε model (Kajima et al., 2013). Numerical information of the thermal environment is completed after the CFD simulation. The numerical information can then be introduced into ParaView, the post-processing software. At last, the numerical information can be changed into 3D graphics information by adding different filters.

2.5. MR VISUALIZATION

2.5.1. MODEL CREATION

After the CFD post-processing, users can watch the CFD model in ParaView. The thermal environment model needs to be separated so that the MR system can recognize and display the CFD data on the HMD. The CFD data in ParaView is point cloud data. Using the code from visualization toolkit (VTK) library can convert the CFD point cloud data to the 3D model frame by frame.

2.5.2. ANIMATION CREATION

The simplest way to create CFD animation is to convert the same angle of the 3D model in different time into frame animation, but it needs a lot of system resources to rendering in real-time. Additionally, the CFD animation with the same angle would have a lot of limitations which might increase the difficulty of communication among the stakeholders. Therefore, another solution is selecting the morphing animation technique which does not need to refresh the whole model in each frame. Moreover, different from frame animation. The morphing animation is the real CG animation and people can watch the CFD data from all directions.

2.5.3. INTEGRATE ANIMATED MODEL

The CFD analyzation system and MR system are operated in different hardware. The method of integrating the animated CFD post-processing data with the SLAM-based MR system is importing all the animated CFD data into unity3D, a game engine which is wildly used in integration system development. Using JavaScript integrates all the data and makes a program package so that the system can be operated on the HMD.

3. System Evaluation

To validate the advantages of the proposed system compared with those of the traditional methods, the evaluation test was implemented in room 411, M3 building, Suita Campus, Osaka University. The area of room 411 is 150m^2. There are three air conditioners on and nine windows with the leftmost one opened (Figure 2, red squares indicate air conditioners in the ceiling). As expected, the airflow and room temperature could be observed through HMD. The HMD used in the experiment is

HoloLens (Figure 3). It projects the virtual objects directly on the translucent screen so that people can see the real-world scene directly (Figure 4). It uses four cameras with SLAM algorithms to implement registration and understand the environment more accurately.

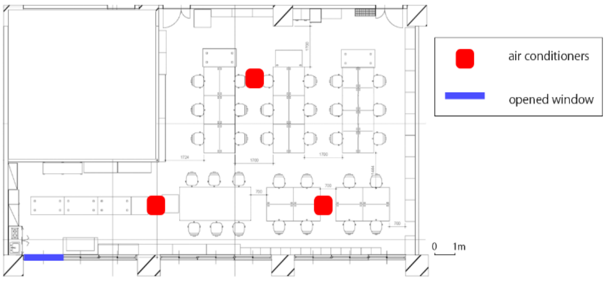

Figure 2: Room 411 floor plan.

Figure 3: HoloLens.

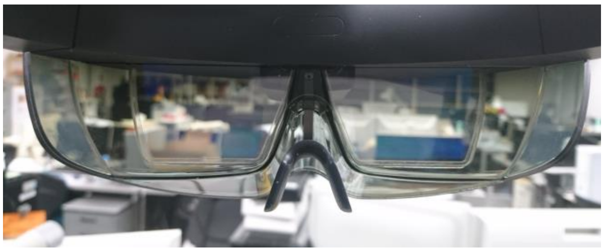

Figure 4: View using HoloLens.

3.1. IMPLEMENTATION

The boundary condition setting of each air conditioner is four outlets and one inlet (Figure 5) with one zeroGradient as showed in Table 1. In order to reproduce the real situation (American Society of Heating, 1998), this system evaluation assumed the situation happened in early winter. Outdoor temperature was set to 273K while the initial indoor temperature was set to 285K.

CFD processing was completed by OpenFOAM 3.0.x. The mesh model was generated according to the BIM model that was created by Autodesk Revit Architecture 2016.

In this system evaluation, the heat transfers due to sunlight radiation and the turbulence from the outside were not considered.

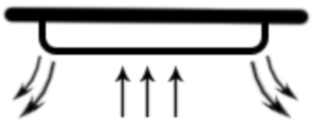

Figure 5: Air conditioner air flow

Table 1: Air conditioner boundary condition.

Factor	Outlet	Inlet	Window
Temperature [K]	300	zeroGradient	273
Wind direction [°]	45	270	90
Wind speed [m/s]	0.2	0.3	0
Turbulence energy [%]	10	10	10
Turbulence loss rate [m^2/s^3]	1	1	1
Coefficient of virtual viscosity [m^2/s]	0	zeroGradient	zeroGradient

3.2. RESULT

The SLAM-based MR system shows almost-perfect registration and stability. The proposed solution is more robust than the past marker-based AR solution, which makes CFD results more easily accepted by the general residents. A more intuitive recognition and better user experience would improve the immersion in CFD visualization. The indoor temperature and the air flow are displayed around users and it's clear and easy to understand. Some screenshots are depicted in Figure 6 which shows the thermal environment when the air conditioning just started. The CFD animation is also displayed smoothly which the entire process of temperature and air-flow changes can be observed (Figure 7). Furthermore, the used HMD HoloLens is different from the other HMDs such as Oculus and HTC Vive. The HoloLens doesn't have cables attached to it. Therefore, it is more user-friendly. Also because of the SLAM technology, the HoloLens has almost no limited areas. It provides users the surrounding environment scanned beforehand. Thus, using the HoloLens can achieve a wider range of indoor environment simulation, and its viewpoint is also more flexible. As an optical see-through HMD, a translucent screen that can see the real-world situation in a larger viewpoint helps to reduce the visual discomfort that some people experience with HMD. Users can also feel a stronger sense of the three-dimensional display through a translucent screen.

But the translucent screen also has some disadvantages. The most important one is that the virtual objects shown on the screen are hard to see when users are standing in a bright environment. The virtual objects would become translucent too. And there is no such problem with the video see-through HMD which is using electronic screen. The FOV (field of view) of

HoloLens sounds incredible which is much lower than video see-through HMD with about 30 horizontal degrees and 17.5 vertical degrees (Oliver, 2017). The experience of using HoloLens is quite like seeing a virtual world through a small magic window in the center of your view. Fortunately, the influence of FOV in MR is not such serious in VR. The rest of the vision is real-world scene, does not like VR with nothing but black, and users would not feel uncomfortable.

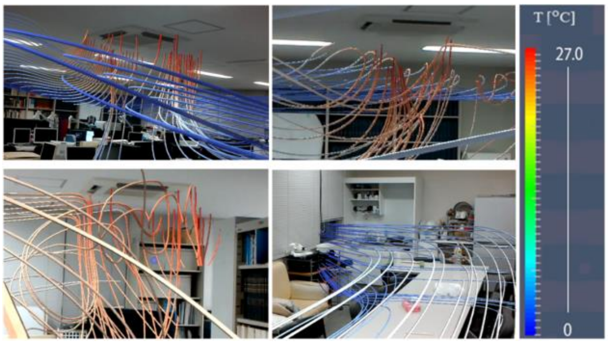

Figure 6: Thermal environment performance by MR.

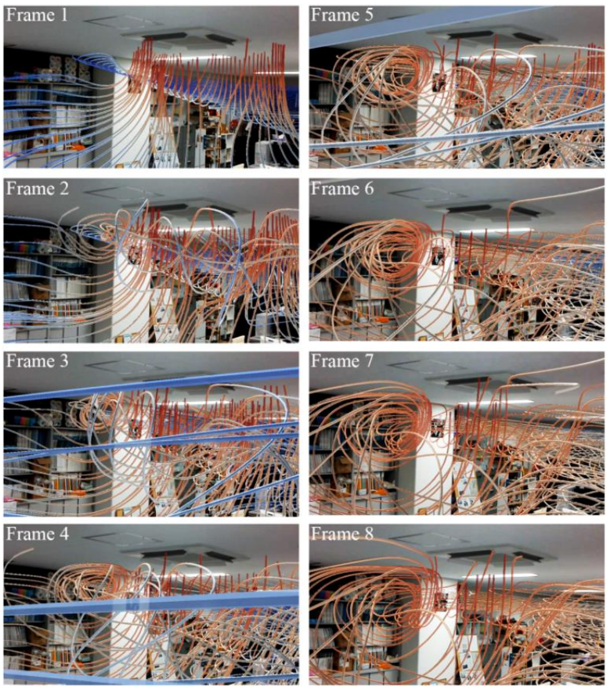

Figure 7: Animated CFD result

4. Conclusions and Future Work

In this study, an MR system that visualizes ventilation of building design based on CFD and a thermal environment is developed. The proposed system shows a better solution than traditional methods by increasing efficiency for design feedback. Especially the CFD animation is proposed in this research. The thermal environment is dynamically expressed so that the user would be able to experience the entire process of temperature and air-flow changes. Thus, this more user-friendly system may be able to achieve the expectations of shortening the construction period and reduce costs.

The wind from the window is assumed as a stable flow in this study. However, in the real world, the wind is approximately similar to the turbulence. Therefore, in future work, adding an unstable turbulence model to the CFD simulation should be considered. Moreover, using other analytic software could contribute to simulating some extreme environments such as high-temperature zones, radiation areas, volcanoes, deep ocean trenches, outer space, and the environment outside the Earth. In that case, the integration of that data into the MR system could be considered.

Acknowledgements

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＊1 Graduate Student, Div. of Sustainable Energy and Environmental Engineering, Osaka University
＊2 Assoc. Prof., Div. of Sustainable Energy and Environmental Engineering, Osaka University, Ph.D.
＊3 Prof., Div. of Sustainable Energy and Environmental Engineering, Osaka University, Ph.D.