In 2021, Facebook's rebranding to Meta brought the concept of the Metaverse—a virtual, digital universe—into mainstream discourse. The Metaverse integrates augmented reality (AR), virtual reality (VR), and the internet to create a shared, immersive, and interactive environment, enabling diverse applications such as education, training, cultural preservation, commerce, and entertainment. Despite the hype about the Metaverse, it has never become a reality. I uncover three main obstacles

Figure 1: AI-System co-design for immersive computing.

faced by existing immersive computing systems: (1) the exploding amount of data brought by a large virtual world, (2) the disturbing artifacts produced by existing 3D modeling techniques, and (3) the unreliable real-world immersive computing systems. To overcome these obstacles, my research advocates AI-system co-design, an approach with two core principles: ❶ **AI-for-Immersion Design**: *Identifying and employing advanced Artificial Intelligence (AI) techniques to transcend the limitation of traditional immersive computing systems*. ❷ **AI-System Joint Optimization**: *Customizing traditional system optimization techniques and AI pipelines to tackle AI-induced system challenges and improve AI performance*. Guided by these principles, my research bridges the gap between current immersive computing systems and the Metaverse, advancing Bandwidth Efficiency, Photo-realism, and Reliability.

Research Impact: My research has culminated in over 20 publications, including in premier conferences such as USENIX NSDI, ACM MobiSys, and ACM SenSys. It has been further distinguished by accolades such as the Best Student Paper Award at ACM MMSys, the Best Paper Award at IEEE ISM, one US Patent, and media recognition from the Siebel School News [18]. Beyond these achievements, my research has fostered extensive collaborations with academic institutions (*e.g.,* Princeton, UMASS, and GMU) and non-academic institutions (*e.g.,* US Army Research Laboratory, Illinois Fire Service Institute, and Boeing).

Towards Efficiency with AI-based Compression

The Metaverse requires connecting clients to vast virtual worlds at city, country, or global scales. While current technologies can handle smaller-scale data (*e.g.,* texts, images, 2D/3D videos), they fall short when faced with the immense data volumes of the Metaverse over consumer-grade networks. AI-based compression, which employs deep neural networks for end-to-end encoding and decoding, offers better bandwidth efficiency but faces challenges in practical deployment. My research bridges this gap by addressing key system challenges:

▶**High Frame Rate.** AI-based video compression often processes frames sequentially, maximizing bandwidth efficiency but impacting frame rate. My work restructures frame dependencies into a binary tree, enabling parallel processing at the same tree level and improving the Quality of Experience (QoE) of state-of-the-art methods by up to 23.8% [12].

▶**Scalability and Generalizability.** AI-based compression systems often rely on symmetric, centralized, and static designs, which struggle with the demands of multi-camera systems. My research addresses these issues through: ❶ *Asymmetric codec design:* Distributed encoders and a centralized decoder based on the distributed coding theorem scale to any number of cameras, achieving over 64% bandwidth savings [4]. ❷ *Decoupled training:* Splitting training into intra-view (offline) and inter-view phases allows rapid adaptation to new scenes (*i.e.,* roughly 10 minutes) without extensive retraining.

▶**Ultra-low Bandwidth.** Under extremely low bandwidth, traditional compression methods produce artifacts (*e.g.,* blurriness and blockiness), hindering visual communication. My research addresses this with: ❶ *Semantic compression:* AI-based methods extract high-level image information during encoding and use it to generate smooth, visually coherent images during decoding, effectively conveying information [20]. ❷ *Context-aware adaptation:* Leveraging underwater light absorption properties, my work reduces transmission payloads by 7× by pruning the compression algorithm's codebook.

▶**Other Research on Efficiency.** Beyond AI-based compression, I have addressed the bandwidth and energy constraints of traditional methods: ❶ *Compression efficiency:* Profiling for visual analytics tasks identifies the complex correlation between compression parameters (*e.g.,* quantization settings) and performance, achieving up to 40% bandwidth reduction and a 2× speedup in computation offloading [2, 11].
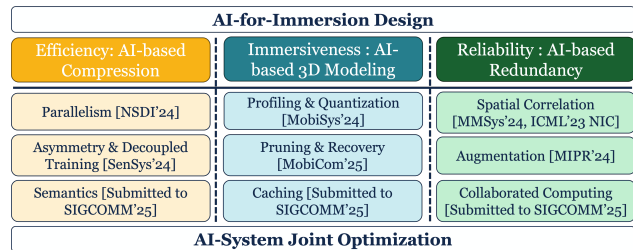
This work earned the Best Student Paper Award at ACM MMSys 2022 and was featured in Siebel School News [18]. Follow-up work with neural image codecs achieved an additional 20% reduction [9]. ❷ **Energy efficiency:** Video analytics is energy-intensive due to high frame rates and inefficient GPU utilization. My research addresses this through (i) frame filtering, reducing redundancy in 2D and 360-degree video analytics [7, 15, 14], and (ii) Dynamic Voltage and Frequency Scaling (DVFS), optimizing CPU and GPU energy use for edge [1] and cloud deployments [13].

▬ Advancing Immersiveness with AI-based 3D Modeling

The virtual world in the Metaverse is built through 3D modeling. Traditional approaches like point clouds and meshes lack the immersive quality needed due to their discrete nature. Recently, AI-based 3D modeling (*i.e.,* representing 3D scenes with continuous and learned functions) has shown promise but struggles to deliver satisfactory QoE. My research addresses these challenges with the following techniques:

▶**Bandwidth efficiency.** Emerging AI-based 3D modeling such as Neural Radiance Fields (NeRFs) involves multiple modalities such as neural networks, feature values, and polygon meshes. The complex relationship between these modalities and the implicit nature of feature values make them bandwidth-consuming in network delivery. My research reduces bandwidth demands through: ❶ **Profiling:** Modeling the complex relationships between compression configurations across modalities, reducing latency in serving neural representations by up to 66% without compromising quality [10]. ❷ **Pruning:** Quantifying the importance of feature values during rendering and pruning less critical ones, achieving up to 68.3% bandwidth savings [23].

▶**Computation Efficiency.** Rendering AI-based 3D models is computation-intensive, posing challenges for resource-constrained clients like wearable VR headsets. My research addresses this through: ❶ **Caching:** Accelerating neural rendering by caching and reusing intermediate computations, improving frame rate by $5.9\times$ with minimal quality loss [6]. ❷ **Quantization:** Fine-tuning neural networks for varying quantization depths, improving rendering quality by up to 5 dB without additional client-side computation [10].

▶**Other Research on Immersiveness.** I have explored enhancing immersiveness through 360-degree video, enabling users to experience panoramic scenes by rotating their heads. My contributions include: ❶ Predicting user viewports with semantic information [17], ❷ Detecting objects using a pyramid neural network [3], ❸ Enhancing interaction with scene segmentation [22], and ❹ Providing guided viewing experiences through saliency analysis [24].

▬ Chasing Reliability with AI-based Redundancy

The Metaverse requires accurately understanding user behaviors and surrounding environments, which involves querying powerful AI models. However, hazards such as packet loss and server failures can disrupt these queries. Existing approaches often consume significant system resources (*e.g.,* bandwidth and computation) to maintain performance under such conditions. My research addresses this issue through AI-based redundancy, which involves proactively training AI models or tailoring inference pipelines to tolerate hazards.

▶**Proactive Augmentation for Sensing.** Low-quality sensor inputs, such as distorted or occluded images, pose challenges for AI models. My research demonstrates that Large Language Vision Models (LLVMs) can assist the generation of high-quality images of analog gauge readings using a limited set of real images [19]. This approach simplifies autonomous gauge reading on an IoT camera into a template-matching process, achieving a $40\times$ speed improvement over traditional methods without sacrificing accuracy.

▶**Reconstruction for Communication.** Data loss during communication, caused by quantization and packet loss, degrades AI model performance. ❶ My research restores lost precision by exploiting correlations between pre- and post-quantization content, improving average QoE by up to 31% compared to state-of-the-art methods [8, 16]. ❷ I extend this work to AI-based 3D modeling by reconstructing lost feature values using spatially and temporally adjacent content, improving SSIM from 0.759 to 0.902 when packet loss rate is above 50% [23].

▶**Collaborative Computation for Inference.** Reliable inference often involves replicating AI models or repeating inference pipelines, which is resource-intensive. My research enables communication between multiple AI models, allowing them to share and reuse intermediate results efficiently. This approach improves accuracy by up to 2.9% compared to replicated methods on ImageNet image classification tasks, while reducing resource demands [5].

▶**Other Research on Reliability.** Beyond AI models, I have investigated the reliability of chemical container tracking. RF signals attenuate quickly inside chemical containers. Since the placement of chemical containers is random, a tracking algorithm based on RF is rather unreliable. Instead, I designed a tracking system using permanent magnets, which maintain stable fields despite attenuation, achieving energy-efficient tracking (0.48 W) with high localization accuracy (2 cm error) [21].

Future Directions

My prior work has been extended into two NSF proposals on (1) Resilient, Bandwidth-efficient, and Low-latency Immersive Video Streaming [10, 23, 6] and (2) Video Analytics at Scale via Collaborative AI [4, 5]. My future work focuses on AI-system co-designs to bring humans closer to a Metaverse that is educational, inclusive, and ubiquitous. I plan to propose these ideas to venues such as **IIS: Human-Centered Computing** and **CNS: Networking Technology and Systems**. Specifically, my future work includes the following thrusts: ❶ **Interactivity with AI-based 3D Modeling:** Training and education are among the most promising applications of the Metaverse. For example, photo-realistic AI-based 3D modeling can be used to create immersive modules for surgeons to practice complex procedures. However, current methods require time-consuming pre-training 3D models before streaming, preventing interactive training sessions between two distant locations. I am motivated to explore techniques to reduce these delays, enabling interactive streaming of AI-based 3D models. For instance, shape similarities among objects (*e.g.,* human faces, cars, and tables) can be leveraged to group objects and pre-train generic models for them offline, which amortizes online training overheads. My previous research in AI-based 3D modeling [10, 23, 6] provides a strong foundation for advancing this direction. ❷ **Inclusiveness with AI-based Interface:** The Metaverse must serve not only those capable of standard interactions (*e.g.,* speech) but also individuals facing communication barriers, such as the 1–2% of the global population unable to speak. While sign language is an option, it is not universally understood, limiting accessibility. My research aims to break these barriers by leveraging LLVMs to interpret context and intent from multi-modal signals (*e.g.,* images, sounds) and convert them into speech. Properly designed prompts based on sign language documentation can guide LLVMs in generating meaningful outputs. One of my ongoing projects uses LLVMs to translate hand signals and environmental images into speech for divers, closely aligning with this vision [19]. ❸ **Ubiquity with AI-based Offloading:** LLVMs are poised to become indispensable agents in the Metaverse, but their high computational overhead limits their feasibility on ubiquitous devices. Retrieval-Augmented Generation (RAG) is a technique that trades storage for computation time by storing relevant documents. Inspired by it, I aim to explore how caching relevant documents can make LLVMs more practical for more ubiquitous usage. My expertise in content streaming [8, 12, 10, 4, 17, 22, 24], analytics systems [3, 7, 2, 5], and LLVMs [19] equips me to tackle this challenge effectively.

Conclusion and Broader Impacts

I envision a future where humans can access the Metaverse in an efficient, immersive, reliable, educational, inclusive, and ubiquitous way. My research focuses on employing AI-system co-designs to make this vision a reality. The proposed research will contribute to a variety of societal domains, as well as undergraduate and graduate education, and further promote Diversity, Equity, and Inclusion (DEI). ❶ This research will enhance diverse applications across domains such as training, healthcare, manufacturing, and entertainment. In these areas, the ability to perceive remote scenes and analyze the physical world is critical. Live streaming of AI-based 3D models and mobile agents with LLVM will help fulfill these demands, offering photo-realistic and interactive scene representations and real-time insights. ❷ This research will incorporate research findings into courses on immersive computing, mobile computing, and multimedia systems. I am also committed to fostering participation from students in traditionally underrepresented groups through mentorship programs and undergraduate research opportunities. ❸ This research will advance DEI by recognizing that people communicate in different ways and providing resources to help those with communication challenges overcome barriers. It will create inclusive systems and opportunities where everyone can fully engage in conversations, social interactions, and professional activities.

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