How to cite this article:

Sanderasagran, A. N., Abd Aziz, A., & Daing Idris, D. M. N. (2020). Real-time computational fluid dynamics flow response visualization and interaction application based on augmented reality. *Journal of Information and Communication Technology*, *19*(4), 559-581. https://doi.org/10.32890/jict2020.19.4.5

REAL-TIME COMPUTATIONAL FLUID DYNAMICS FLOW RESPONSE VISUALISATION AND INTERACTION APPLICATION BASED ON AUGMENTED REALITY

Ashwindran Naidu Sanderasagran, Azizuddin Abd Aziz & Daing Mohamad Nafiz Daing Idris

Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, Malaysia.
sai.ashwindran@gmail.com; azizuddin, daingnafiz@ump.edu.my

ABSTRACT

The behaviour of fluid flow is a complex paradigm for cognitive interpretation and visualisation. Engineers need to visualise the behaviour mechanics of flow field response in order to enhance the cognitive ability in problem solving. Therefore, mixed reality related technology is the solution for enhanced virtual interactive learning environment. However, there are limited augmented reality platforms on fluid flow interactive learning. Therefore, an interactive education application is proposed for students and engineers to interact and understand the complex flow behaviour pattern subjected to elementary geometry body relative to external flow. This paper presented the technical development of a real-time flow response visualisation augmented reality application for computational fluid dynamics application. It was developed with the assistance of several applications such as Unity, Vuforia, and Android. Particle system modules available in the Unity engine were used to create a two-dimensional flow stream domain. The flow visualisation and interaction were limited to two-dimensional and the numerical fluid continuum response was not analysed.

Received: 14/6/2019 **Revised:** 27/5/2020 **Accepted:** 27/5/2020 **Published:** 20/8/2020

The physical flow response pattern of three simple geometry bodies was validated against ANSYS simulated results based on visual empirical observation. The particle size and number of particles emitted were adjusted in order to emulate the physical representation of fluid flow. Colour contour was set to change according to fluid velocity. Visual validation indicated trivial dissimilarities between FLUENT generated results and flow response exhibited by the proposed augmented reality application.

Keywords: Augmented reality, computational fluid dynamics, image target, Vuforia, Unity engine, particle system.

INTRODUCTION

In the world of emerging technology advancement, visualisation and interaction with realistic and virtual reality worlds are enhanced using mixed reality technology. Mixed technology is the fusion of real-world and computer-generated virtual objects, where mixed reality can be classified into groups, namely virtual reality (VR) and augmented reality (AR). Generally, mixed reality is used by graphic processing and rendering relevant sectors, including gaming, education, and marketing. Research on AR indicates promising and potential applications in engineering. Augmented reality provides an environment and platform for engineers and students to experience, learn, and render daily engineering case scenarios in a more interactive manner. It is predicted that from 2014 onwards, the application of AR technology will increase due to the advancement in hardware and software capabilities (Chi et al., 2013). The utilisation of AR technology in education (Liarokapis et al., 2004), construction, architecture, manufacturing, and archaeology (Barratt, 2018) has rapidly increased over the years. As the complexity of technology and engineering studies increases, a robust and intuitive visualisation platform is needed. With the rise in the number of robust AR platforms such as Unity, ARtoolkit, and EyePet Sony, more interactive and intuitive apps are being created. Research shows that AR technology can improve the cognitive ability of users in gathering and acquiring information. Graphical interface virtual environment in AR technology has improved the perception and interaction by superimposing real-world scenarios with a virtual environment. The traditional method of information gathering has to be less effective and tangible than AR-assisted environment due to the lack of interactives. Furthermore, AR technology tools are cost efficient and time savvy for training and assessment specially related to skills and routine-based tasks (Manca et al., 2013). Apart from comprehending the theoretical and numerical reasonings, engineers must also be able to visualise the behaviour mechanics of the given problem in order to enhance the cognitive ability in problem solving. Nonetheless, the growth of AR platforms with regard to the engineering field, especially fluid and thermal engineering, is limited and constrained due to complexity and numerical technicality. A well-established AR or VR platform would help engineers and technologists to comprehend complex flow behaviours via virtual environment.

The objective of this research is to present an interactive AR application for computational fluid dynamics (CFD) flow field response visualisation and interaction in real time. The proposed application will provide a visual virtual environment for the user to understand the complex fluid flow behaviour relative to the presented geometry.

LITERATURE SURVEY

Computational Fluid Dynamics

Computational fluid mechanics is a field of study to analyse and interpret fluid flow in various conditions. Fluid flow is governed by a large number of parameters and laws of fluid dynamics, which makes it fairly tedious to numerically analyse the fluid response. Prior to the development in computational technology, engineers and scientists are analysing fluid-related equations such as Navier-Stokes equation and Euler equation manually, which consume a large amount of time and resources. Subsequently, later in the 1970s, after the rise of computational power systems, a rudimentary computational programme was developed to calculate and analyse fluid dynamic governing equations. This effort has reduced a significant amount of analytical time and gave birth to several innovations such as efficient aerodynamics cars and aerofoils. In terms of technicality, CFD is a hybrid of fluid-related mathematical models and computer programming. This hybrid field has provided platforms for scientists and engineers to test and validate numerical turbulent models such as k-ε, which was developed by Launder and Spalding (Khalil, 2012). CFD is considered as a major breakthrough development for research-based industries such as automotive, aeronautics, design, and space technology.

Past Studies

A previous research study developed a novel data format for representing CFD result data via AR mobile application using Tango tablet for visualisation of indoor thermal environment (Lin et al., 2019). Since CFD computational result generates a large set of data, the authors utilised a pre-processing server-side data approach in order to reduce the computational cost on mobile devices for CFD result visualisation. The authors employed a Unity engine for three-dimensional (3D) visualisation and 3ds Max for simulation data format conversion. The authors stated that the proposed method had significantly reduced computational cost, 63.4% on loading time and 89.3% in performance benchmark. Malkawi and Srinivasan (2005) described a research study conducted on Human-Building Interaction (HBI) model for CFD result visualisation in real time through AR. The developed HBI model worked on the principle of gesture and speech recognition. The authors stated that limitation in human capabilities in detecting registration errors limits the potential of developing the HBI-AR system. Nee et al. (2012) provided a review study on the implementation of AR in manufacturing and design sectors. In the world of emerging technology in business and industries, integration of AR into manufacturing industries could improve the perspective on manufacturing sectors in terms of customer-market interaction and manufacturing attributes. The authors also stated that AR played an important role in the automotive industry relevant to design.

Webel et al. (2013) conducted a study on the effectiveness of maintenance and training skills of technicians using AR. Due to the rising complexity in technological systems, maintenance tasks have become sophisticated for a technician with traditional teaching methods. The authors stated that AR provided an added advantage for users to interact with real-world objects and access virtual information and instruction. Hořejší (2015) stated that AR is an effective, cheap, and easy virtual training experience for workers in the parts assembly industry. The author conducted an experiment on the effectiveness of learning among the workers in assembling gully traps with respect to time. The results showed that a worker consumes approximately an average of 5–7 minutes to learn the techniques to assemble a gully trap. Furthermore, the workers required an average of 12 attempts to assemble the product without instruction. The author suggested that AR could be the solution to improve the learning curve.

Daponte et al. (2014) stated that AR system is categorised into two groups, namely marker and markerless. There are two types to marker-based AR systems: picture and ID encoded. Meanwhile, markerless is based on feature points recognition. The authors also specified that AR technologies are accessible to smartphone users, as smartphones are integrated with sensors and processing capabilities for AR application. Current smartphones are equipped with the necessary key elements such as camera, inertial measurement unit (IMU), Internet connectivity, and Global Positioning System (GPS) to stably process an AR application. On the grounds of interaction and user interface, there are tangible AR, collaborative AR, and hybrid interface. Tangible AR systems use the real world as an interface integrated with virtual contents. In collaborative AR systems, virtual and real-word objects are shared by user space. For sensor-based tracking systems based on smartphones, there are four sensors mainly available in smartphones, such as 3-axis gyroscope, 3-axis accelerometer, 3-axis magnetometer, and barometer.

Ong and Huang (2017) stated that traditional finite element analysis (FEA) is dependent on computer-generated graphics. These computer-generated graphics are not adequate for interpreting FEA results without the actual physical representation. Traditional FEA software is sophisticated and requires user input data based on experimental results to validate and conduct a simulation. Therefore, this may discourage users from conducting FEA on complex structures due to the tedious requirements. The authors also stated that visualisation through AR had improved the understanding and perception of FEA results. The authors utilised ANSYS to perform the FEA task and ARtoolkit software for AR visualisation. ANSYS Parametric Design Language (APDL) was used as a communication tool between ANSYS and AR-FEA. Fiorentino et al. (2014) studied the effectiveness of technical maintenance of motorcycle engines aided with AR and manual instruction. The empirical study indicated that execution time and error rate of the participants reduced significantly when aided with AR instructions. The authors employed Latin square design in data treatment for analysis of variance (ANOVA).

Neges et al. (2018) described the impact of AR performing maintenance tasks under stress conditions. The authors integrated real-world objects with virtual objects assisted by a head-mounted display (HMD) in order to separate haptic and visual perceptions. Mixed reality (MR) was shown to be effective for learning and evaluating tasks relevant to industrial maintenance and assembly (IMA). Huang et al. (2017) presented a study on visualisation and interaction on structural FEA using AR in the real world. The system was integrated with sensors and AR equipment to input data for visualisation and interaction. Users were able to interact and analyse the structural system with virtual loading or predefined loading for real-time FEA simulation. Furthermore, user were able to perform mesh refinement and modification of finite element models. In order to improve the visualisation and interaction, the authors developed novel interfaces.

Huang et al. (2015) developed a simulation system to perform FEA analysis on the structural systems in real time using AR. The authors stated that the augmented system consists of three modules, which are tracking, rendering, and interaction. The modules are assisted by sensors and augmented related equipment. Ttracking modules are driven by sensor-based, vision-based, and hybrid-based techniques. The authors specified that in order to obtain real-time simulation, the computational time per time-step has to be less than the total duration. Li et al. (2018) presented a review study on construction safety with the application of virtual and augmented reality. The authors stated that due to the inaccurate and ineffective results displayed by AR and VR, real-time integration to AR and VR could enhance the mechanics in simulating construction projects. VR and AR are able to improve the cognitive learning capabilities of users as compared to the traditional learning method. The authors also stated that teaching elements driven by AR/VR safety hazards have improved the learning performance of the students. Novak-Marcincin (2013) discussed the potential of implementing AR in manufacturing industries. In preparation for the 3D environment in real time for AR, suitable equipment or hardware are required to calibrate and scan the spatial area. In order to perform the task, devices such as kinetics assisted by a software called Skanect are used for 3D digitalisation.

COMPUTATIONAL METHODOLOGY

In this study, Unity engine was used to create the 3D model and augmented virtual environment. Since the application was in the beta phase to test the credibility of the proposed application, a simple marker-based AR system was developed for the proposed application. A picture was used as an image target and reference for the augmented system to deduce and arrange the defined virtual environment as presented in Figure 1. Vuforia platform was used in order to create an image target with suitable and adequate score and feature point for the augmented system to read and render the environment. Vuforia engine is an online platform for AR enthusiasts to develop AR applications with computer vision algorithms and features provided by Vuforia. Image target rendering and feature point score can be interpreted in the Vuforia developer portal. Since the proposed application was under development mode, the license key was obtained under development licence manager. Under the target manager option, the desired image target was required to be uploaded to the target database under the device option. In the target database, four target type options are provided, whereby in this study, the plane type target was selected. Target type is the reference boundary for the defined virtual environment to be placed on. For the plane type target, the width of the image target was required to be defined in order for the system to provide digital metadata for tracking. The dimensions of the width were measured in units, whereby 1 unit = 1 m. Therefore, the actual dimension of the image target as displayed in Figure 1(a) was 0.028 m x 0.019 m. Once the desired image was uploaded, Vuforia platform would provide a result score. The quality of the image target was defined by distinct feature points that could be extracted by the software from the desired image target as shown in Figure 1(b). Under the score, an image target might lead to tracking failure by the system. The image had to be high contrast, non-uniform, and asymmetrical in order to obtain a high number of feature points.

Once the image target was uploaded to the database, the package was then imported to Unity engine for the AR development. By default, the view projection in Unity engine was defined by a standard camera. In order to enable AR capabilities, an AR camera module was imported to the system. The AR camera projection was set to (x, y, z); (0, 0, 0) by default. The position of the AR camera as positioned at (x, y, z); (-0.3, 0.4, 0) and panned to (x, y, z); (90°, 0, 90°) in order to obtain top view projection of the virtual environment as displayed in Figure 2. The position and projection of AR camera played an important role in rendering the virtual environment in the real world.

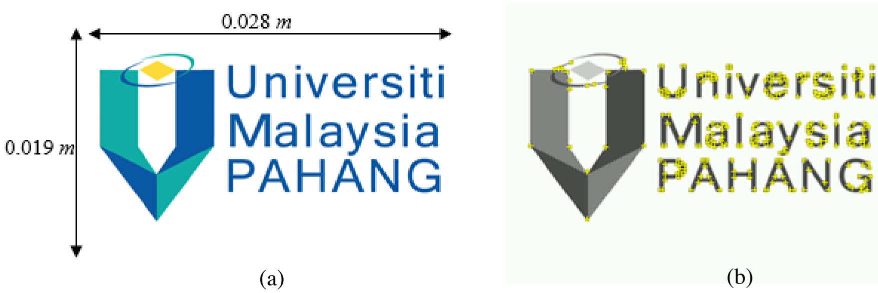


Figure 1. *(a) Image target actual dimension, (b) Yellow points representing extracted feature points.*

Figure 2. *AR camera projection with respect to the defined coordinate and rotation.*

In order to create a flowing fluid virtual system, a specialised module available in Unity called particle system was utilised. A particle system is a feature that allows users to create a graphical effect like fluid, smoke, fire, and explosion with property control features so that users can create a user-defined particle system. Furthermore, Unity provides scripting options under the editor mode, which allows users to create specific particle system effects. The particle system module in Unity version 2017.3 is embedded with 17 feature controls. Each control dictates the physical representation and aspects of the defined particle system. In this study, selected features were used as illustrated in Table 1.

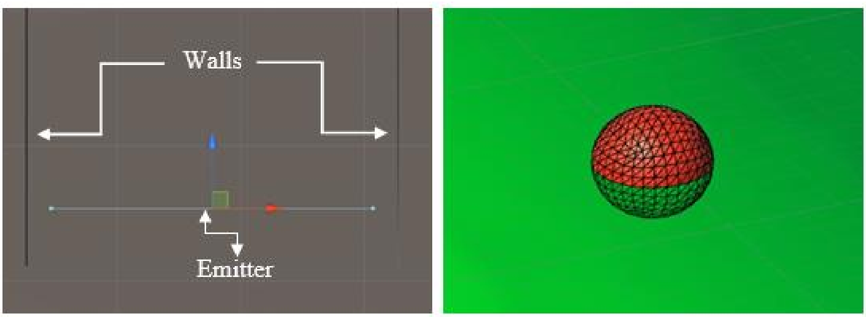
Table 1

Augmented simulation environment parameters

Particle system configuration	Parameters
Emitter	Edge type
Particle type	2D
Simulation environment	Local
Number of particles	30,000
Particle size	0.05 units
Particle speed	5 units/s
Simulation run time	0.01
Noise frequency	0.5
Octave	1
3D model	Sphere mesh collider type

By default, the particle system was set to emit 10 three-dimensional (3D) particles in random direction with a limited particle lifetime from a cone-shaped emitter. In order to create a two-dimensional (2D) effect, the emitted shape was changed to the edge option, in which the particles were emitted from a one-dimensional (1D) emitter as displayed in Figure 3. The particle system would emit in a random direction; therefore, a local boundary system was required to cope with the defined parameters in order for the particles to operate in the defined local space. Two symmetrical bounding walls were created as shown in Figure 3. The simulation space was set to local, where the particles operated within the layer of the walls. In Unity, any imported or internally created physical model has to be defined. An undefined physical object or layer will not be read as a colliding obstacle by the particle. As a result, the particles flowed through the physical object as shown in Figure 3(b). In order to avoid such circumstances, the physical property of the model was defined as a collider. For simplicity, a spherical model was imported as shown in Figure 3(b). Rigid body and collider component features were added to the assets of the object. Therefore, when the particle was in contact with the surface of the object, the particle treated the object as a colliding surface and responded accordingly as shown in Figure 4(a) by diverging when in contact and creating a flow separation according to the geometry. The behaviour of the particle depended on the type of mesh collider being used. For this study, spherical mesh collider, which wasconcurrent to the geometry, was used as shown in Figure 4(b). For complex geometries, user-defined mesh collider had to be assigned by application programming interface (API) scripting. Since the proposed augmented design was not meant for flow field numerical analysis, the simulation rendered was based on the fundamental theoretical assumptions in order to reduce the computational cost and complexity of the project. The assumptions were as follows:

(a) Constant inlet velocity.
(b) Constant inherit velocity property of the particles.
(c) Surface friction and Darcy friction factor excluded.
(d) Low turbulent flow.
(e) Turbulent parameters are excluded.
(f) Boundary layer properties are excluded.

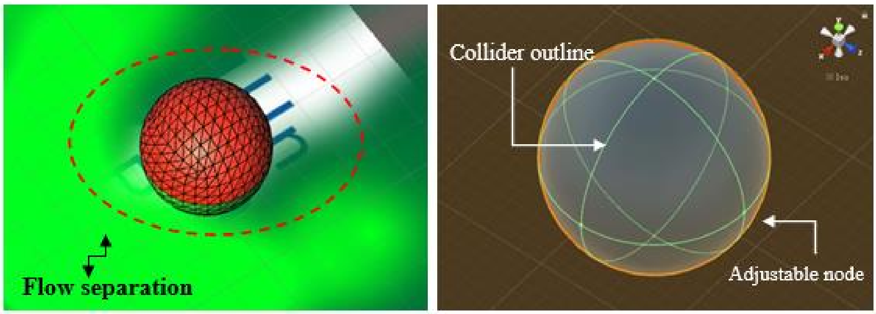


(a) (b)

Figure 3. *(a) 1D particle system edge type emitter, (b) particles flowing through the physical object*

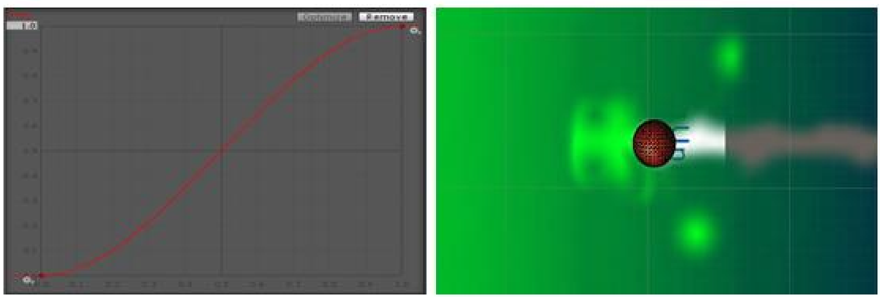
The behaviour of the particles was altered in order to emulate the physical and flow behaviour representations of a fluid. The virtual environment was intended to be a wind tunnel. The modifiers of the particle system were set to represent a smoke effect. In order to create a smoke effect, the number of particles was set to 30,000 at a constant rate over distance. The particles were set to a constant size of 0.05 units in order to create a denser smoke effect as shown in Figure 4(a). The duration of the simulation was set to a default value of 5 with looping and prewarm features enabled. In order to create a streamflow from the right in the *Z*-axis, the gravity modifier was disabled. For simplicity and lower computational cost, the speed behaviour of the particles was set to a constant rate of 5 units/s. Simulation speed or simulation runtime was set to an adequate value of 0.01 based on empirical observation in order to provide a clear visualisation of the flow response. The particle system was set to play at wake to ensure it was displayed instantly once the application was activated by the marker. Meanwhile, in the velocity over lifetime module, the multipliers were set to curve type modifier for the *Z*-axis with a speed modifier of 1. The speed of the particles was controlled by a drag modifier in the limit velocity over lifetime module as shown in Figure 5(a). The speed of each the particles was controlled by the defined drag value when in contact to the collider object by enabling the multiply drag by velocity option. As for turbulent effect, noise modifier was used. Since the flow was in the Z-direction, the noise effect was limited to Z-direction where the X-axis and Y-axis were set to 0. In order to save computational power, the frequency of the noise or turbulent intensity was set to 0.5 with an octave value of 1. Octave is the combination of layers of coherent noise. The value for octave was set based on empirical observation. It was observed that the higher the value of octave, the larger the computational load for rendering the virtual environment.

In computational fluid dynamics, colour contour plays an important role in identifying and interpreting the flow field response in a particular region. Therefore, a colour over lifetime module was used. The colour of the particles was set to green as the starting colour. The particles initially flowed in green, as the velocity decreased the colour, changing it to dark green gradient as shown in Figure 5(b). The change in colour gradient did not represent a numerical value as in the CFD software; it merely intended to represent a visual indication. The renderer module was set in billboard mode with a normal direction value of 1. The material property for the renderer module was left to default setting. As presented in Figure 5(b), the final flow field responded well within the assumptions and logical reasoning. In order to execute a real-time interactive application, an open-source asset module called Lean Touch was used. Lean Touch is a free touch response lightweight module suitable for smartphone processing capabilities. Lean Touch provides a wide range of touch responsive module such as zoom in/out, scale, rotate, and translate by axis. The Lean Touch module script was added to the hierarchy of the sphere model. Zoom in/out, rotate, and scale modifiers were used for this application. In the scale Lean Touch script, the required fingers were set to 2. The minimum scale factor was set to 0.4 in all axis directions, whereas the maximum scale factor was set to 0.6. Prior to exporting the application, the augmented programme was previewed through the computer webcam. The preview module displayed a visual indication of the configured virtual environment.



(a) (b)

Figure 4. *(a) Flow separation, (b) collider configuration.*



(a) (b)

Figure 5. *(a) Drag modifier, (b) Change in contour gradient relative to velocity.*

The programme was then built using the Android platform. By default, Unity would be in PC standalone platform. Prior to executing the application, it was advised to configure Android SDK files to prevent compiling issues. Once the default platform was switched to Android, it enabled Vuforia augmented reality function under the XR player setting. Furthermore, the API compatibility level was set to net 2.0. The methodology in preparation of the augmented system was reflected in Figure 6. In terms of Vuforia configuration, a similar development methodology can be found in the research conducted by Tsai (2014).

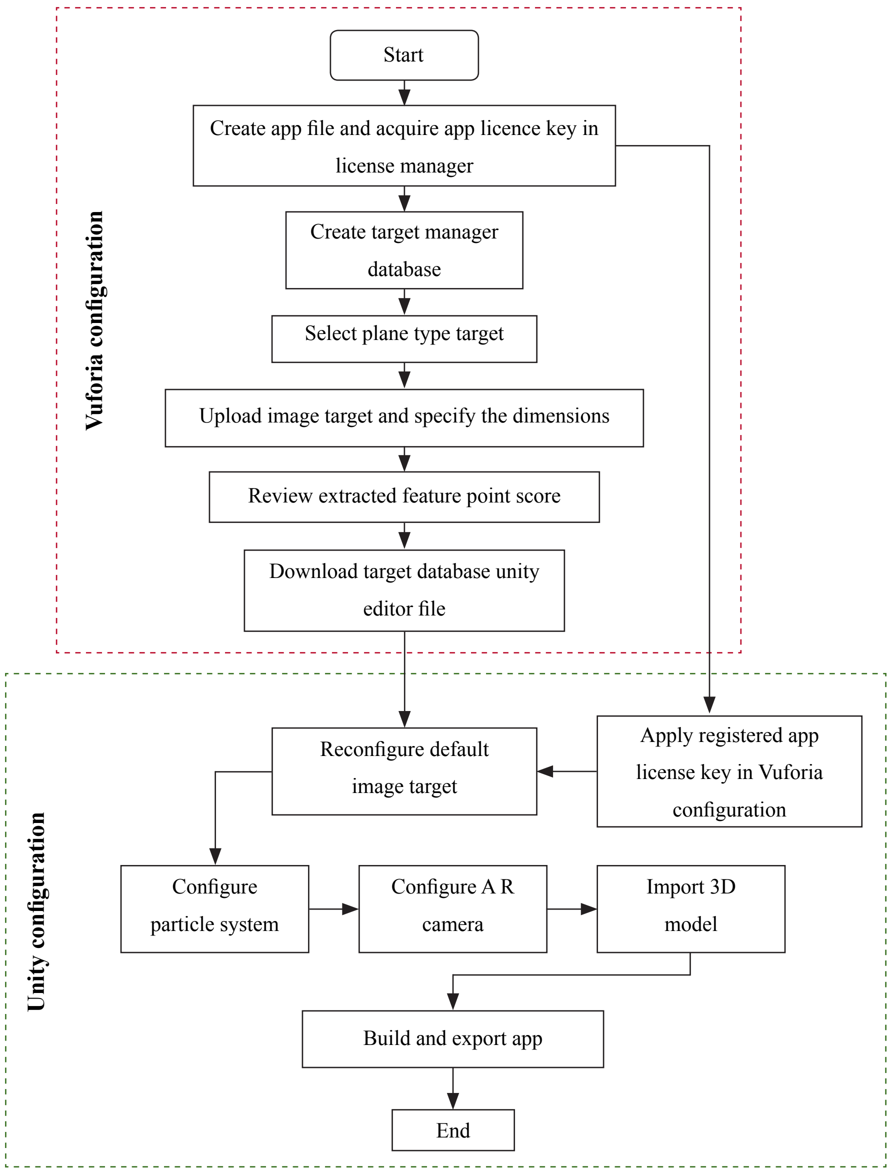


Figure 6. *Vuforia and Unity programme configuration.*

COMPUTATIONAL RESULT

Computational Fluid Dynamics Result

In order to validate the credibility and accuracy of the augmented simulation, a simple unsteady 2D CFD simulation was conducted in ANSYS FLUENT. The geometry shape and dimension were similar to the defined geometry in Unity to avoid large discrepancies in the generated results. The finite volume method (FVM) was utilised in this CFD simulation. The simulation as conducted in 2D in order to save computational load and to match the augmented simulation. The boundary conditions and turbulent parameters were similar to Unity.

In spatial discretisation, a medium-mesh was selected due to its minimal computational load. The gird was discretised with all triangular mesh as shown in Figure 7(a). Since the simulation was conducted in 2D, the outline boundary of the sphere was the circular wall. In order to capture the flow field properties accurately, the wall was defined with an edge size of 0.02 m. The first layer height of 0.02 with 15 layers of inflation was discretised along the circumference of the circle. The inflations layer was set to 1.3 growth ratio as shown in Figure 7(b). The 2D planar model was simulated in transient mode using a pressure-based solver. Unsteady Reynolds-averaged Navier-Stokes (URANS) numerical model technique was used for this analysis. As for viscous model, two-equation turbulent model *SST k-ω* was employed. The wall of the 2D sphere was set to no-slip condition. Meanwhile, the pressure velocity solver configurations were set to the SIMPLEC scheme. Table 2 reports the boundary conditions and unsteady numerical parameters. No specific attention was given to mesh dependency, turbulent sensitivity, and time-step sensitivity to save computational time. The time step size was set to 0.1 with 1,000 iterations. The visual empirical observation was based on the contours generated in static pressure, velocity magnitude, and vorticity magnitude.

Table 2

Solver configuration and boundary condition

Configuration	Parameter	Value
Spatial discretisation	Medium	
Simulation space	2D Planar	
Time configuration	Transient	
Viscous model	SST *k-ω*	
Inlet	Component velocity	5 m/s
Outlet	Pressure outlet	0-gauge pressure
Pressure-velocity coupling	SIMPLE	

As displayed in Figure 8, high pressure was indicated at the front contact region of the sphere. Since the presented geometry was symmetrical, the flow field properties were the same along the walls of the sphere. The colour contour changed according to the range of generated pressure gradient. The high-pressure region was indicated in red and as the pressure decreased, the colour contour faded to the steady pressure regions. Figure 9 illustrates the velocity magnitude flow response contour. It was observed that there was a clear indication in colour change of the flow separation region due to the behaviour of the fluid flow with regard to the defined geometry and solver configurations. As manifested in Figure 10, dense wake region and vortex shedding region were observed passing the sphere. The flow passed the sphere and exhibited an oscillating behaviour due to the turbulent effect and boundary condition properties. Vorticity magnitude contour provided a clear indication of flow field behaviour.

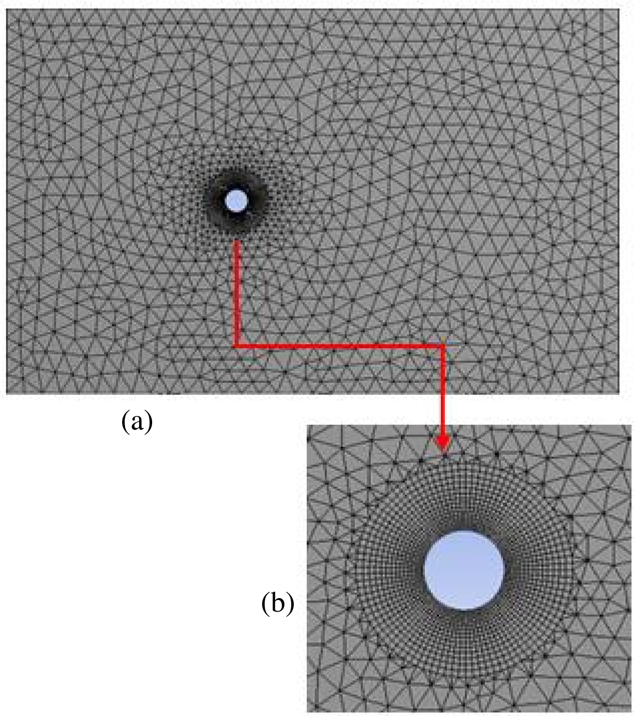


Figure 7. *Grid discretisation: (a) Overall mesh topology, (b) Inflation layers along wall region.*

ANSYS provided options in selecting the range of colour of the study. Generally, the recommended range of colour contours is 11. A high number of colour contour pallets will consume a large amount of graphical processing power. The generated colour contours are based on numerical value, resulting in the defined simulation configuration. Therefore, it is reasonable to increase the range of colour contour in order to study the simulation model clearly. There are several options of colour map type, the widely used options are rainbow and inverse rainbow due to their distinct colour feature, which is convenient to distinguish between the gradient. Meanwhile, there are other colour map options that consume less graphical processing cost such as zebra, grayscale, inverse grayscale, and monochrome. It is noted that there is no absolute colour map standard in visualising the flow properties as long as it is clear and distinguishable by the user.

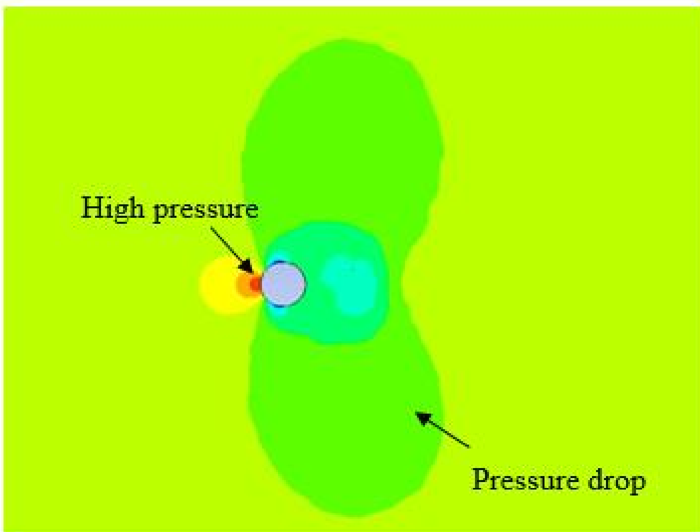


Figure 8. *Pressure contour.*

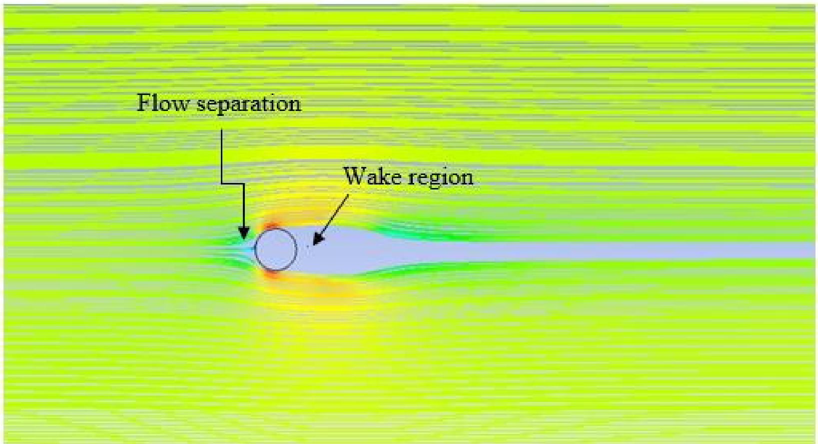


Figure 9. *Velocity magnitude streamline.*

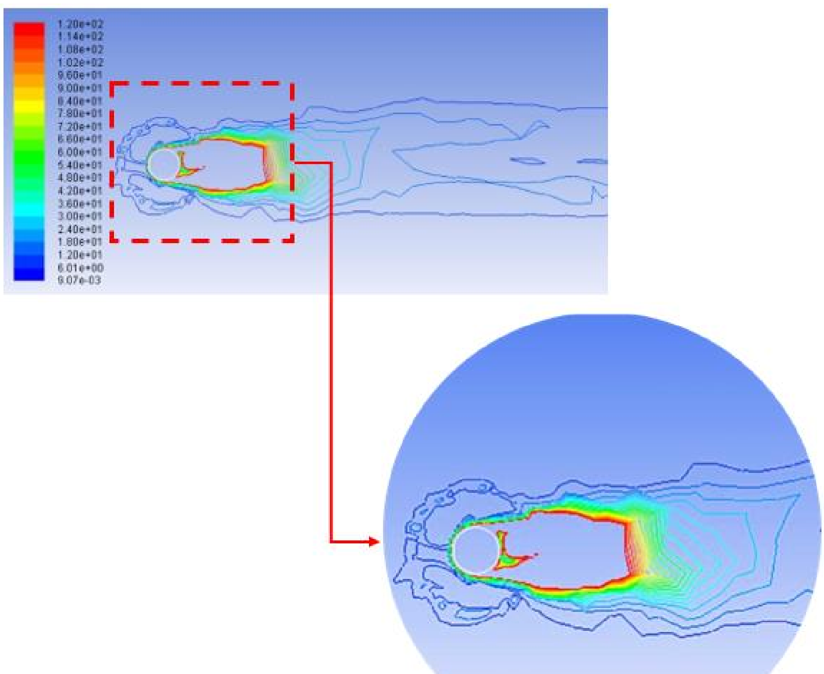


Figure 10. *Vorticity magnitude.*

Validation

In order to test the credibility of the proposed application, the augmented environment was validated against the conducted FLUENT simulation result. As displayed in Figures 11(a) and 11(b), the augmented environment and generated CFD result indicated trivial dissimilarities in flow response. FLUENT results showed higher accuracy in comparison to the augmented simulation by capturing detailed flow field response within the defined solver configuration. This is because FLUENT was governed by numerical formulation and numerical models. Therefore, it is sensible for FLUENT to exhibit higher accuracy and precision than the proposed augmented programme. However, the flow properties shown by the proposed augmented system could be taken into consideration as the flow field response did not indicate a major difference as in the CFD result.

In order to further test the credibility of the application, other simple geometries were tested such as flat plate and a cube. The plate is orientated at three different angular positions, namely 0°, 45°, and 90°. The augmented result was compared to the result gathered from the research conducted by Lam and Wei (2014). The validation was only limited to the visual representation flow behaviour pattern presented by the author. This is because the simulation conducted by the author was in different numerical parameters and solver configurations. Therefore, it is sensible to notice a major difference in terms of technicality and turbulent effect. As manifested in Figures 12 (a), (b), (c), and (d), the particle system showed a similar general flow pattern behaviour to the result presented by the author aforementioned. The augmented environment indicated a clear flow separation and change in colour contour as the fluid was in contact at the leading edge of the plate. Furthermore, change vortex shedding intensity could be observed as the angular position of the flat plate changes. Although it was not as precise and accurate as the result generated in CFD simulation or actual wind tunnel experiment result, it still provided a clear indication of the important fluid behaviour such as wake, vortex shedding, and flow separation. It was noticed that the turbulent effect was only limited to Z-direction as the noise modifiers in Unity was set to the Z-direction. Therefore, no turbulence was augmented in X-direction. On the other hand, rendering turbulence in two directions would incur a large computational load.

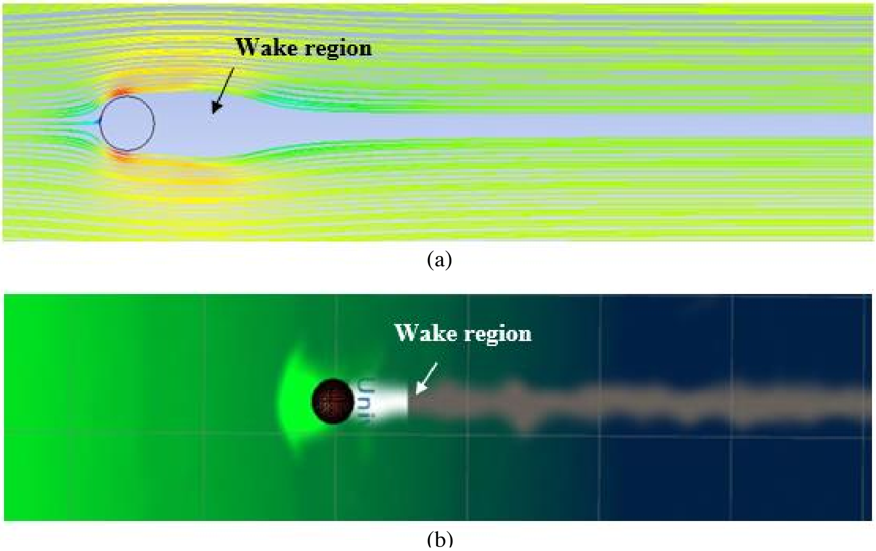


Figure 11. *Result contour validation: (a) Simulated streamline result, (b) augmented flow response*

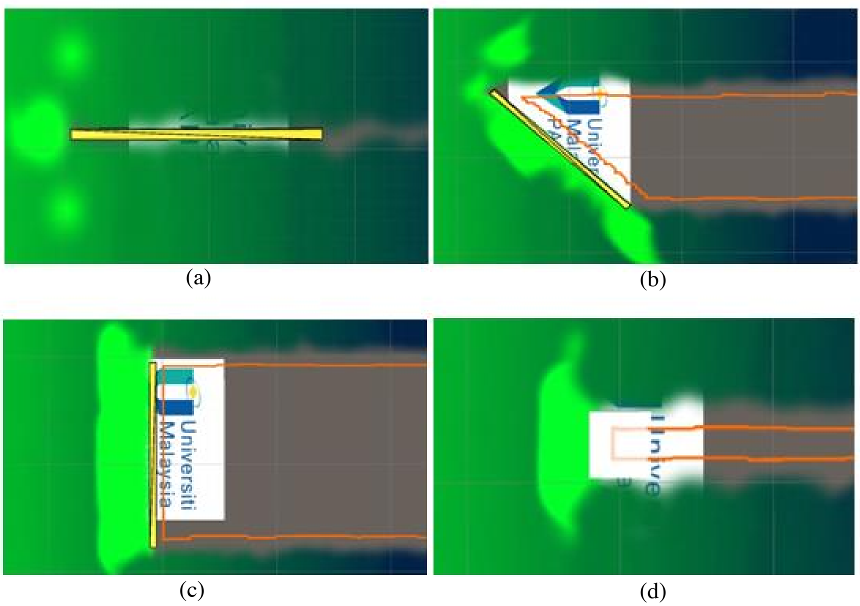


Figure 12. *Augmented geometries configuration of plane and cube : (a) 0°, (b) 45°, (c) 90°, (d) cube.*

Augmented Application Result

Figure 13 presents the augmented application result created in Unity. The application responded well in a moderate processing smartphone. The interactive interface of the application responded well with minor lagging as the user interacted with an application via touch. The touch interface was tested and indicated no issues. The application presented real-time results as the geometry was being altered. The particle system worked accordingly to touch functions such as scale and rotate as displayed in Figure 13. The flow of the particle system changed instantly without delay in response time.

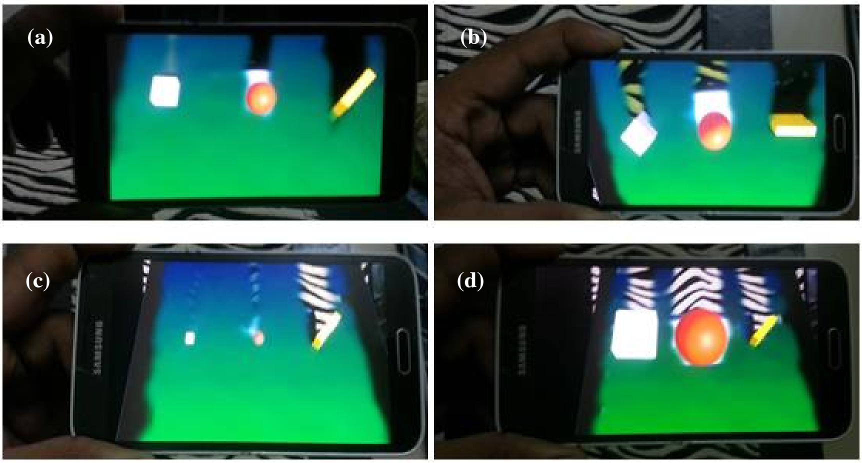


Figure 13. *Flow response at random configuration: (a) random angular position, (b) normal to flow, (c) small scale, (d) large scale.*

Utilising the proposed application within the grounds of fundamental education application for visual interaction was fairly satisfactory. The proposed application did not entirely exhibit a result of an actual flow response due to the flow properties of the particles that were not governed by the laws of fluid mechanics. However, the application could be utilised to enhance general fluid behaviour understanding with regard to the complex fluid flow field. Furthermore, it has potential as an educational application for intuitive and interactive learning methods for students and engineers. The application could be used as the preliminary stage of research prior to actual experiment or high resourcing CFD numerical analysis. It would also be an added value for research purposes via mixed reality hardware development and technologies. Regardless of the accurate and precise numerical and flow properties result presented by the CFD result and experimental result, the accuracy and precision of the augmented environment could be enhanced with the user-defined script module provided by Unity. More information on the implementation of AR application in an education sector can be found in Al-Megren and Almutairi (2019b; 2019a), Alkhattabi (2017), and Bistaman et al. (2018).

CONCLUSION

This paper described the development of a proposed augmented environment of fluid flow response for three simple geometries. The augmented result was validated against CFD simulated results and past studies based on empirical observation of the flow. The augmented environment responded well in indicating flow separation and vortex shedding with respect to the defined parameters. The augmented environment indicated trivial dissimilarities against the CFD results. In this research, integrated application in Unity is able to generate visual flow field results in real time without the need for digital overlay. However, the generated application via Unity and Vuforia requires additional scripting and hardware assistance to ensure its robustness, better accuracy, and reliable results with data extraction and user interface (UI) capabilities. For basic educational purposes or preliminary stages of research, this proposed application is adequate. Since the application is built based on specific requirements, further modification is required in order to enhance its credibility. The modification includes FVM mesh topology algorithm integration with regard to specified CFD software, mesh and node real-time editing UI functionality, CFD numerical model integration-RANS and URANS models, hardware enhancement (Google Cardboard; Microsoft HoloLens) for more interactive visualisation, real-world spatial mapping with grid option via Microsoft HoloLens with grid type, and cloud-based application for user library and database.

ACKNOWLEDGEMENT

This research work was conducted under the Fundamental Research Grant Scheme no. FRGS/1/2019/TK10/UMP/02/4 (RDU1901131). The authors would also like to thank Universiti Malaysia Pahang for providing the computing resources.

REFERENCES

Al-Megren, S., & Almutairi, A. (2019a). Analysis of user requirements for a mobile augmented reality application to support literacy development amongst hearing-impaired children. *Journal of Information and Communication Technology*, *1*(1), 97–121.

Al-Megren, S., & Almutairi, A. (2019b). User requirement analysis of a mobile augmented reality application to support literacy development amongst children with hearing impairments. *Journal of Information and Communication Technology*, *18*(2), 207–231.

Alkhattabi, M. (2017). Augmented reality as e-learning tool in primary schools' education: Barriers to teachers' adoption. *International Journal of Emerging Technologies in Learning*, *12*(2), 91–100. https://doi.org/10.3991/ijet. v12i02.6158

Barratt, R. P. (2018). A unity 3D script for calculating solar alignment at the neolithic temples complex at Ggantija, Gozo. *Journal of Archaeological Science: Reports*, *17*(November 2017), 634–639. https://doi.org/10.1016/j.jasrep.2017.12.012

Bistaman, I. N. M., Idrus, S. Z. S., & Rashid, S. A. (2018). The use of augmented reality technology for primary school education in Perlis, Malaysia. *Journal of Physics: Conference Series*, *1019*(1). https://doi.org/10.1088/1742-6596/1019/1/012064

Chi, H. L., Kang, S. C., & Wang, X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in Construction*, *33*, 116–122. https://doi.org/10.1016/j.autcon.2012.12.017

Daponte, P., De Vito, L., Picariello, F., & Riccio, M. (2014). State of the art and future developments of the augmented reality for measurement applications. *Measurement: Journal of the International Measurement Confederation*, *57*, 53–70. https://doi.org/10.1016/j.measurement.2014.07.009

Fiorentino, M., Uva, A. E., Gattullo, M., Debernardis, S., & Monno, G. (2014). Augmented reality on large screen for interactive maintenance instructions. *Computers in Industry*, *65*(2), 270–278. https://doi.org/10.1016/j.compind.2013.11.004

Hořejší, P. (2015). Augmented reality system for virtual training of parts assembly. *Procedia Engineering*, *100*(January), 699–706. https://doi.org/10.1016/j.proeng.2015.01.422

Huang, J. M., Ong, S. K., & Nee, A. Y. C. (2015). Real-time finite element structural analysis in augmented reality. *Advances in Engineering Software*, *87*, 43–56. https://doi.org/10.1016/j.advengsoft.2015.04.014

Huang, J. M., Ong, S. K., & Nee, A. Y. C. (2017). Visualization and interaction of finite element analysis in augmented reality. *CAD Computer Aided Design*, *84*, 1–14. https://doi.org/10.1016/j.cad.2016.10.004

Khalil, E. E. (2012). CFD history and applications. *CFD Letters*, *4*(2), 43–46.

Lam, K. M., & Wei, C. T. (2014). Numerical simulation of vortex shedding from an inclined flat plate. *Engineering Applications of Computational Fluid Mechanics*, *4*(4), 569–579. https://doi.org/10.1080/19942060.2010.11015342

Li, X., Yi, W., Chi, H. L., Wang, X., & Chan, A. P. C. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Automation in Construction*, *86*(October 2017), 150–162. https://doi.org/10.1016/j.autcon.2017.11.003

Liarokapis, F., Mourkoussis, N., White, M., Darcy, J., Sifniotis, M., Panos, P., Basu, A., & Lister, P. F. (2004). Web3D and augmented reality to support engineering education. *World Transactions on Engineering and Technology Education*, *3*(1), 11–14.

Lin, J. R., Cao, J., Zhang, J. P., van Treeck, C., & Frisch, J. (2019). Visualization of indoor thermal environment on mobile devices based on augmented reality and computational fluid dynamics. *Automation in Construction*, *103*(January), 26–40. https://doi.org/10.1016/j.autcon.2019.02.007

Malkawi, A. M., & Srinivasan, R. S. (2005). A new paradigm for human-building interaction: The use of CFD and augmented reality. *Automation in Construction*, *14*(1), 71–84. https://doi.org/10.1016/j.autcon.2004.08.001

Manca, D., Brambilla, S., & Colombo, S. (2013). Bridging between virtual reality and accident simulation for training of process-industry operators. *Advances in Engineering Software*, *55*, 1–9. https://doi.org/10.1016/j.advengsoft.2012.09.002

Nee, A. Y. C., Ong, S. K., Chryssolouris, G., & Mourtzis, D. (2012). Augmented reality applications in design and manufacturing. *CIRP Annals - Manufacturing Technology*, *61*(2), 657–679. https://doi.org/10.1016/j.cirp.2012.05.010

Neges, M., Adwernat, S., & Abramovici, M. (2018). Augmented virtuality for maintenance training simulation under various stress conditions. *Procedia Manufacturing*, *19*, 171–178. https://doi.org/10.1016/j.promfg.2018.01.024

Novak-Marcincin, J., Barna, J., Janak, M., & Novakova-Marcincinova, L. (2013). Augmented reality aided manufacturing. *Procedia Computer Science*, *25*, 23–31. https://doi.org/10.1016/j.procs.2013.11.004

Ong, S. K., & Huang, J. M. (2017). Structure design and analysis with integrated AR-FEA. *CIRP Annals - Manufacturing Technology*, *66*(1), 149–152. https://doi.org/10.1016/j.cirp.2017.04.035

Tsai, C.-H., & Yen, J.-C. (2014). The augmented reality application of multimedia technology in aquatic organisms instruction. *Journal of Software Engineering and Applications*, *7*(9), 745–755. https://doi.org/10.4236/jsea.2014.79069

Webel, S., Bockholt, U., Engelke, T., Gavish, N., Olbrich, M., & Preusche, C. (2013). An augmented reality training platform for assembly and maintenance skills. *Robotics and Autonomous Systems*, *61*(4), 398–403. https://doi.org/10.1016/j.robot.2012.09.013