

A Mixed Reality Simulator Framework for 3D Object Optimization and Depth-of-Field Analysis

Received:
6 January 2026
Accepted:
12 May 2026
Published:
21 June 2026

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Abstract— Background: Mixed Reality (MR) technology enables real-time interaction between physical and digital environments and has become increasingly important in immersive simulation and visualization applications. However, MR implementation still faces challenges related to system performance limitations and the complexity of 3D object rendering, which may reduce immersion quality and interaction realism. Therefore, optimization of 3D assets and visual effects is urgently needed to improve MR efficiency and user experience. **Objective:** This study aims to propose a design and evaluation framework for Mixed Reality systems by focusing on 3D object optimization and Depth-of-Field (DoF) enhancement in Mixed Reality Simulator (MRSi) development. **Methods:** The proposed framework integrates vertex decimation-based 3D object optimization and DoF analysis using Circle of Confusion (CoC) calculations. Low-poly 3D assets were optimized through vertex and triangle reduction, while DoF parameters were adjusted based on focal length, aperture, and object distance. **Results:** The results showed that the proposed approach successfully reduced 3D model complexity by 16.280%–90.950% while maintaining visual quality, with CoC values ranging from 0.0066 to 0.2414, indicating improved depth perception and more realistic visual focus effects in MR environments. The optimization process improved rendering efficiency and enhanced visual realism in Mixed Reality environments. **Conclusion:** The proposed framework effectively improves MR system performance and immersion quality, providing practical guidance for the development of efficient and visually realistic Mixed Reality applications.

Keywords— Mixed Reality; Immersive; Framework; Vertex Decimation; Optimization; Depth of Field

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I. INTRODUCTION

Metaverse is one of the trending topics discussed along with the emergence of AI and IoT technology. Metaverse service providers strive to innovate to provide the best solutions for companies and consumers [1],[2]. Extended Reality (XR) technologies, such as Virtual Reality (VR), Augmented Reality (AR), and Mixed reality (MR), are important components of the metaverse [3]. The technology serves as a gateway offering a truly immersive 3D world of the metaverse. Mixed reality is a merger of the real and virtual worlds that creates new environments and visualizations, where physical and digital objects run together and interact in real-time [4]. Mixed reality plays an important role in the development of the metaverse since this technology covers all the shortcomings of AR and VR [5]. MR not only displays virtual objects but also receives all new information, processes feedback, and synchronizes data from users. The mixed reality technology revolution is generating new levels of functionality and empowerment in all sectors of society [6]. MR has been widely used in various fields, especially those related to learning, training, and simulation, such as the use of mixed reality technology to simulate types of heart disease [7]. MR can be used to educate patients, allowing patients to visualize and better understand medical conditions and procedures [8]. Utilizing MR for occupational health and safety operator training can also reduce training costs [9], [10]. Simulation using MR can reduce the gap between classroom instruction and clinical experience [11]. Simulation-based training using MR offers an interesting and immersive learning experience that can improve students' learning comprehension [12], [13]. Learning using an immersive learning environment provides the advantage for students to learn and play at the same time [14].

However, during its development, there are several challenges, obstacles, and limitations to implementing this technology widely in various sectors. There are nine (9) critical challenges in implementing immersive technology, namely infrastructure, algorithm development, interoperability, safety and health, virtual content modeling, cost, skills, multi-censor limitations, and ethical issues [15]. The biggest problem in using mixed reality technology is related to two aspects, including limited field of view (FoV) and interface design [16]. The lack of a common framework in mixed-reality application development makes it difficult for users to get an immersive experience. To get an immersive environment, users must have expensive hardware, a Head Mounted Display (HMD). There are two problems to be addressed to build effective XR interactions, namely understanding the user and the environment and adapting the interface according to user needs [17]. It is necessary to develop a mixed-reality application framework to enable immersive experiences for everyone easily by leveraging the rendering capabilities of modern smartphones [18]. The progress of XR technology (AR, VR, MR) will greatly depend on

user experience (UX) and the level of acceptance of the technology. Systematic framework development is needed to increase the level of user acceptance in XR systems [19]. The design and evaluation of Mixed Reality (MR) device interfaces have several unique challenges, and the interface design recommendations presented in several studies are still limited and need more attention [20],[21]. The use of mixed reality may also influence the user's perception, confidence, and experience while in the field [22].

Several literatures reveal research on the development of mixed reality frameworks. Elliott and Alrashidi [23] developed a conceptual framework for understanding immersive learning environments, specifically those based on the use of augmented and mixed reality. Sharma and Alharthi [23] developed a framework that provides design implications for space selection in mixed-reality environments. Hammady and Strathern [24] in their research on a prototype MR framework for tour guide programs, explained that the current MR approach is more focused on visitor engagement with specific content. Kostov and Wolfartsberger [26] proposed a framework that allows collaborative simulation and training in a mixed-reality context. Furthermore, Zellerbach and Robert [27] developed a mixed reality music instrument (MRMI) framework. The development of the mixed reality music instrument (MRMI) framework is an interesting way of combining mixed reality technology with music. MRMI allows musicians or users to create, play, and interact with musical instruments using a mixed-reality environment. Mixed reality application design development is a complex process that involves many aspects. It is important to have a strong understanding of mixed reality technology and focus on user needs. There are five layers suggested to produce a comprehensive MR framework: the first layer considers system components, the second and third layers focus on architectural issues for component integration, the fourth layer is the application layer executing the architecture, and the fifth layer is the user [25]. The interface design of mixed-reality applications has a significant influence on the user experience and successful use of immersive technology. This research also has the same goal, namely developing a framework for developing mixed reality systems; However, the work to be carried out in this research is more oriented towards various problematic factors that users often experience in implementing MR technology, especially the design and modeling of 3D objects.

However, previous studies primarily focused on conceptual frameworks, interface design, collaborative environments, and user interaction aspects of Mixed Reality systems. Limited studies have specifically addressed the integration of 3D object optimization and Depth-of-Field (DoF) evaluation within a unified Mixed Reality Simulator (MRSi) framework. Consequently, rendering efficiency and immersive visual realism remain insufficiently explored in current MR framework development. The difference between this research and previous research is the integration of vertex decimation-based 3D object optimization and DoF analysis into a

comprehensive MRSi framework to improve both computational efficiency and immersive user experience. Therefore, the purpose of this research is to develop and evaluate a Mixed Reality design and evaluation framework focusing on optimized 3D modeling and visual depth enhancement.

II. RESEARCH METHOD

The development of MR involves various research areas, such as computer geometry, computer networks, image processing, 3D modeling and rendering, sound and motion recognition, etc. The use of MR technology focuses on three aspects including, product design, interactive design, and display design [26]. There are various types of design guidelines to maintain consistency and usability in interactive systems. However, some researchers consider this guide to be less relevant and practical in its implementation [27]. The long-term goal of MR research is to make MR systems fully usable and easy to use, but there are problems in dealing with human factors in MR systems. In some cases, the implementation of MR technology is still a problem for users, as stated in several previous studies according to quotes from various sources [15], [16], [17], [19], [20], [28]. The problems in the research are shown in table 1 below:

Table 1. Problem Mapping (Previous Work)

Author	Problem Identification
A. Prabhakaran [15]	<ul style="list-style-type: none"> ▪ Infrastructure ▪ Algorithm Development ▪ Interoperability ▪ Safety & Health ▪ Virtual content modeling ▪ Cost ▪ Skills ▪ Multisensory limitations ▪ Ethics
M. Filipenko, <i>et al.</i> [16], V. Yepes, <i>et al.</i> [20], Wei, Li, Dong-Min Cho [28]	<ul style="list-style-type: none"> ▪ Field of View (FoV) ▪ Interface design
T. R. Jonker [17]	<ul style="list-style-type: none"> ▪ User Interaction ▪ Simulation environment
L. Gong [19],[22]	<ul style="list-style-type: none"> ▪ User acceptance Evaluation

Based on the problem identification data presented in Table 1, several technical and non-technical challenges have been identified in the implementation of Mixed Reality technology. However, this research specifically focuses on technical challenges related to 3D object optimization, rendering efficiency, and Depth-of-Field (DoF) enhancement within the Mixed Reality Simulator (MRSi) framework. To address these challenges, a new framework for implementing Mixed Reality technology is proposed, as shown in Figure 1. The proposed

framework focuses on three main aspects related to Mixed Reality development, including:

- Aspect of user needs
- Aspect of design and interaction

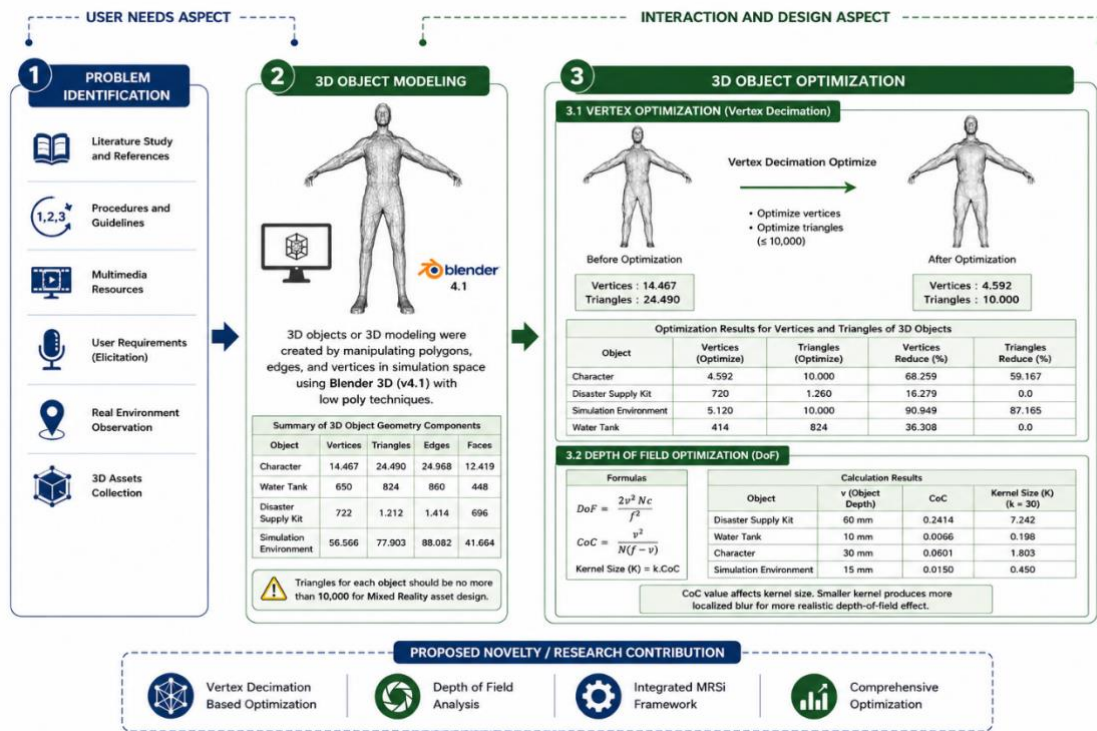


Fig 1. Proposed Mixed Reality Simulator (MRSi) Framework

III. RESULTS AND DISCUSSION

Design evaluation is an important stage in the development of a Mixed Reality (MR) system to ensure that the system meets user needs and provides an optimal experience. In this research, the Mixed Reality system design model is evaluated as follows:

A. 3D-Object Modelling

The 3D objects or 3D modeling in this research were created by manipulating polygons, edges, and vertices in simulation space using Blender 3D software version 4.1. The model was created using low poly techniques since it has a faster processing rate [29]. Figure 2 shows the results of 3D modeling of various assets in the Mixed Reality Simulator (MRSi) system.

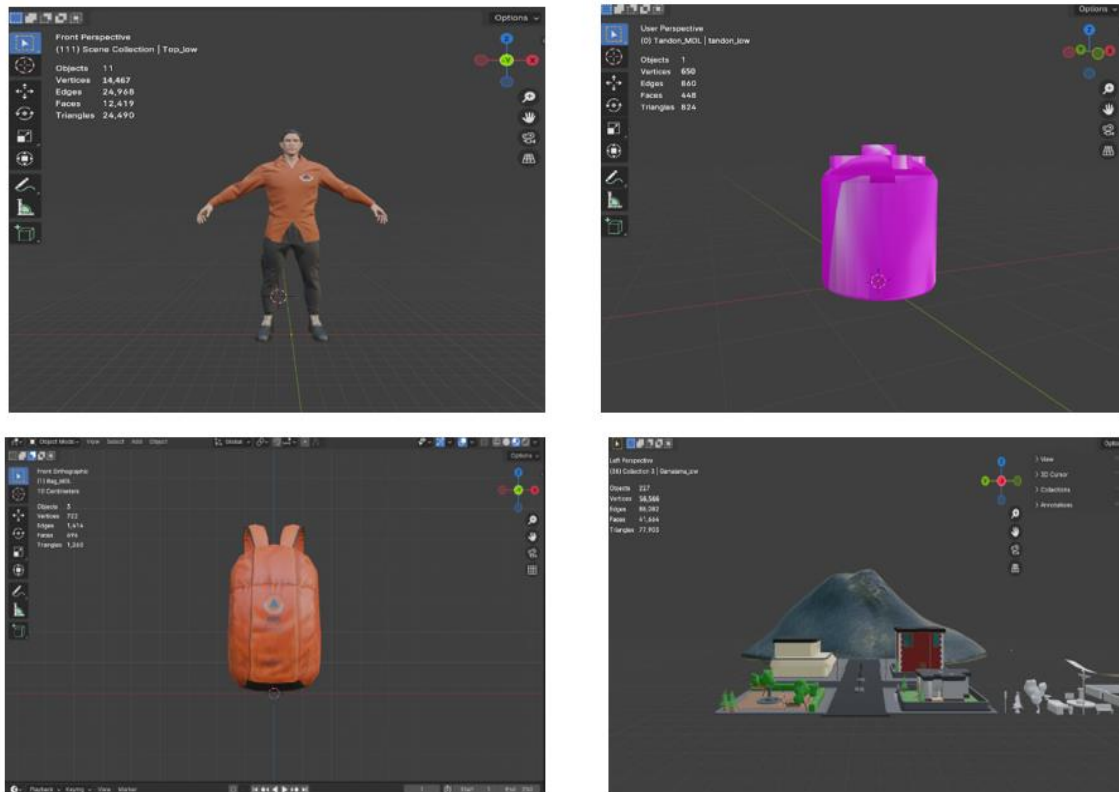


Fig 2. Results of MRSi 3D Object Modeling

Based on the results of 3D object modeling, it can be observed that each asset has a different number of geometric components (polygons) such as vertices, triangles, edges, and faces. This is due to the complexity and level of detail of each object. The more vertices, triangles, edges, and faces used in a 3D design, the more detailed and complex the object is in representing real-world objects; however, it increasingly impacts the performance of computer resources used when designing 3D object images [30]. Table 2 below shows a summary of the number of geometric components based on 3D object modeling.

Table 2. Summary of Number of 3D Object Modeling Geometry Components

Object	Vertices	Triangles	Edges	Faces
Character	14.467	24.490	24.968	12.419
Water tank	650	824	860	448
Disaster Supply Kit	722	1.212	1.414	696
Simulation environment	56.566	77.903	88.082	41.664

Based on Table 2, objects in the form of a simulation environment have a greater number of vertices and triangles than other objects. In developing mixed reality asset designs, the number of triangles required is no more than 10,000 triangles, so this research requires a further optimization process to reduce the number of triangles.

B. Optimization of 3D Objects and Characters

The process of optimizing 3D objects in this research was carried out in two stages, namely optimizing object modeling and spatial depth levels.

1. Results of 3D Object Modeling Optimization

The object modeling optimization process aims to meet technical requirements in designing Mixed Reality systems. Optimization is carried out using the Open3D library in Python software, calling the `optimize_vertex_triangles` function to optimize vertices and triangles until the desired number of triangles is reached, namely 10,000 triangles. Figure 3 shows an example of the results of implementing the vertices and triangles algorithm using the vertex decimation optimize system.

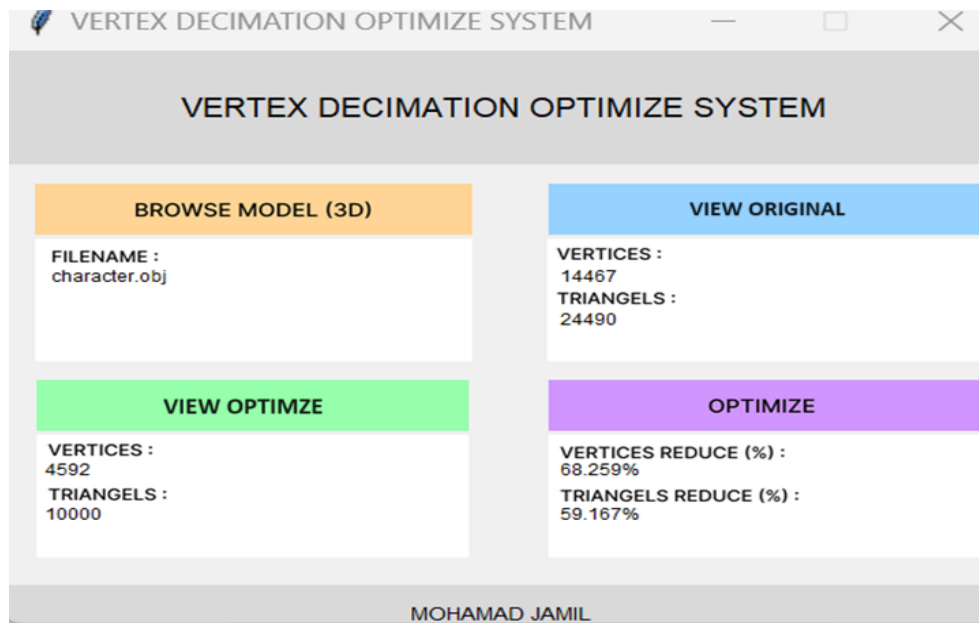


Fig 3. Vertex Decimation Optimize System

Figure 3 above shows the results of the optimization process using Vertex Decimation Optimize. By using one object (character), the optimization process can reduce the number of vertices and triangles by 4592 vertices and 10000 triangles. Even though there is a reduction in vertices and triangles, the object is still identical to the initial shape, as shown in Figure 4 and Figure 5. Table 3 shows the results of the 3D Object Vertices and Triangle optimization tests.

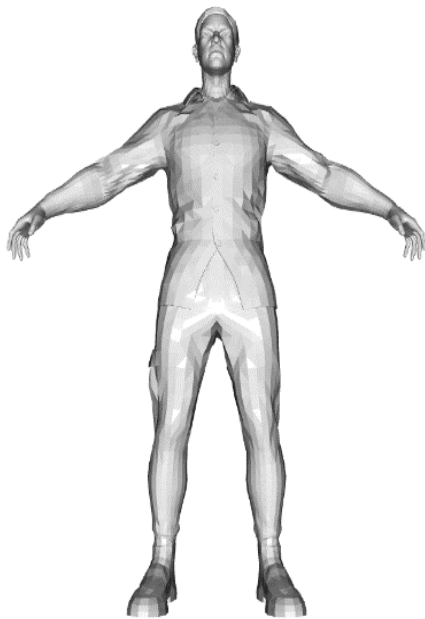


Fig 4. Character before Optimization

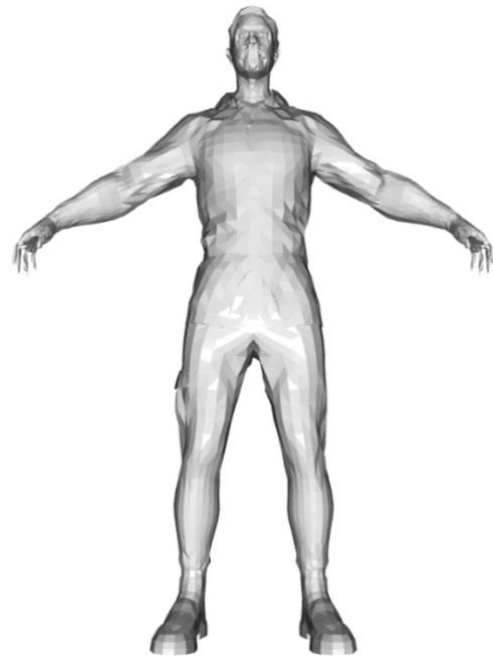


Fig 5. Character after Optimization

Table 3. Optimization Results for Vertices and Triangles of 3D Objects

Object	Vertices Optimize	Triangle Optimize	Vertice Reduce (%)	Triangle Reduce (%)
Character	4592	10000	68.259	59.167
Disaster Supply Kit	720	1260	16.279	0.0
Simulation Environment	5120	10000	90.949	87.165
Water Tank	414	824	36.308	0.0

Based on the results of object modeling optimization testing in Table 3, there is a reduction in vertices and triangles on each object. In the Character object before optimization, the number of vertices and triangles is 14,467 and 24,490 respectively, and after optimization, the number of vertices and triangles is 4592 and 10,000 respectively. In the Simulation Environment object, it can be seen that before optimization, the number of vertices and triangles is 56,566 and 77,903 respectively. After optimization, the number of vertices and triangles is 5120 and 10000 respectively. Meanwhile, for the Emergency Preparedness Kit and Water Tank objects, the results of the reduction process only occur in the number of vertices and have no impact on the number of triangles. This may be due to the complexity of the geometric structure of these two objects (Emergency Preparedness Kit and Water Tank) simpler and fulfill the visual details of a 3D object compared to other objects, such as Characters and Simulation Environment. The more triangles there are, the closer the surface is to the ideal surface. However, too many triangles can also lead

to excessive detail, which may not always be necessary depending on the context in which the object is used [34]

2. Depth of Field Optimization

The depth of field optimization process in this research is carried out using the Depth of Field (DoF) algorithm. This process aims to create a sharp focusing point to create a more realistic space/object effect. In this research, based on equation 1, there are several variables used to determine the depth of an object, including Focus Distance, Focal Length, Aperture, and Object Depth (CoC).

$$DoF = \frac{2v^2Nc}{f^2} \quad (1)$$

The value of the Circle of Confused (CoC) is calculated using the following equation:

$$CoC = \frac{v^2}{N.(f - v)} \quad (2)$$

The results of calculating the CoC value for each object are as follows:

a. Disaster Supply Kit:

$$CoC = \frac{60^2}{1.5 \times (10000 - 60)} = \frac{3600}{1.5 \times (9940)} = \frac{3600}{14.910} = 0.2414$$

b. Water Tank:

$$CoC = \frac{10^2}{1.5 \times (10000 - 10)} = \frac{100}{1.5 \times (9990)} = \frac{100}{14.985} = 0.0066$$

c. Character:

$$CoC = \frac{30^2}{1.5 \times (10000 - 30)} = \frac{900}{1.5 \times (9970)} = \frac{900}{14.955} = 0.0601$$

d. Simulation Environment:

$$CoC = \frac{15^2}{1.5 \times (10000 - 15)} = \frac{225}{1.5 \times (9985)} = \frac{225}{14.955} = 0.0150$$

Circle of Confusion (CoC) has a direct effect on kernel size in the context of photography and image processing. The use of smaller kernels produces a more localized blur effect, which may be suitable for producing depth-of-field effects [35]. The kernel size is calculated using the following equation:

$$K = k \cdot CoC \quad (4)$$

The k is a scaling factor, which is determined based on the experimental results in this research, namely 0.0333. Thus, the kernel size of each object is obtained as follows:

a. Disaster Supply Kit:

$$K = 0.0333 \times 0.2414 = 0.0080$$

b. Water Kit:

$$K = 0.0333 \times 0.0066 = 0.00022$$

c. Character:

$$K = 0.0333 \times 0.0601 = 0.00200$$

d. Simulation Environment:

$$K = 0.0333 \times 0.0150 = 0.0005$$

Figures 6, 7, 8, and 9 show the results of DoF implementation on objects.

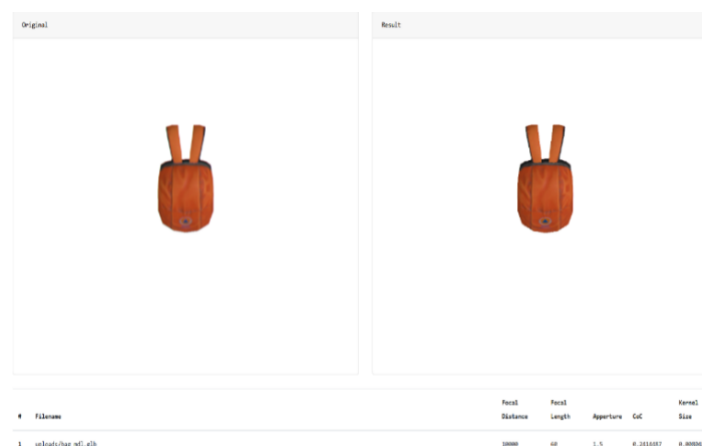


Fig 6. Results of Implementation of DoF (Disaster Supply Kit)

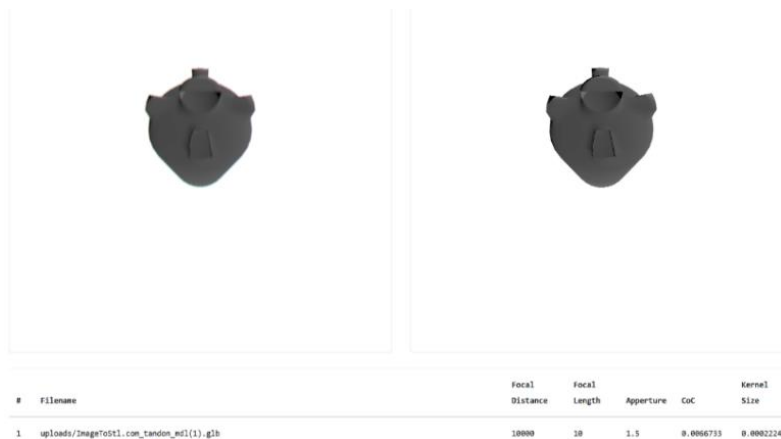


Fig 7. Results of Implementation of DoF (Water Tank)

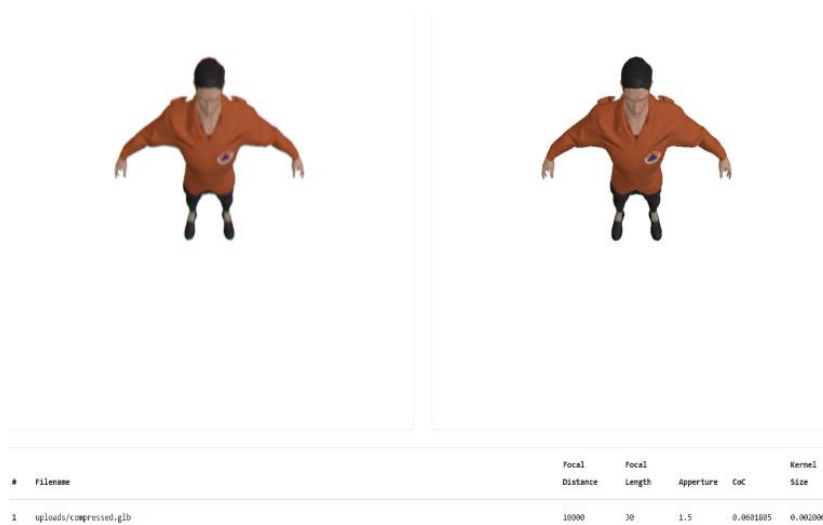


Fig 8. Results of Implementation of DoF (Character)

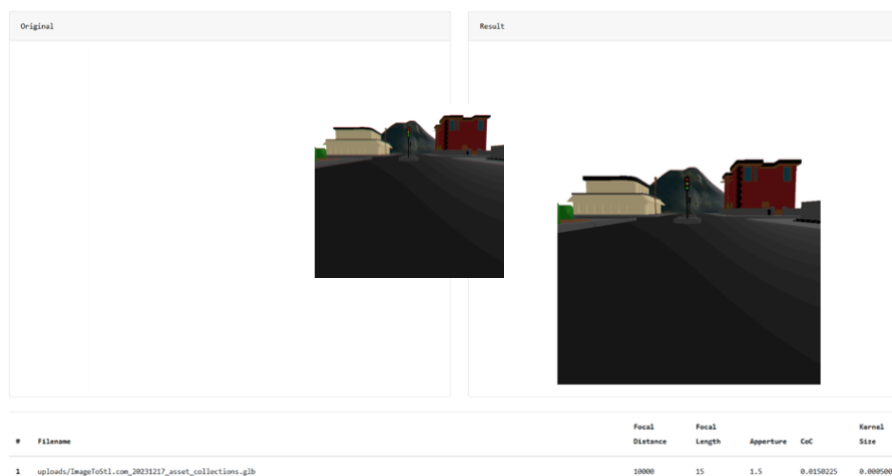


Fig 9. Results of Implementation of DoF (Simulation Environment)

The following table 4 shows a summary of the results of the depth of field optimization on various objects in the Mixed Reality Simulator system.

Table 4. Summary of the Results of Depth of Field Optimization

Object	V	F	N	CoC	Kernel
Character	10000	30	1.5	0.0618	0.0224
Disaster Supply Kit	10000	60	1.5	0.2414	0.0080
Simulation Environment	10000	15	1.5	0,0150	0.0005
Water Tank	10000	10	1.5	0.0066	0.0002

Based on Table 4, each row represents the depth of field optimization results for various objects. For example, for “Character”, the camera is set at a focus (F) of 30 mm with an aperture (N) of 1.5, and the Circle of Confusion (CoC) of 0.0618 mm, with a kernel of 0.0224. The difference in these values shows how the depth of field is organized based on different object characteristics. The smaller the CoC value, the greater the depth of field obtained, meaning more objects can remain sharp in the image.

The findings of this research are that the proposed vertex decimation optimization and Depth-of-Field (DoF) analysis effectively reduce 3D object complexity while maintaining visual quality and improving immersive perception in Mixed Reality environments. The optimization process successfully reduced the number of vertices and triangles by up to 90.949% and 87.165%, respectively, while the DoF implementation improved depth perception through appropriate Circle of Confusion (CoC) and kernel size calculations. The results of this research are in line with or supported by previous studies stating that low-poly modeling techniques improve rendering efficiency and processing performance in 3D environments [29], and that systematic optimization and framework development in XR systems can enhance immersive user experience and visual interaction quality [19].

IV. CONCLUSIONS

In this study, a new framework for the design and optimization of Mixed Reality (MR) technology was proposed to address challenges in developing immersive MR environments. The proposed framework focuses on 3D object optimization and Depth-of-Field (DoF) analysis within the Mixed Reality Simulator (MRSi) system. The findings of this research indicate that the proposed vertex decimation optimization successfully reduced the number of vertices and triangles by up to 90.949% and 87.165%, respectively, while maintaining visual quality and improving rendering efficiency. In addition, the implementation of DoF analysis using Circle of Confusion (CoC) and kernel size calculations enhanced depth perception and immersive visual effects in MR environments. These results demonstrate that the proposed framework can support more efficient and visually realistic Mixed Reality system development. However, this research is limited to static 3D object optimization and DoF analysis within specific MRSi simulation scenarios. Excessive vertex decimation may potentially reduce geometric detail and affect object

topology in highly complex models. In addition, this research has not yet evaluated real-time frame rate (FPS) performance, real-time user interaction, or multi-device MR implementation. Future research may focus on FPS-based rendering evaluation on mobile and Head-Mounted Display (HMD) devices, adaptive real-time rendering optimization, AI-based optimization methods, user experience evaluation, and cross-platform Mixed Reality implementation to further improve immersive interaction quality and system performance

Author Contributions: *Mohamad Jamil:* Conceptualization, Methodology, Framework Design, Software Development, Formal Analysis, Writing-Original Draft. *Iis Hamsir Ayub Wahab:* Methodology, Experimental Design, Investigation, System Validation, Writing-Review & Editing, Supervision. *Kiswanto:* Software Implementation, Data Curation, Performance Evaluation, Visualization, Technical Review. *Seh Turuy:* Investigation, Data Collection, 3D Object Optimization Support, Depth-of-Field Testing, Manuscript Editing

All authors have read and agreed to the published version of the manuscript.

Funding: This research received no specific grant from any funding agency.

Conflicts of Interest: The authors declare no conflict of interest.

Data Availability: Data is available upon request to the corresponding author.

Informed Consent: There were no human subjects.

Animal Subjects: There were no animal subjects.

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