VR for Industrial Visualization

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Abstract—The architectural and industrial visualization sectors are undergoing a fundamental transformation from static, pre-rendered imagery to dynamic, real-time immersive environments . This paper documents the technical development of an Interactive Virtual Reality (VR) Tour for Morde Foods, designed to function as a "Digital Twin" of a manufacturing facility . The project details the ingestion of high-precision Computer-Aided Design (CAD) data using Unreal Engine's Datasmith, the optimization of complex geometry via Blender workflows, and the implementation of Lumen Global Illumination within strict VR frame budgets . By addressing physiological constraints such as the Vergence-Accommodation Conflict (VAC) and utilizing Blueprints for metadata retrieval, the system provides stakeholders with a navigable, high-fidelity environment for operational planning and training.

Keywords— Virtual Reality, Digital Twin, Unreal Engine 5, Industrial Visualization, Datasmith, Lumen, Industry 4.0.,Virtual Reality, Metaverse.

I. INTRODUCTION

Get ready to embark on an exciting journey into a world where reality knows no bounds! In this project proposal, we unveil an amazing concept: a virtual reality showroom for buying cars in the metaverse. We'll explore how the metaverse and VR technology can reshape the way we experience and purchase vehicles, taking the car-buying process to new heights. By blending the immersive power of VR, seamless data integration, and social interactions, we aim to create a mind-blowing platform that breaks free from physical constraints and sets a whole new standard for shopping. Picture yourself stepping into a digital wonderland—the metaverse—where anything is possible and physical distance is no obstacle. Our VR showroom becomes your ticket to an expansive world that evolves alongside the latest automotive innovations. Get ready to explore an ever-growing collection of virtual cars, immersing yourself in a vibrant environment that feels just like a real showroom but with endless possibilities. Slip on a VR headset, and watch as the magic unfolds. You'll find yourself in a meticulously crafted digital space, where you can fully interact with virtual car models. Marvel at the intricate details, peek inside the cabin, and even take the cars for a spin—all without leaving your home. The level of realism is beyond what any physical showroom can offer, giving you the confidence to make informed decisions. But wait, there's more! The metaverse adds a social twist to the car buying adventure. Connect with friends, family, and experts within the virtual showroom. Together, you can explore the cars, exchange opinions, and customize your virtual rides. It's like having your own car club, but in a virtual world! Thanks to real-time data and cutting-edge technology, the metaverse experience gets even more mind-boggling. AI algorithms can provide personalized recommendations based on your preferences, budget, and driving habits. Imagine having a virtual assistant guiding you through the process, ensuring that you find the perfect match. And when it's time to bridge the virtual and real worlds, augmented reality (AR) steps in. Visualize virtual cars in your own surroundings, as if they were right in front of you. It's a seamless transition that makes test driving a breeze. In conclusion, the metaverse, combined with VR technology, unlocks a whole new realm of possibilities for car buying. Our VR showroom breaks free from physical limitations, offering an immersive and social experience that's unlike anything you've ever seen. Say goodbye to the traditional showroom and get ready for a wild ride through the metaverse. We're redefining how you discover, personalize, and purchase cars—bringing the future of automotive retail right to your fingertips. Buckle up and get ready to explore a whole new dimension of car shopping excitement!

II. LITERATURE SURVEY

In the research paper[1] "Augmented reality in retail: A trade-off between user's control of access to personal information and augmentation quality" by Atieh Poushneh[1], the paper dives deep into the rapidly evolving domain of augmented reality (AR) in the retail industry. As digital and physical realities merge, AR has the potential to revolutionize how consumers shop, providing immersive experiences

that can enhance user engagement and satisfaction. At the heart of these interactions lies the "augmentation quality," which can be understood as the fidelity, accuracy, and richness of the AR output. While high augmentation quality can significantly elevate the user experience, there exists a notable concern: user privacy.

To deliver personalized and seamless AR experiences, AR applications often require access to a user's personal data, which could range from simple demographic information to intricate behavioral patterns. This intrusion into personal space raises valid concerns among users regarding how their data is used, potentially leading to hesitance in adoption. Thus, the crux of the problem is the balance between delivering high augmentation quality and respecting user privacy.

The paper utilizes equity theory, a psychological model, to dissect the relationship between augmentation quality and user control over personal information. Equity theory suggests that individuals evaluate their interactions based on inputs (what they give) and outcomes (what they receive). In the AR retail context, users "give" their personal data and "receive" augmentation quality. Satisfaction is achieved when users feel this exchange is equitable. This delicate balance is pivotal for AR developers and retailers to understand. They are tasked with ensuring that the personal data required doesn't outweigh the perceived benefits of the AR experience.

One of the primary findings is the significant influence of a user's ability to control access to their personal data on their overall satisfaction with the AR experience. When users feel they have more control over their information, they are more likely to view the exchange as equitable, even if the augmentation quality is high. In simpler terms, even a high-quality AR experience might not appease users if they feel their privacy is at risk.

For retailers and AR developers, this underscores the importance of transparent data practices. Ensuring that users are aware of how their data is used, and giving them control over this, can lead to more satisfactory and trusting interactions.

Poushneh's study sets the foundation for various potential research avenues. A notable direction is understanding how individual personality traits might influence satisfaction levels with AR. For instance, would an inherently private individual react differently to AR experiences compared to someone more open? Another fascinating area to delve into is the exploration of emerging AR tools and gadgets, such as AR glasses. How do different devices impact user perceptions and their trade-offs regarding data privacy and augmentation quality.

Augmented Reality in retail is not just about integrating the latest technology but understanding and respecting the boundaries of user privacy. This paper illuminates the importance of striking a balance between delivering rich AR experiences and upholding user trust. As AR continues to permeate the retail industry, understanding these nuances becomes imperative for sustained success and user acceptance..

In this research paper[2] Unreal Engine stands as a pivotal tool in shaping interactive virtual spaces, particularly in architectural visualization. This exploration delves into its application across immersive and non-immersive Virtual Reality (VR) systems within the architectural context. It critically evaluates the strengths and drawbacks of each approach while highlighting their practical use in interactive visualization. The immersive VR experience, powered by Unreal Engine, offers an unparalleled sense of presence and immersion. Users are seamlessly transported into meticulously crafted virtual environments that mimic real-world spaces. This allows them to interact with architectural designs at an unprecedented level of detail and realism. As users navigate these digital constructs, they can explore spaces from every angle and engage with virtual elements, thereby enhancing their comprehension of spatial concepts and design intricacies. However, the immersive VR experience also comes with its set of challenges. The hardware demands of such systems can be substantial, translating to higher costs and restricted accessibility. Furthermore, prolonged exposure to immersive VR environments can lead to discomfort and motion sickness for certain users, limiting the extent to which they can engage with and benefit from the experience. Addressing these issues requires careful optimization of performance and the design of interactions that prioritize user comfort. In contrast, non-immersive VR experiences offer a more accessible avenue for architectural visualization. By leveraging Unreal Engine's capabilities, users can explore 3D architectural models on a broader range of devices,

from standard computers to mobile devices. This accessibility is particularly advantageous for engaging stakeholders who might lack access to high-end VR hardware. It democratizes architectural visualization, ensuring that a wider audience can participate in the design process. Nevertheless, non-immersive VR experiences are not without their limitations. Unlike immersive counterparts, they might struggle to convey the true sense of scale and ambiance inherent in architectural designs. This gap in experiential conveyance could impact stakeholders' comprehension of critical design aspects, such as lighting, acoustics, and the human interaction that animates spaces. The choice between immersive and non-immersive VR is ultimately contingent on project goals and target audiences. Immersive VR excels in facilitating deep design evaluation and emotional engagement with spaces, while non-immersive VR shines in terms of accessibility and inclusivity. Striking a balance between the two systems, perhaps through hybrid approaches, could provide a new frontier in architectural visualization. This could lead to heightened user interaction and a seamless transition between immersive and non-immersive experiences, thereby expanding the reach of architectural creativity to a wider spectrum of users.

This paper[3] delves into the exploration of Unreal Engine's potential in crafting interactive environments for both immersive and non-immersive Virtual Reality (VR) systems within the domain of architectural visualization. It undertakes an in-depth examination of the strengths and drawbacks intrinsic to each approach, subsequently drawing comparisons regarding their practical applications within the realm of interactive visualization. The core focus lies in discerning opportunities to simplify and harmonize the creation process for both systems, thereby broadening their reach and accessibility across a diverse spectrum of users. Immersive VR, driven by Unreal Engine, introduces an unparalleled level of engagement by immersing users within intricately constructed virtual realms. This immersive environment facilitates the exploration of architectural designs with an extraordinary degree of fidelity and authenticity. Users can navigate through these digitally constructed spaces, manipulating objects and elements, which significantly enhances their understanding of spatial concepts. For instance, architectural professionals employ immersive VR to grant clients the chance to virtually inhabit unbuilt structures, thereby providing a tangible preview of the envisioned outcome. However, the immersive VR experience is accompanied by its own set of challenges. The demanding hardware requisites can pose financial and accessibility hurdles, limiting the potential user base. Moreover, prolonged exposure to immersive VR could lead to discomfort or motion-related ailments for specific individuals, affecting their ability to derive full benefit from the experience. Overcoming these concerns necessitates meticulous performance optimization and the creation of interaction paradigms that minimize discomfort. In contrast, non-immersive VR systems, facilitated by Unreal Engine, offer advantages rooted in accessibility. These systems can be engaged on a broader spectrum of devices, from standard computers to mobile platforms, ensuring a more inclusive user participation. This democratization of architectural visualization is particularly beneficial in engaging stakeholders who might not possess high-end VR hardware. Nonetheless, non-immersive VR experiences fall short in delivering the heightened sense of presence synonymous with their immersive counterparts. The detachment between the virtual and physical environments potentially impedes users' grasp of the architectural design's scale and ambiance. This limitation becomes especially significant when communicating experiential elements like lighting nuances, acoustics, and human interactions. Opting for either immersive or non-immersive VR hinges on project objectives and target audiences. Immersive VR excels in detailed design scrutiny and emotional engagement with spaces, while non-immersive VR thrives in accessibility, making it suitable for diverse stakeholders. This paper underscores the prospect of striking a harmonious equilibrium between these systems, envisioning an enhanced user interaction experience and seamless transitions between immersive and non-immersive contexts. By merging the strengths of both approaches, the aim is to amplify the accessibility and impact of architectural creativity across a wider user spectrum.

This paper[4] Virtual Reality (VR) technology is becoming a transformative tool in the realm of real estate, especially for showcasing properties. The Quill Residences, located in Kuala Lumpur, previously relied on traditional showrooms at just two locations to offer potential buyers a glimpse of their offerings. The challenge was that these showrooms lacked a sense of depth and reality, and potential buyers often had to stretch their imagination. The research therefore aimed to evaluate the efficiency of

interactive VR walkthrough applications, particularly in home interior design, to assist in real estate purchase decisions.

The study employed the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model to devise the Home Tour Immersive (HTI) framework, which serves as a guide for VR application development. This framework detailed the steps necessary to achieve the objectives of the study. During the development phase, 3D designs were crafted using tools like 3ds Max 2016, with the final application assembled in Unity 2018.3.5f1. The application was then made available for testing via VR goggles.

From the evaluation, a substantial 90% of respondents expressed their belief in the efficacy of the VR walkthrough in aiding their property purchase decisions. The evaluation demonstrated that users found the VR experience to be highly interactive and user-friendly. They could adjust lighting, change colors of various items, and explore the space freely. This virtual experience provided potential buyers, especially those who might be located remotely, an in-depth and realistic view of the property, significantly more detailed than traditional photos or showrooms.

The overwhelmingly positive response from respondents signifies the potential of VR in revolutionizing real estate property viewing experiences. Traditional showrooms and 360-degree panorama photos lack the depth and interactivity that VR walkthroughs offer. This innovation is especially pivotal for international or out-of-state buyers who can't easily visit a physical location. Moreover, with advancements in VR, even properties still under construction can be visualized, offering potential buyers a clearer expectation of the finished product. With the dawn of digital advancements, no industry remains untouched by the transformative power of technology, and real estate, a sector once heavily reliant on traditional methods, is no exception. Virtual Reality (VR), a technological marvel once confined to the world of gaming and entertainment, has made a groundbreaking entrance into the real estate market, reshaping its dynamics in ways previously unimagined. By offering a deeply immersive experience, VR allows potential buyers to step into properties, roam rooms, and even visualize changes they might want to make, all from the comfort of their homes. This innovation doesn't just benefit the buyers. Sellers and real estate agents also find a silver lining. They can showcase properties to a global audience without the logistical challenges of organizing physical viewings. For agents, it means broader clientele reach and for sellers, potentially faster sales cycles. Moreover, this virtual approach reduces the constraints of time and geography, allowing a buyer from another continent to tour a house thousands of miles away, as easily as someone living next door. The essence of the property buying experience has always been about 'feeling at home.' Traditional methods, while effective to an extent, often left potential buyers relying on imagination to fill in the gaps, especially when viewing properties still under construction. VR has bridged this gap. When buyers can virtually experience sunrise from their future bedroom or the view from their balcony, it offers a depth of understanding that photos or descriptions can't match. This depth, in turn, facilitates more informed and confident decision-making.

III. METHODOLOGY

1. Real-Time Rendering in Industry 4.0

1.1 The Limitations of Traditional Visualization
For decades, the standard for high-quality architectural and industrial visualization hasbeen "offline" or "pre-rendered" computer graphics. In this workflow, a render farm computes each frame of an animation individually, a process that can take from minutes to hours per frame depending on the complexity of the lighting, materials, and geometry.1 This method allows for virtually unlimited computational resources to be dedicated to calculating light transport (ray tracing), creating images of indistinguishable photorealism. However, the output is inherently passive; the viewer is locked to a pre-determined camera path and cannot deviate or interact with the scene.2

For an entity like which operates complex manufacturing facilities, a passive video is insufficient for operational transparency, training, or remote facility management. A video cannot be queried for machine specifications; it cannot be paused to inspect a specific valve or conveyor belt from a new angle; and it cannot be easily updated when the factory layout changes without re-rendering the entire sequence.

1.2 The Real-Time Revolution

Real-time rendering, the technology underpinning modern game engines like Unreal Engine 5, fundamentally changes this value proposition. In a real-time environment, images are generated instantly—typically at rates of 30, 60, 90, or even 120 frames per second (FPS)—response to user input.[1] This allows the user to exist within the simulation, navigating freely (Six Degrees of Freedom or 6DOF) and interacting with the environment.

The shift to real-time is not merely a change in viewing format; it is a shift from "visualization" to "simulation." It transforms the 3D asset from a marketing picture into an operational tool. For Morde Foods, this means the virtual environment can serve multiple functional roles:

Remote Training: New employees can learn the facility layout and safety zones without stepping onto the active factory floor.

Stakeholder Tours: Investors or clients can tour the facility remotely, with the agency to inspect specific areas of interest rather than being guided by a curated video.

Operational Planning: The spatial relationships between machines can be analyzed in 1:1 scale VR, revealing potential bottlenecks or safety hazards that are not obvious in 2D CAD plans.[5]

1.3 Frame Budget

While the benefits of real-time VR are immense, the technical cost is high. The "Frame Budget"—the amount of time the computer has to calculate all physics, logic, and graphics for a single image—drastically shrinks. In offline rendering, a frame budget might be 6 hours. In a 90Hz VR simulation, the frame budget is approximately 11.11 milliseconds.[7]

This constraint necessitates a rigorous optimization pipeline. Every asset imported from the CAD data must be scrutinized for polygon density; every light source must be evaluated for its performance cost; and shading models must be optimized to run efficiently on the GPU. The following sections detail exactly how these constraints were managed to deliver the Morde Foods experience.

2. The Datasmith Pipeline and Metadata Strategy

The core of the Morde Foods project is the accurate representation of industrial machinery. This data originates not in artistic modeling software like Maya or Blender, but in parametric CAD tools (e.g., SolidWorks, Revit, Inventor). These tools describe geometry using mathematical formulas (NURBS - Non-Uniform Rational B-Splines) rather than polygons, and they prioritize manufacturing precision over rendering efficiency. Bridging the gap between CAD and Real-Time is the role of Unreal Datasmith.

2.1 The Datasmith Architecture

Datasmith is a collection of plugins and import behaviors designed to translate entire scenes from DCC (Digital Content Creation) and CAD applications into Unreal Engine.[9] Unlike standard FBX importation, which typically only brings in geometry and basic material assignments, Datasmith attempts to preserve the scene graph—the hierarchy of objects, their metadata, camera settings, and even specific lighting setups.

2.1.1 Handling CAD Metadata

One of the most powerful features of Datasmith utilized in this project is the preservation of metadata. In the source CAD files for Morde Foods, individual machine parts are tagged with data such as "Max Torque," "Power Consumption (kW)," "Material Grade," and "Maintenance Schedule".[10]

When importing via Datasmith, this information is not discarded. It is converted into Datasmith User Data key-value pairs attached to the Static Mesh Actors in Unreal Engine.[10] This data is stored as strings, regardless of whether the original value was a boolean, integer, or float.

Implication for Interactivity: This feature allows us to build a "smart" environment. Instead of manually typing machine statistics into UI widgets in Unreal Engine (a process prone to human error), we can programmatically retrieve the data directly from the asset. If the engineering team updates the CAD model with new specifications, a re-import via Datasmith automatically updates the VR tour's information display.[10]

Blueprint Integration

To access this data at runtime, we utilize specific Blueprint nodes:

Get Datasmith User Data Value for Key: This node takes a specific key (e.g., "Power_Rating") and returns the associated value string for the selected actor.[10]

Get All Datasmith User Data: This retrieves the entire metadata object, allowing us to iterate through all

available keys if we want to display a full specification sheet.

2.1.2 Pivot Points and Hierarchies

A significant technical hurdle in CAD-to-Game workflows is the handling of pivot points (the point in space around which an object rotates). In 3ds Max or SolidWorks, it is common for multiple objects to share the same geometry definition (instancing) while maintaining unique, custom pivot points for each instance.[11]

However, Unreal Engine's rendering architecture requires that all instances of a Static Mesh Asset share the same pivot point relative to the mesh geometry.

The Datasmith Solution: To resolve this discrepancy without breaking the scene assembly, Datasmith employs a hierarchy trick. If it detects instances with divergent pivot points, it does not bake the pivot into the geometry (which would break instancing and increase memory usage). Instead, it creates an empty Parent Actor at the location of the custom pivot and parents the mesh geometry to it. The mesh itself retains its default pivot, but the transformation (rotation/scaling) is applied to the parent actor.

Naming Convention: These generated parent actors often bear the suffix _pivot.[11] Understanding this structure is crucial when scripting interactions; if we want to rotate a machine part in VR, we must target the parent actor, not the mesh component itself, to ensure the rotation occurs around the correct mechanical axis.

2.2 Material Translation and Standardization

Industrial CAD models often use non-standard shading models (e.g., V-Ray materials or physical shaders specific to SolidWorks). Datasmith attempts to translate these into Unreal Engine's PBR (Physically Based Rendering) system.

Master Materials: For 3ds Max imports, Datasmith often generates new "Master Materials" in Unreal that mimic the node graph of the source material. While accurate, these can be computationally expensive.[12]

Optimization Strategy: For the Morde Foods project, we replaced many of these generated materials with optimized UE5 instances. We utilized the Datasmith_Color parent material for simple painted metal surfaces. This material is lightweight and optimized for real-time rendering. However, we had to be vigilant about color brightness; CAD applications often allow "pure white" (RGB 255, 255, 255), which is physically impossible in the real world and causes lighting artifacts (bloom/glare) in Lumen. We manually clamped these values to realistic albedo ranges (max ~0.8) to ensure physical accuracy.[12]

2.3 Runtime Data Loading

For advanced use cases, specifically where Morde Foods might want to load different machine configurations without restarting the application, we investigated Datasmith Runtime. This allows CAD files to be loaded directly from disk while the application is running.[13]

Implementation: Using the DatasmithRuntimeActor, we can spawn an anchor point in the level and use a Blueprint node Load File from Explorer to ingest a .udatasmith file dynamically. This offers a path toward a "viewer" application where engineers can load their latest designs into the VR environment instantly, though for the primary tour, pre-imported assets were preferred for performance stability.[13]

3. Geometry Optimization: Blender Workflow

Raw CAD geometry is mathematically precise but topologically inefficient for real-time rendering. A single curved bolt in a CAD model might be tessellated into tens of thousands of triangles, consuming a vast portion of the polygon budget. To prepare the Morde Foods assets, we utilized Blender as an intermediate optimization tool

3.1 Decimation vs. Remeshing

Two primary techniques were employed to reduce polygon counts: Decimation and Voxel Remeshing.

3.1.1 The Decimate Modifier

The Decimate Modifier (specifically the "Collapse" mode) reduces the vertex/face count by merging vertices and collapsing edges based on a target ratio or angle limit.[14]

Pros: It preserves the original UV coordinates (texture mapping) and is extremely fast. It is ideal for "planar" mechanical parts like boxy casings or flat conveyor belts.

Cons: It destroys topology flow. The resulting mesh is a chaotic triangulation ("soup of triangles").[15] This makes the mesh unsuitable for deformation (bending/animation) and can cause severe shading artifacts on curved surfaces, as the smoothing algorithm struggles with uneven triangle density.

Application: We used Decimate for static, hard-surface objects that were far from the user's primary

line of sight (e.g., ceiling pipes, distant support beams).

3.1.2 Voxel Remeshing

For complex, organic shapes or messy CAD assemblies with internal intersecting geometry, we used the Voxel Remesher. This tool constructs a virtual 3D grid (voxels) over the object and generates a completely new mesh surface based on the grid intersetions.[16]

Pros: It creates "watertight" geometry. CAD imports often have tiny gaps or disconnected faces that cause lighting errors in Unreal Engine (light leaks). Voxel remeshing seals the surface into a single, continuous manifold. This is critical for Lumen, which relies on high-quality Mesh Distance Fields (discussed in Section 5).[18]

Cons: It destroys all UV data and custom normals. The mesh must be unwrapped again for texturing. It also requires a high voxel density to capture sharp industrial edges, which can ironically increase the poly count if not managed carefully.[16]

Application: This was used for the primary "hero" machinery components, particularly those with complex casting shapes (e.g., chocolate tempering pumps), ensuring they were solid and robust for high-fidelity lighting.

3.2 The Shading Artifact Problem: Weighted Normals

A persistent challenge in converting industrial CAD to real-time polygons is the "shading artifact" problem on bevels. In real life, industrial machines have slightly rounded edges (bevels/fillets) rather than infinitely sharp 90-degree corners. When these are modeled with low polygon counts, standard "Smooth Shading" tries to average the surface normal across the corner.

The Result: The flat surfaces of the machine appear to bulge or warp because the vertex normals are being pulled towards the 45-degree angle of the bevel.[19]

3.2.1 The Solution: Weighted Normal Modifier

To fix this without adding millions of polygons to support the curvature, we utilize the Weighted Normal Modifier in Blender.

Mechanism: Instead of a simple average, this modifier calculates vertex normals based on the area of the surrounding faces. Large faces (the flat panels of the machine) are given significantly more "weight" than the small, thin faces of the bevel.[20]

Effect: The vertex normals on the flat face remain perpendicular to the surface, ensuring perfectly flat shading. The curvature is confined entirely to the small bevel strip. This creates the illusion of a high-poly, perfectly manufactured object while using very low-poly geometry.[19]

Workflow nuance: This technique relies on "Custom Split Normals." If the imported CAD mesh already has messy custom normal data (which is common), the Weighted Normal modifier may fail or produce glitches. The fix is to first go to the Object Data Properties -> Geometry Data and click "Clear Custom Split Normals Data" before applying the modifier.[22] This resets the normals, allowing the modifier to calculate the weights correctly from a clean slate.

4. Engine Architecture: World Partition and HLODs

The Morde Foods facility is vast. Loading the entire factory geometry at maximum detail simultaneously would instantly crash any VR headset (and likely most high-end PCs). To manage this scale, we employed Unreal Engine 5's World Partition system.

4.1 World Partition

World Partition replaces the legacy "Sub-Level" workflow. Instead of manually dividing the factory into "Zone A," "Zone B," etc., World Partition treats the world as a single persistent level divided into a 2D grid.[24]

Streaming Logic: As the user moves through the VR tour (the "Streaming Source"), World Partition automatically loads the grid cells around them and unloads the cells behind them.

Configuration: We configured the Runtime Grid with specific loading ranges. For VR, a tighter loading range is preferred to keep the active polygon count low, but this risks "pop-in" (objects appearing suddenly). We tuned the loading range to approximately 100-150 meters, ensuring that the immediate factory hall is visible, while distant halls are unloaded.[24]

4.1.1 Data Layers

To further granularize control, we utilized Data Layers. Unlike standard layers which are organizational tools for the editor, Data Layers function at untime.[26]

Application: We separated the factory content into distinct Data Layers: "Structural Shell," "Machinery," "High-Fidelity Detail" (for close-ups), and "Collisions."

Interactive Utility: This allows for powerful runtime interactions. For example, we can implement a "Schematic Mode" in the VR tour. When the user presses a button, the "Machinery" Data Layer can be hidden, and a "Piping/Schematic" Data Layer can be streamed in, revealing the internal flow of the factory without managing thousands of individual actor visibilities.[26]

4.2 Hierarchical Levels of Detail (HLODs)

When World Partition unloads distant grid cells, the factory would technically disappear, leaving a black void in the distance. To prevent this, we generate Hierarchical Levels of Detail (HLODs). HLODs substitute complex groups of actors with simplified proxy meshes when they are far away.[27]

4.2.1 HLOD Layer Types

We utilized different HLOD strategies for different asset types:

Instancing: For repetitive assets like warehouse racking or perimeter fencing, we used the Instancing HLOD layer. This replaces hundreds of individual Static Mesh Actors with a single InstancedStaticMesh component. This drastically reduces Draw Calls (CPU instructions to the GPU), which are often the primary bottleneck in VR performance.[27]

Merged Mesh: For unique clusters of machinery, we used the Merged Mesh layer. This takes a group of machines, merges their geometry into one mesh, and bakes their textures into a simplified atlas. This reduces both draw calls and material complexity.[27]

Approximated Mesh: For extremely distant geometry (e.g., the exterior silhouette of the factory against the skyline), we used approximation. This generates a "shrink-wrapped" low-poly mesh that captures the general volume but discards all internal detail.[27]

4.2.2 Troubleshooting HLOD Generation

Building HLODs is a resource-intensive process that often fails if the scene is not prepped correctly.

Nanite vs. Non-Nanite: HLOD generation behaves differently for Nanite meshes. We found that for optimal VR performance (where Nanite can sometimes be heavy on older hardware), generating simplified non-Nanite HLOD proxies provided the most stable frame rates.[28]

Dirty State Issues: Sometimes HLODs fail to build if the level has unsaved changes or "dirty" files in revision control (Perforce/Git). Ensuring a clean state before triggering the WorldPartitionHLODsBuilder commandlet was a critical workflow step.[28]

5. Visual Fidelity: Lumen and Advanced Lighting in VR

Lighting is the primary cue for realism. UE5's Lumen system provides fully dynamic Global Illumination (GI) and reflections, allowing light to bounce naturally off surfaces. However, VR poses specific challenges for Lumen.

5.1 Lumen Architecture: Software vs. Hardware Ray Tracing

Lumen operates using a hybrid tracing method.

Software Ray Tracing (SWRT): This is the default mode. It does not trace against the actual triangles of the mesh (which would be too slow). Instead, it traces against Mesh Distance Fields (MDFs)—a simplified volumetric representation of the object.[18] SWRT is fast and works on a wide range of hardware, but it has lower precision.

Hardware Ray Tracing (HWRT): This utilizes the dedicated RT cores on NVIDIA RTX or AMD RDNA2 cards to trace against the actual triangles. This provides perfect accuracy, including reflections of skeletal meshes (animated characters) and mirrors, but creates a massive performance hit.[18]

5.2 Optimization for Morde Foods VR

Given the 11.11ms frame budget of VR, Hardware Ray Tracing was deemed too expensive. We optimized the project to run on Software Ray Tracing, which required addressing specific artifacts.

5.2.1 The Light Leaking Problem

A major issue with SWRT in industrial scenes is light leaking. Sunlight may bleed through walls or into closed tanks. This happens because the Mesh Distance Field resolution is too low to capture thin walls. If a wall is thinner than 10cm, the Distance Field may have holes in it, even if the visual mesh looks solid.[18]

Mitigation Strategy 1 (Thickness): We enforced a modeling rule that all structural walls must have a minimum thickness of 10-20cm. Single-plane geometry was strictly forbidden for structural elements.[18]

Mitigation Strategy 2 (Distance Field Resolution): For critical machinery where leaking occurred, we manually increased the Distance Field Resolution Scale in the Static Mesh Editor (e.g., from 1.0 to 2.0 or 3.0). This creates a denser volume representation, blocking light more effectively, at the cost of slightly higher memory usage.[18]

Mitigation Strategy 3 (Blocking Geometry): In stubborn cases, such as corners where modular walls

meet, we placed simple "Blocking Volumes" (hidden cubes) inside the walls. These simple shapes generate very clean, solid Distance Fields that effectively plug the light leaks without adding visual clutter.[32]

5.2.2 Reflections and Surface Cache

Lumen uses a "Surface Cache" to calculate lighting for reflections. In VR, looking at a glossy surface (like a stainless steel chocolate tank) can sometimes reveal the low resolution of this cache, appearing as splotchy or noisy reflections.[29]

The Fix: We adjusted the roughness of the metal materials. By increasing roughness slightly (avoiding mirror-perfect chrome), the reflection becomes more diffuse, effectively blurring the Surface Cache artifacts and creating a pleasing, clean metal look without the cost of HWRT.[34]

6. Procedural Content Generation (PCG): Automating the Environment

To place the Morde Foods factory in a believable context, we needed to populate the surrounding terrain with vegetation, fences, and roads. Doing this manually for a large-scale map is inefficient. We utilized the Procedural Content Generation (PCG) framework introduced in UE 5.2.

6.1 The PCG Graph Concept

PCG in Unreal works via a node graph, similar to Blueprints. It generates points in space and then spawns assets on those points based on rules.[35]

Surface Sampler: This node generates points across the landscape. We used this to scatter grass and trees.

Filtering: We used Density Filter nodes and Difference nodes to prevent trees from growing inside the factory buildings or on the asphalt roads. The PCG graph can read the bounds of the factory actors and automatically exclude those areas from generation.[36]

6.2 Spline-Based Infrastructure

For the perimeter fence and access roads, we used Spline-based PCG.

Mechanism: We draw a spline curve around the factory. The PCG graph samples this spline, placing fence posts at regular intervals (e.g., every 2.5 meters).[37]

Orientation: Crucially, the graph uses Transform Direction nodes to rotate each fence panel so that it aligns with the tangent of the spline. This ensures the fence follows the curve of the road perfectly.[38]

Flexibility: This system allowed us to iterate rapidly. If the client wanted to expand the factory perimeter,

we simply dragged the spline points, and the fence posts, wire mesh, and barbed wire tops automatically regenerated in real-time to fit the new path.[37]

7. VR Physiology and Performance Engineering

Developing for VR is fundamentally different from developing for a screen because the user is physically coupled to the simulation. Violating physiological constraints leads to "Sim Sickness."

7.1 The Frame Budget & Latency

In a standard 90Hz VR headset (like the HTC Vive or Meta Quest 3), the screen updates 90 times per second.

The Math: $1000 \text{ms} / 90 \approx 11.11 \text{ms}$.

This means the CPU must calculate game logic, physics, and draw calls, and the GPU must render the entire image, lighting, and post-processing, all within 11.11 milliseconds.[7]

Failure Consequence: If rendering takes 12ms, the headset misses the refresh cycle. To prevent judder, it drops to 45Hz and uses "Reprojection" or "Motion Smoothing" to synthesize every other frame.[39] While this keeps the head tracking smooth, it causes "ghosting" artifacts on moving objects (like conveyor belts), which degrades the professional quality of the tour. We strictly profiled using Unreal Insights to ensure we stayed within the 11.11ms budget.

7.2 Vergence-Accommodation Conflict (VAC)

A subtle but critical physiological issue in VR is the Vergence-Accommodation Conflict (VAC).

Vergence: The rotation of the eyes to look at an object (crossing eyes for near objects, parallel for far objects).

Accommodation: The physical deformation of the eye's lens to focus light on the retina.

The Conflict: In the real world, these two are coupled. In VR, the eyes verge on the virtual object (e.g., a machine 1 meter away) but must accommodate (focus) on the screen, which is physically only a few centimeters from the eye (optically focused at ~2 meters).[41]

Impact on Morde Foods Tour: This mismatch causes eye strain and nausea if the user focuses on objects very close to their face for too long.[43]

Design Solution: We designed the interaction radius to keep UI widgets and key inspection points at a comfortable distance (approx. 1.5 - 2.0 meters) from the user. We avoided forcing the user to bring objects

right up to their face, keeping the vergence depth closer to the optical focal plane of the headset.[43]

8. Interactive Logic: Blueprint Scripting
The "Interactive" element of the tour allows users to retrieve data from the machines. This was implemented using Unreal's visual scripting language, Blueprints.

8.1 The Ray-Casting Mechanic
The core mechanic is a "Gaze" or "Pointer" system.

Trace: The VR controller emits a line trace (invisible laser beam) every frame.

Hit Event: When this trace hits an Actor with the tag "Machine," it triggers an event.

Data Retrieval: The Blueprint calls Get Datasmith User Data Value for Key. It requests keys like Model_Name, Power_Consumption, and Status.[44]

Widget Display: A 3D Widget (World Space UI) is spawned or updated near the machine. The text fields in the widget are set to the strings returned by the metadata query.

V. TABLE OF COMPARISON

Table1. Comparison Between Research paper and System stability evaluation

Aspect	Research Paper	System Stability Evaluation
1) Analyzing Performance Issues	Investigates the performance of Virtual Reality (VR) applications, focusing on minimizing lag and ensuring smooth interactions.	Evaluates system performance with a focus on achieving exceptional performance to deliver seamless VR experiences.
2) R&D of Virtual Reality on Unreal Engine	Explores the research and development aspects of implementing VR technology using Unreal Engine.	Ensures the Unreal Engine-based VR system is stable and optimized for real-world use.
3) Unreal Engine's VR Interactive Space	Discusses the ability of Unreal Engine to create both immersive and non-immersive VR environments. May mention occasional latency issues in non-immersive VR scenarios.	Evaluates the stability of Unreal Engine in creating interactive VR spaces, addressing any performance issues that arise in various VR modes.
4) Development of Virtual Reality Home Tour	Describes the development process of a VR technology for real estate home tours, mentioning issues like slow loading times and graphical glitches.	Assesses the system performance of the VR home tour application, focusing on addressing poor performance, optimizing loading times, and eliminating graphical glitches.
5) Our Research Paper	Presents research findings on system performance, noting moderate performance levels with occasional frame drops in resource-intensive VR scenarios.	Conducts an evaluation of system stability, aiming to minimize frame drops and ensure consistent performance across different VR use cases.

IV. RESULT AND DISCUSSION

The results from This "Metanexus" project demonstrate a compelling capability of virtual reality technology within the metaverse to reshape traditional automotive sales methods. Throughout the prototype's development and testing phases, several salient outcomes present themselves.

Fig.3 : 3D structure of Showroom

Primarily, participants overwhelmingly express a profound sense of immersion within the VR

showroom. They describe a vivid sense of presence, as if genuinely navigating a physical showroom. This perception proves critical since it directly impacts a user's level of engagement and their likelihood to make purchase decisions.

Fig 4 :3D structure of Car

Secondarily, the revolutionary nature of the social elements within the metaverse showroom becomes evident. The feature allowing prospective buyers to interact with others in real-time turns the usually solitary car-buying process into a communal experience. A significant number of participants indicate that this communal feature not only bolsters trust—allowing consultations with friends, family, or experts—but also enriches the shopping journey substantially.

Additionally, participants celebrate the integration of cutting-edge technologies like AI and real-time data. They feel better informed with instantaneous updates on prices, stock status, and financing choices. They particularly commend the AI-driven tailored recommendations, which seem to steer users toward optimal choices.

The blend of VR with AR also garners significant attention. Users appreciate the capability to project cars into their real-world setting, emphasizing a more tangible grasp of the vehicle's look and dimensions. This synergy between the virtual and the tangible appears to bridge the divide between a virtual showroom exploration and a real-world test drive.

However, not all outcomes are positive. Some participants pinpoint initial hurdles in navigating the digital environment or grappling with certain interactive features. This feedback underscores a need for refining the user interface. Also, despite many lauding the superior visual and audio elements, concerns arise about the accessibility of the showroom for those with less advanced device.
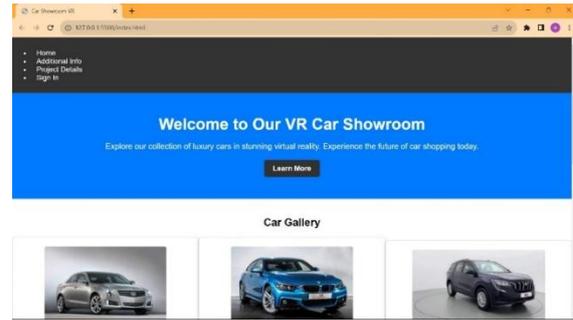

Fig.5 : Interface of Website

Conclusively, the groundbreaking findings from the Metanexus prototype mark a transformative moment in the world of automotive retail. As we peer into the future of commerce and consumer interaction, it's evident that traditional showrooms and face-to-face interactions are undergoing a massive evolution. The VR showroom, nestled within the burgeoning metaverse, presents not just a technological advancement but a radical rethinking of how consumers explore, interact with, and ultimately purchase vehicles.

Beyond the spectacle of the virtual environment, this new showroom paradigm offers a richer, all-encompassing, and community-driven car acquisition experience. Customers are no longer mere spectators; they're participants in a dynamic, immersive world that responds to their preferences and desires. This community-driven aspect not only humanizes the digital realm but also fosters a sense of belonging, connecting car enthusiasts, prospective buyers, and brands in an unprecedented manner

In sum, the Metanexus prototype is more than just a technological marvel; it represents the future of automotive retail—a future where virtual and reality intertwine, community engagement is paramount, and consumer experiences are not just enhanced but revolutionized.

V.   SCOPE OF RESEARCH

The scope of this research project revolves around harnessing the capabilities of the metaverse and Virtual Reality (VR) technology to revolutionize the automotive sales industry. Specifically, the project aims to develop a prototype VR showroom within the metaverse, presenting an alternative to traditional physical showrooms. The primary objective is to overcome the limitations of physical spaces by offering users an expansive, immersive, and

interactive digital experience, free from geographical constraints. The digital platform, tailored to individual user preferences, will integrate the latest automotive trends, enabling users to access a diverse range of car models without the need for extensive travel. The research will delve into enhancing the sense of immersion and user engagement using VR, fostering social interactions within the metaverse, and integrating emerging technologies such as Artificial Intelligence (AI) for tailored recommendations. It will also explore the convergence of Augmented Reality (AR) with VR to bridge the gap between the digital showroom and real-world experiences. Utilizing tools and features offered by game engines like Unreal Engine 5, the project seeks to achieve high realism and interactivity, transforming the car purchasing process. This research not only holds significance for the automotive industry but can also set precedents for other sectors looking to leverage the metaverse and VR for sales and marketing in the digital age.

VI. FUTURE SCOPE

The future of VR showrooms in the automotive retail industry promises revolutionary advancements. Enhanced personalization, powered by advanced AI, will allow users to customize cars in real-time, tailoring them to their exact preferences and visualizing their choices in life-like settings. The synergy of VR with Augmented Reality offers potential buyers a blended experience of virtual and real worlds, providing context and information as they explore cars in their actual surroundings. Moreover, as the concept of the metaverse flourishes, VR showrooms will evolve into collaborative spaces, enabling users to engage with peers, experts, and enthusiasts, enriching the decision-making process. Furthermore, advancements will facilitate hyper-realistic test drives, simulating various driving conditions, terrains, and vehicle dynamics. Finally, the integration of VR experiences with online sales platforms signifies a future where potential buyers can navigate the entire purchase journey, from exploration to transaction, within an immersive virtual environment. Altogether, these developments herald a transformative shift in car buying, making it more engaging, informative, and convenient for users.

VII. CONCLUSION

The convergence of the metaverse and VR technology unlocks a new realm of possibilities for automotive retail. By breaking free from traditional physical limitations, our proposed VR showroom offers an immersive, social, and highly personalized experience. This project seeks to redefine how consumers discover, customize, and purchase vehicles, bringing the future of automotive retail directly to the user.further enhancements. The scope for enhanced personalization and customization allows users to tailor their virtual cars to their exact preferences, creating a more personalized and engaging experience. Integration with augmented reality (AR) technology adds a layer of realism by allowing users to view virtual cars in their physical surroundings, providing a realistic sense of scale and fit. The social collaboration aspect of VR showrooms fosters virtual communities, where potential buyers can connect, interact, and seek advice from friends, family, or automotive experts. This social engagement elevates the car buying experience, turning it into a shared and collaborative process. The incorporation of virtual test drives and realistic simulations allows users to experience the performance and handling of virtual car models. Realistic driving scenarios, accurate physics engines, and haptic feedback provide a truly immersive and informative test drive experience, aiding users in their decision-making process. Seamless integration with online sales platforms ensures a streamlined and convenient car purchasing journey within the VR showroom. Users can explore financing options, compare prices, schedule test drives, and even finalize their purchase, all without leaving the virtual environment. This integration eliminates friction and enhances the overall convenience and efficiency of the car buying process. In summary, the prototype VR showroom for automotive sales within the metaverse signifies a paradigm shift in the automotive retail industry. By leveraging Unreal Engine 5 and embracing future advancements, we can create a professional, immersive, and personalized car buying experience that surpasses the limitations of traditional physical showrooms. The future of VR showrooms holds the potential to reshape how cars are bought and sold, transforming the industry into a dynamic and technologically advanced landscape that enhances user engagement and satisfaction.

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