

One algebra for all : Geometric Algebra methods for neurosymbolic XR scene authoring, animation and neural rendering

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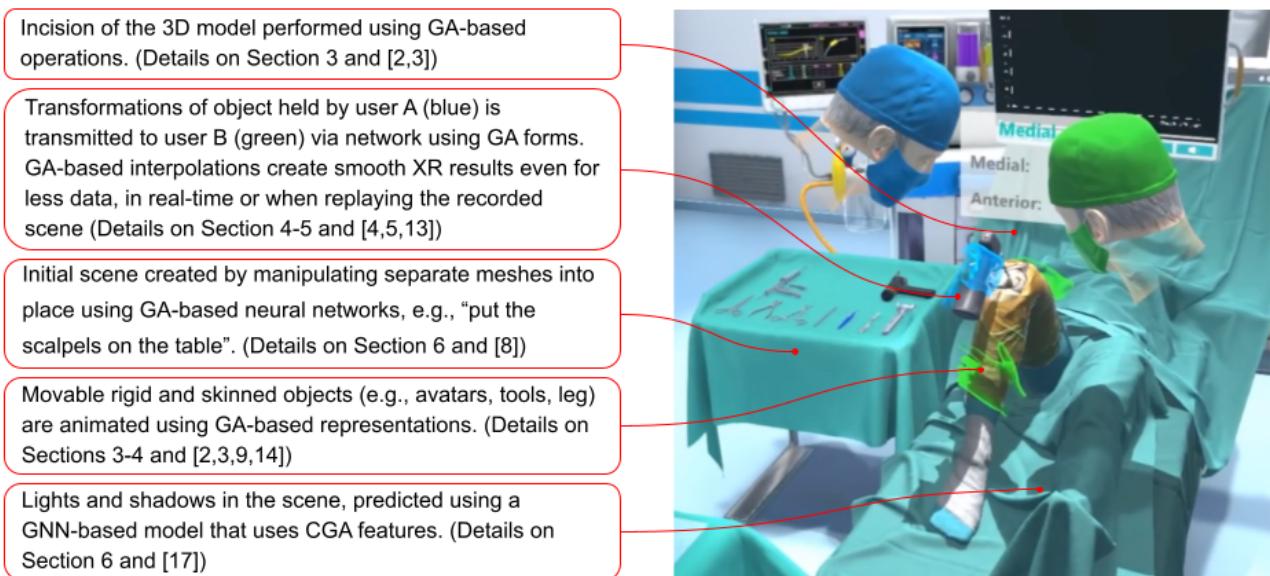


Figure 1: The GA-Powered Graphics Pipeline: Geometric Algebra as one coherent framework unifying and enhancing generative AI, character animation, neural rendering, and networked XR.

Abstract

This position paper delves into the transformative role of Geometric Algebra (GA) in advancing specific areas of Computer Graphics (CG) and Extended Reality (XR), particularly in character animation, rendering, rigging, neural rendering, and generative AI-driven scene editing. Common CG algorithms require handling rotations, translations, and dilations (uniform scalings) in operations such as object rendering, rigged model animation, soft-body deformation, and XR simulations. Traditional representation forms—such as matrices, quaternions, and vectors—often introduce limitations in precision and performance. Recent breakthroughs in the use of GA suggest it can significantly enhance these processes by encapsulating geometric forms and transformations into uniform algebraic expressions, which maintain critical geometric properties throughout multi-step transformations. Furthermore, we explore how GA can serve as a unifying mathematical substrate for neurosymbolic XR scene authoring, bridging learned neural representations and

explicit geometric reasoning. This paper outlines how GA-based approaches can improve the fidelity of rigged character animations, enhance soft-body simulations, streamline real-time rendering, and optimize neural and generative AI scene editing. GA offers a coherent and efficient framework for these processes, resulting in superior visual outcomes and computational efficiency, particularly in XR environments.

Keywords

Geometric Algebra, Real-time Rendering, Soft-Body Simulation, Generative Scene Editing

1 Introduction

The field of Computer Graphics (CG) has historically relied on a fragmented collection of mathematical algebras and geometrical systems to represent and manipulate 3D objects, scenes and transformations. Developers routinely switch between vectors for

position, matrices for linear transformations, and quaternions or dual-quaternions for handling rotations to avoid issues like gimbal lock. While each of these formalisms is powerful in its specific domain, their coexistence within a single pipeline necessitates constant, computationally expensive conversions. This fragmentation not only introduces performance overhead and potential for numerical instability but also creates a conceptual disconnect and lack of intuition: the underlying geometry is often obscured by the disparate algebraic representations. For example, Euler angles provide an intuitive description of rotations, whereas quaternions, though more robust computationally, obscure the geometric intuition behind them.

This paper posits that Geometric Algebra (GA)—a Clifford Algebra over the real numbers [4]—provides a comprehensive and unified mathematical language capable of streamlining the entire computer graphics pipeline—from modeling and animation to simulation, rendering, and interactive XR manipulation. GA offers a single, intuitive framework where geometric entities (points, lines, planes, spheres) and transformations (rotations, translations, dilations) are represented as uniform algebraic objects called multivectors. Our position is that by adopting GA, we can develop algorithms that are not only more computationally efficient and numerically robust, but also more geometrically intuitive. This unified approach preserves the intrinsic meaning of geometric operations throughout complex computations, leading to higher-fidelity results in character simulation, interactive deformation, and generative scene manipulation.

Our research program has demonstrated the practical benefits of this position across several critical areas of CG and Extended Reality (XR). We have developed novel algorithms for real-time mesh deformation, cutting, and tearing that leverage the expressive power of GA to handle complex topological changes [11, 12]. Our award-winning work in character animation has shown that GA-based skinning and interpolation methods can reduce data transmission in networked environments while improving animation quality [9, 10]. These advances culminated in the introduction of *GA-Unity*, the first Unity package that seamlessly integrates GA principles into collaborative, networked applications. GA-Unity extends the benefits of GA into practical 3D scene management and rendering, offering an accessible interface for real-time multivector operations that enhance both runtime efficiency and bandwidth usage in multiplayer scenarios. We have further validated these methods by integrating them into a modern XR authoring platform, enabling high-performance, artifact-free interactions in demanding applications such as surgical simulations [17, 18]. More recently, we are extending this framework to the domain of generative AI, exploring how GA can provide a structure-preserving latent space for intuitive, instruction-based scene manipulation with Large Language Models (LLMs) [13].

This paper is structured to highlight this unified perspective across the entire graphics pipeline. Section 2 introduces the core principles of Geometric Algebra as a unified framework for geometric modeling. Subsequent sections describe its applications to mesh manipulation, character animation [14], and networked XR environments, including the GA-Unity framework as a key integration layer for real-time deployment. Figure 1 provides a visual summary of this vision, illustrating how GA can serve as a unified substrate

for the entire modern graphics pipeline, a concept we will detail in the following sections. Finally, we synthesize these directions to outline the emerging vision of GA as a foundational language for geometry, simulation, and intelligence in computer graphics.

2 Geometric Algebra as a Unified Framework for Computer Graphics

At its core, GA extends familiar vector algebra with a new, invertible product: the geometric product. For any two basis vectors \mathbf{u} and \mathbf{v} , their geometric product \mathbf{uv} is defined as the sum of their inner (dot) and outer (wedge) products:

$$\mathbf{uv} = \mathbf{u} \cdot \mathbf{v} + \mathbf{u} \wedge \mathbf{v}$$

The scalar part, $\mathbf{u} \cdot \mathbf{v}$, captures metric information such as length and angle, while the new entity, $\mathbf{u} \wedge \mathbf{v}$, is a *bivector*. A bivector represents the oriented plane segment swept out by the two vectors. This simple addition is profound. By combining scalars, vectors, bivectors, and higher-grade elements (trivectors for volume, etc.) into a single algebraic structure, GA allows us to represent geometric objects and the operations acting upon them in a unified manner.

Building upon this foundation, the *3D Euclidean Geometric Algebra* (EGA), denoted as \mathbb{R}^3 , provides the fundamental model for representing points, lines, planes, and rotations in ordinary three-dimensional space. It consists of three orthogonal basis vectors \mathbf{e}_1 , \mathbf{e}_2 , and \mathbf{e}_3 , together with all their outer products, yielding $2^3 = 8$ basis elements in total. EGA thus spans scalars, vectors, bivectors, and a trivector, enabling a compact and intuitive encoding of geometric entities and operations. Rotations, for example, are naturally represented by *rotors*—multivectors that generalize quaternion-based rotations without losing geometric clarity. More interested readers may consult [2, 5, 6] for comprehensive treatments of Geometric Algebra and its applications.

Extending further, the *Conformal Geometric Algebra* (CGA) has emerged as a particularly powerful model for computer graphics. CGA, the geometric algebra of $\mathbb{R}^{4,1,0}$, unifies rigid-body transformations (rotations and translations) as operations within a single algebraic structure, and represents points, spheres, and planes in 3D space as 5D vectors (null vectors of the algebra). The notation $\mathbb{R}^{4,1,0}$ indicates four positive, one negative, and zero null dimensions in the metric signature. The resulting 5D conformal model arises by extending the 3D Euclidean basis with two additional vectors, \mathbf{e}_0 and \mathbf{e}_∞ , corresponding respectively to the origin and the point at infinity. Although the conformal basis is five-dimensional, the complete algebra contains $2^5 = 32$ elements, as all possible outer-product combinations of the basis vectors are included. Rotations, translations, and dilations are all represented by special multivectors (called rotors, translators, and dilators) that act on geometric objects through the “sandwich” product:

$$\text{Object}_{\text{transformed}} = M \cdot \text{Object}_{\text{original}} \cdot M^{-1}$$

where M is the multivector representing the transformation.

This structure allows GA to generalize and subsume other algebraic systems used in computer graphics. Quaternions, for instance, are isomorphic to the bivectors in 3D Euclidean GA, and dual-quaternions find their natural home within the even subalgebra of 3D Projective Geometric Algebra (PGA) or CGA [12]. This means

that any operation performed with quaternions or dual-quaternions has a direct, and often more intuitive, counterpart in GA.

The fundamental property that makes GA so powerful is that *geometry is preserved through algebraic manipulation*. When we compose transformations by multiplying their corresponding multivectors ($M_{\text{composite}} = M_2M_1$), the resulting multivector $M_{\text{composite}}$ correctly represents the composite geometric transformation. When we interpolate between two transformations by linearly interpolating their multivectors, the result is a geometrically meaningful intermediate transformation [8, 9]. This is not true for matrices where, for example, interpolating two rotation matrices does not generally yield another rotation matrix. This property simplifies CG pipelines immensely, eliminating the need for special interpolation schemes like SLERP for quaternions and removing the conceptual clutter of managing multiple, incompatible mathematical representations.

Beyond its theoretical elegance, GA’s unifying capability now extends into practical deployment. The recently introduced *GA-Unity* framework [10] operationalizes these principles within the Unity game engine, offering a modular environment where multivector-based transformations are computed natively. The relationship among these representation forms and their seamless transmutation into GA equivalents is illustrated in Figure 9, where *GA-Unity* facilitates conversion between conventional transformation representations (vectors, matrices, quaternions) and their geometric-algebraic counterparts within modern game engines. By enabling automatic conversion between GA objects and standard engine constructs, *GA-Unity* bridges the gap between mathematical abstraction and real-time implementation. It supports efficient interpolation, deformation, and scene manipulation in collaborative, networked applications, demonstrating that the benefits of GA are not confined to theoretical rigor but translate directly into measurable performance gains and development efficiency within contemporary 3D engines.

3 Applications in Geometry Processing and Mesh Manipulation

One of the most compelling demonstrations of Geometric Algebra’s power is in the domain of real-time geometry processing and 3D mesh manipulation. Traditional methods for simulating deformable objects or performing interactive mesh modifications like cutting, tearing, and drilling often rely on complex data structures (e.g., tetrahedral meshes) and computationally intensive methods like the Finite Element Method (FEM). These approaches frequently require heavy pre-processing and struggle to maintain interactive frame rates, especially in immersive XR applications.

Our research has shown that CGA provides a remarkably compact and efficient framework for these tasks [11, 12]. By representing vertices, planes, and spheres as uniform multivectors, we can express complex geometric predicates and operations as simple algebraic manipulations. For example, the intersection of a cutting plane and a mesh edge can be determined directly through GA products, simplifying the logic required for real-time cutting.

In our work [12], we introduced a unified geometric algorithm to cut, tear, and drill deformable, rigged models. This framework leverages CGA to perform these operations on-the-fly, even after the model has been animated, while robustly maintaining the

deformation topology. Unlike previous methods, our approach requires minimal pre-processing and is “GA-ready,” meaning all sub-predicates are implemented in terms of multivector operations. This unified approach yields algorithms that are not only compact but also achieve excellent numerical stability and topological robustness. For instance, during a cut operation, our method creates new vertices along the intersection and instantly computes their skinning weights using barycentric coordinates. This allows the newly separated mesh parts to be further deformed and animated smoothly and without artifacts. This ability to perform dynamic topological changes on animated characters is crucial for realistic surgical XR simulations and other interactive training applications [18].

A core benefit of this GA-native approach is its radical simplification of geometric constraints. The algebra itself encodes the geometric relationships, freeing developers from managing complex conditional logic and data structures required by traditional methods. This results in cleaner, more maintainable code and delivers real-time performance, essential for demanding interactive XR environments.

4 Rigged Character Animation and Scene-Level Transformations

Animating rigged characters is a cornerstone of modern CG. The standard method, Linear Blend Skinning (LBS), is prone to well-known artifacts like collapsing joints (“candy-wrapper” effect). In contrast, Dual-Quaternion Skinning (DQS) largely solves many of these issues, achieving superior volume preservation and more realistic deformations by blending rigid-body transformations (rotations and translations) directly, rather than matrices [14, 15]. Despite its advantages, DQS does not elegantly handle non-uniform scaling, a common requirement for stylized animation.

Geometric Algebra offers a natural and more powerful extension to these techniques. As dual-quaternions can be represented within GA, any DQS algorithm has a direct equivalent in a GA framework. More importantly, GA provides a unified way to handle all affine transformations, including scaling. In CGA, rotations, translations, and dilations (i.e., uniform scalings) are all represented by multivectors (rotors, translators, and dilators) that can be composed via the geometric product.

Our research has leveraged this unified handling of transformations to improve both the fidelity and efficiency of deformable character animation. In our award-winning work [9, 10], we developed a methodology for rigged character animation and deformation entirely within CGA. The standard skinning equation, which blends transformations on a per-vertex basis, is translated into its multivector equivalent. This allows us to apply a blend of rotations, translations, and dilations in a single, coherent framework, using a simple sandwich product to deform the vertices.

$$C_k[m] = \sum_{n \in I_m} w_{m,n}(M_{n,k}B_n)c[m](M_{n,k}B_n)^{-1}$$

Here, the final vertex position $C_k[m]$ is a weighted sum of the vertex $c[m]$ being transformed by the composite multivector $(M_{n,k}B_n)$ for each influencing bone (see Figure 2).

This approach not only simplifies the underlying mathematics but also yields tangible performance and quality benefits. We have

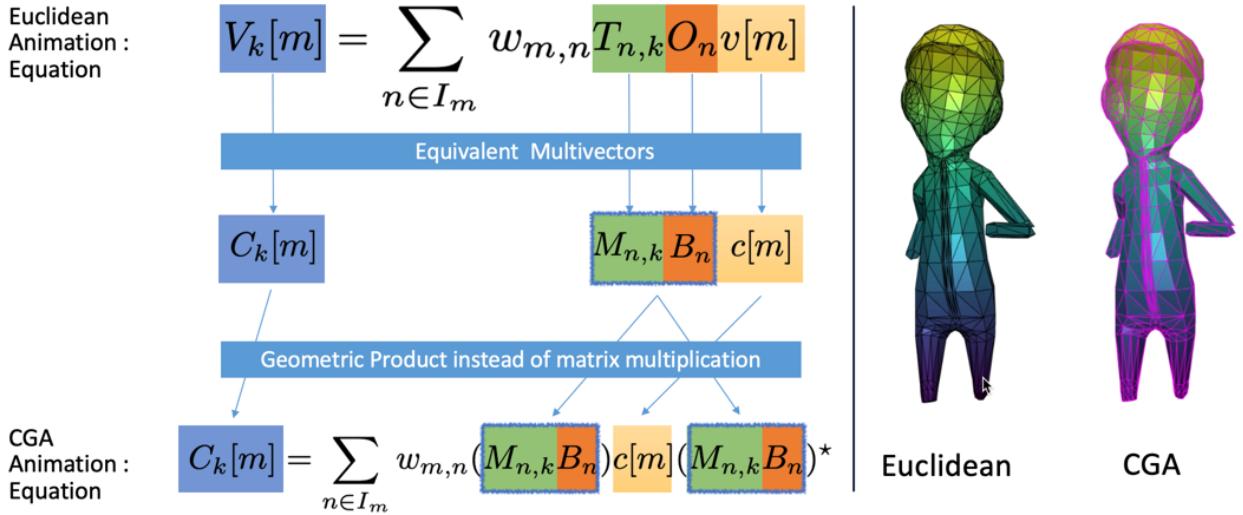


Figure 2: The “original” euclidean animation equation involves vectors and matrices can be transformed to an equivalent one that only involves multivectors [11, 12]. Results for keyframes are identical, with interpolated frames showing minor deviations (see Figure 3). Notation: $V_k[m]$ is the position vector of the position of the m -th vertex at animation time k (in homogeneous coordinates), $T_{n,k}$ is the 4×4 matrix storing the transformation of the n -th bone at animation time k and O_n is the offset matrix corresponding to the n -th bone. $w_{m,n}$ denotes the weight of the n -th bone on the m -th vertex, I_m is the set of indices of bones that affect the m -th vertex, $c[m]$ is the original position of the m -th vertex. $C_k[m]$, $M_{n,k}$, B_n and $c[m]$ are the equivalent multivector forms of $V_k[m]$, $T_{n,k}$, B_n and $v[m]$.

demonstrated that linear interpolation of GA multivectors (motors) produces smooth, artifact-free intermediate animation frames. This capability is especially valuable for generating keyframes on-the-fly, enabling high-fidelity motion that directly enhances the perceived realism of the animation.

Beyond traditional animation, this same GA-based representation has proven highly effective for capturing, encoding, and replaying full-body motion in immersive environments. In our VR Recorder and Replay system [8], user movements are captured as GA multivectors, allowing each recorded session to be compactly stored and later replayed with high geometric fidelity. By leveraging GA’s compact and expressive representation, we can significantly reduce the amount of stored motion data, while maintaining interpolation accuracy comparable to standard representations such as Euler angles, vectors, or even dual-quaternions (see Figure 3). This capacity to capture and reproduce motion precisely further validates GA’s versatility as a unified mathematical foundation for the graphics pipeline.

5 Networked and Collaborative XR Environments

The demands of real-time, multi-user XR applications place a significant strain on network bandwidth. In a collaborative virtual environment, the position, orientation, and scale of every user-controlled object and avatar must be continuously synchronized across all clients. Transmitting full transformation matrices (16

floats) for every update is inefficient and can lead to high latency, which breaks the sense of shared presence and immersion.

This representational efficiency provides a clear and measurable advantage in networked environments, a critical factor for real-time XR. A rigid-body transformation (rotation and translation) represented using a GA multivector (a “motor” in Projective or Conformal GA) is far more compact than a 4×4 matrix. For example, a motor in 3D PGA requires only 8 floats, equivalent to a dual-quaternion. Leveraging this compactness significantly reduces data payload that must be transmitted over the network for each transformation update.

Our research, detailed in [8, 9], validates this approach experimentally. We implemented a shared VR system where transformation data for objects and hand-controllers are encoded as GA multivectors before transmission. Critically, the client side receives these compact multivectors and used them to locally interpolate intermediate frames. This GA-based pipeline reduced the required network bandwidth by up to 58% compared to traditional vectors and quaternion-based methods, while achieving an equivalent or superior Quality of Experience (QoE).

This efficiency comes from the power of multivector interpolation. Because interpolating between two GA motors yields a geometrically meaningful results, we can send fewer keyframe updates per second and rely on the client to generate smooth, jitter-less motion locally. This is particularly effective in bandwidth-restricted cases; for instance, our GA-based method can achieve a visual quality 30 updates/sec with a traditional approach using only 20 updates/sec

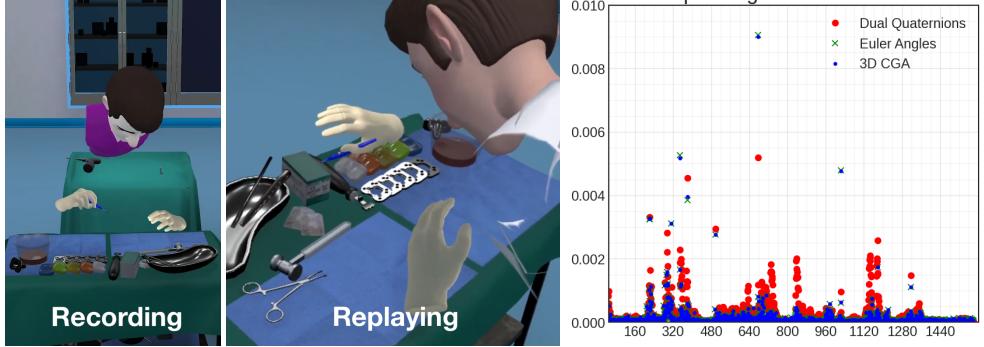


Figure 3: GA for Accurate Psychomotor Action Replay: Our VR Record and Replay system (left, center) enables high-fidelity playback of user actions for analysis or training [7]. (Right) The system’s accuracy is built on GA, which provides a more robust transformation representation with significantly lower relative error compared to traditional quaternions.



Figure 4: Robust Real-Time Surgery Training in XR: Our GA framework powers high-fidelity collaborative medical training, enabling dynamic, artifact-free mesh cutting and deformation on deformable patient models [17, 18].

[9]. This reduction in data traffic is critical for scaling collaborative XR experiences to include more users and dynamic objects, establishing it as a key enabling technology for multiplayer gaming, remote collaboration, and shared educational simulations (see Figure 4), work that was recognized through a poster presentation at SIGGRAPH 2022 [7].

6 From Geometry to Intelligence: GA in Neural and Generative Graphics

The recent explosion of generative AI and Large Language Models (LLMs) has opened new frontiers for content creation and scene manipulation. The ability to edit a 3D scene using natural language instructions—“move the chair to the right of the table”—is a paradigm shift for artists, designers, and everyday users. However, a fundamental challenge remains: bridging the gap between the semantic, often ambiguous, nature of human language and the precise, mathematical descriptions required by a graphics engine. Current methods often rely on machine learning models that operate on unstructured representations like pixels or voxels (e.g., NeRFs CITE NEEDED), which makes precise, object-level manipulation difficult.

We propose that Geometric Algebra can serve as the ideal structure-preserving latent space for AI-driven graphics. Because GA multivectors encode both geometric entities and their spatial relationships within a single algebraic framework, they provide a perfect symbolic language for an AI to reason about a 3D scene. An LLM’s task is simplified from generating raw coordinate data to generating

the correct algebraic operators (GA multivectors) that achieve the desired transformation.

Our current research on LLM-based scene manipulation, “Shenlong” [13], demonstrates this GA-AI integration. The system leverages an LLM to interpret a user’s natural language command, with a crucial distinction: the LLM’s role is not to generate code or vertex positions, but to translate user intent into a precise CGA expression. For example, the instruction “place object A on top of object B” causes the LLM to construct a CGA expression. This expression, when executed, resolves to a CGA translator multivector that computes the necessary displacement based on the objects’ bounding boxes. This final CGA motor is then applied directly to the object’s transformation component in the scene graph.

This GA-centric approach has several advantages. First, it leverages the zero-shot reasoning capabilities of pre-trained LLMs, eliminating the need for massive, scene-specific training datasets. Second, it ensures geometric precision, as the final transformation is a mathematically exact GA operation, not a probabilistic approximation. Our preliminary results (see Figure 7) validate this method, showing that it significantly outperforms baselines by reducing LLM response times and boosting success rates on complex spatial queries.

This GA-AI synergy extends beyond high-level logic and into the core rendering pipeline. Our recent work on “Neural-GASH” [6] introduces a novel real-time shading architecture based on a neural radiance field. This approach, which utilized an initial Multi-Layer Perceptron (MLP) model (see Figure 5), outperforms

traditional Precomputed Radiance Transfer (PRT) methods. The key advantage is that our model is trained to directly consume CGA representations of vertex positions and normals, completely eliminating the expensive, static pre-computation step required by PRT. This enables high-fidelity, dynamic shading of fully animated meshes in real-time (see Figure 6). The framework’s robustness is further demonstrated by its ability to shade scenes generated via 3D Gaussian Splatting, proving its flexibility beyond traditional mesh-based geometry (see Figure 8). Furthermore, preliminary results from a new GNN-based extension of this method show even greater fidelity, as the GNN architecture better captures mesh topology to yield superior results in complex self-shadowing scenarios. This architectural progression provides a concrete validation for the new class of geometrically-aware neural architectures we propose.

Looking forward, we envision a new class of GA-embedded neural architectures. These models would not merely learn pixel correlations but would be structured to inherently understand geometric meaning. By training models to operate directly on multivector representations, we can create generative-AI systems that respect geometric constraints, understand symmetry, and can perform complex spatial reasoning, currently out of reach for purely data-driven approaches. This synergy between the symbolic precision of GA and the learning power of neural networks defines a compelling new frontier for intelligent graphics.

7 Integration into Modern XR Authoring Platforms

A significant part of our research has focused on the practical validation and integration of our GA-based methods into modern XR authoring platforms. By primarily focusing on C# implementations within the Unity game engine, we bridge the gap between theoretical advancements and production-ready tools. This focus on implementation ensures that our algorithms can be readily applied in production environments for creating interactive and high-performance applications.

We have successfully integrated our GA algorithms for mesh manipulation, character animation, and efficient network transmission into a cohesive XR authoring platform [18]. This framework built upon contemporary game engines, directly exposes our GA-based functionalities to developers. Our ‘GA-Unity’ package, for instance, provides a streamlined workflow for developers to represent object transformations as GA multivectors. It handles the conversion from standard Unity formats (Vector3, Quaternion) to multivectors and provides optimized interpolation functions essential for networked applications [10]. Demonstrating significant performance improvements over previous methods, this work was recognized with both the Best Paper and the Best Application Award at the CGI 2024 ENGAGE Workshop.

Our platform has been used to build high-fidelity surgical simulations where the real-time, artifact-free deformation, cutting, and tearing of soft-body tissues is a critical requirement [12, 18]. In these medical VR applications, the robustness and performance of our GA algorithms allow for a level of realism and interactivity that would be difficult to achieve with traditional methods. Similarly, our framework has been used to create collaborative training and

educational tools (see Figure 3) where the efficient synchronization of actions in a shared virtual environment is paramount [7, 16].

By packaging these advanced geometric methods into accessible tools for platforms like Unity, we are lowering the barrier to entry for developers. This simultaneously validates the performance and utility of GA in a production context and accelerates the dissemination of these powerful techniques into broader industry and academic curricula, paving the way for wider adoption.

8 Unified Perspective and Outlook

The research presented in this paper establishes GA not as a mere mathematical abstraction, but as a practical framework capable of unifying and transforming many parts of the modern graphics pipeline. Across multiple domains—mesh manipulation, character animation, XR interaction, and generative scene editing—GA provides a single, coherent algebraic framework that supersedes the traditional fragmented representations based on vectors, matrices, and quaternions.

In mesh manipulation, GA allows us to encode vertices, edges, faces, and local transformations as multivectors, enabling real-time operations such as deformation, cutting, and tearing while preserving geometric coherence. Unlike conventional approaches that treat rotation and translation separately, GA unifies these transformations, resulting in more robust and numerically stable algorithms. This unified framework provides a foundation for techniques previously difficult or impossible to express compactly, while simultaneously reducing the computational overhead associated with multiple converting between different algebraic forms.

GA extends this unification to character animation, replacing specialized schemes like SLERP and dual quaternion interpolation. By representing rotations, translations, and interpolations as multivectors, we achieve geometrically meaningful blends using a single, consistent algebraic tool. The integration of GA into networked systems, as realized in our *GA-Unity* framework, directly enables compressed pose transmission, reduces runtime, and ensures coherent behavior across distributed simulations. This provides a tangible improvement over traditional pipelines, demonstrating how GA is able to transform not only the mathematical representation but also the fundamental system-level architecture for interactive applications.

In XR and collaborative authoring contexts, GA provides a unifying language for transformations, deformations, and interactions, ensuring that scene updates, manipulations, and physics computations remain consistent across local and remote environments. Our *GA-Unity* framework operationalizes these concepts within modern game engines. It handles conversions between traditional representations and their GA equivalents (Figure 9) while allowing developers to leverage GA-based operations without modifying existing rendering or simulation subsystems. This capability is essential for enabling high-fidelity, multi-user XR experiences where both geometric accuracy and performance are critical.

GA also extends naturally into neural and generative graphics, where maintaining geometric fidelity in learned latent spaces is a primary challenge. By structuring latent representations as multivectors, we provide geometrically meaningful foundation for instruction-driven scene editing with LLMs [13]. This integration

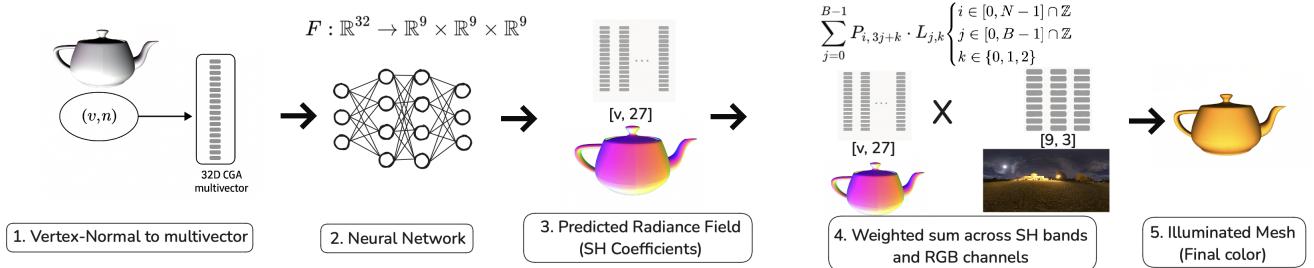


Figure 5: A Geometrically-Aware Neural Architecture: The NeuralGASH pipeline consumes CGA multivectors—which compactly encode vertex position and normal data—to directly predict Spherical Harmonic (SH) coefficients for light and shadow, eliminating traditional pre-computation steps [3].



Figure 6: Enhanced Realism with GA-Powered Neural Rendering: (Left) Standard Unity engine lighting on a dynamic character. (Right) The same scene rendered with our "NeuralGASH" pipeline, which achieves superior, dynamic lighting and shadow fidelity without pre-computation [3].

ensures that semantic instructions translate into valid transformations, enabling AI-assisted content creation that remains coherent and interpretable, even in complex 3D environments.

This GA-AI integration is equally transformative in neural rendering. Our "Neural-GASH" architecture [3] demonstrates this by training a neural model to consume CGA representations directly as input. This approach completely eliminates the static pre-computation step of traditional PRT, enabling high-fidelity, dynamic shading of fully animated and deformed meshes. This use of GA as a native input for neural networks provides a concrete validation for a new class of high-performance, geometrically-aware rendering and simulation architectures.

9 On Practical Adoption and Future Directions

A critical reader might ask: if GA's benefits are this clear, why has it not already superseded traditional methods? The answer involves a combination of historical inertia, a narrow definition of "performance," and a prior lack of production-ready tools.

Historically, the entire graphics ecosystem—from GPU hardware to rendering APIs—has been aggressively optimized for 4x4 matrix operations. This created a significant performance barrier for alternative algebras. However, this "operation-level" performance view is too narrow for modern, complex applications. As this paper has demonstrated, the system-level benefits of GA are now proving more significant. The massive reduction in network bandwidth

(Section 5) and the complete elimination of static pre-computation in neural rendering (Section 6) represent performance gains that far outweigh any micro-level cost of a multivector operation.

The primary barrier, therefore, has been one of usability and tooling. The perceived learning curve of GA and the lack of integration into standard engines have historically prevented widespread adoption. Our work on GA-Unity (Section 7) was developed specifically to solve this problem. By providing an accessible, high-performance bridge that integrates GA-native operations directly into a mainstream engine, we lower the barrier to entry, allowing developers to leverage GA's power without needing to be experts in the underlying algebra. As the demands of XR and generative AI continue to push traditional fragmented tools past their limits, we believe that practical, high-performance frameworks like GA-Unity finally pave the way for GA's wider adoption as the new standard.

Collectively, these contributions establish GA as a comprehensive substrate for graphics computation: it not only replaces fragmented mathematical tools but also enables new algorithms and tools that exploit its algebraic expressiveness. GA-Unity exemplifies this by bridging the theoretical advantages of GA with practical implementation in modern engines, empowering developers and researchers to create interactive, networked, and generative graphics pipelines that were previously difficult to realize. Figure 1 summarizes this vision, illustrating how GA permeates the full pipeline—from geometry definition to physics-based animation,

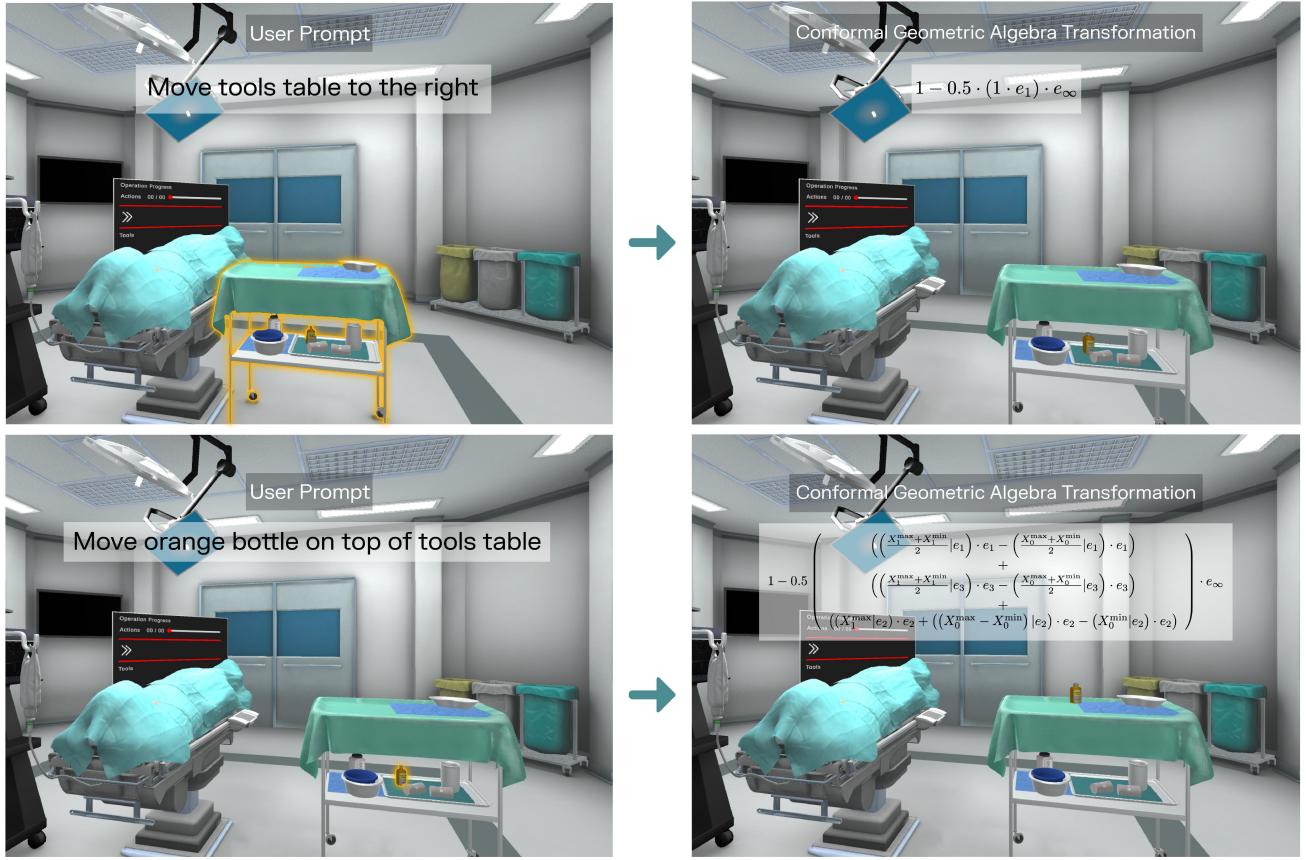


Figure 7: AI-Driven Editing with Geometric Precision: The “shenlong” system, where a LLM translates ambiguous user intent (“on top of”) into a mathematically precise CGA expression for robust 3D manipulation [13].



Figure 8: GA-Powered Shading for 3D Gaussian Splats: Our NeuralGASH pipeline demonstrating its robustness and flexibility by providing real-time, dynamic lighting and shadows for modern scene representations like 3D Gaussian Splatting, not just traditional meshes [3].

real-time rendering, XR interaction, and AI-driven scene manipulation—providing a single unifying framework that elevates both the efficiency and the expressive power of modern graphics systems.

In summary, Geometric Algebra is not only an elegant mathematical framework but also a practical catalyst for innovation in

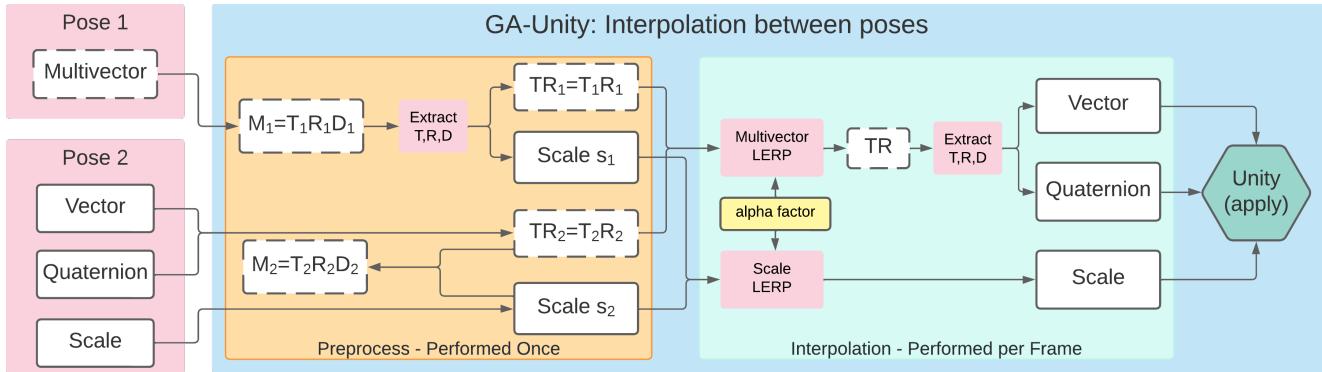


Figure 9: Optimizing Networked XR with GA-Unity: The interpolation engine converts Unity’s standard transforms into compact GA multivectors (motors). By interpolating these motors, we generate smooth motion from fewer keyframes, significantly reducing network bandwidth in collaborative applications [10].

computer graphics and XR. By preserving geometry across transformations, reducing redundancy, and enabling coherent multi-domain operations, GA augments existing pipelines and facilitates the creation of new techniques and tools that fully exploit the potential of a unified algebraic representation. This positions GA as a next-generation foundation for graphics, interactive systems, and generative environments alike.

While our work demonstrates production-level performance by minimizing overhead, the ultimate step is to challenge the hardware-level inertia directly. The industry’s reliance on 4x4 matrices is an optimization for a legacy paradigm. The emergence of GA-based, matrix-free implementations, such as the one presented in [1], marks the beginning of this transition. In that work, GA operations were executed directly within vertex and fragment shaders, achieving superior performance compared to state-of-the-art matrix-based pipelines. These findings suggest that a paradigm shift is both feasible and beneficial. We therefore propose that future GPU and CPU architectures should explore GA-native hardware acceleration. Just as modern GPUs now include “RT Cores” for ray tracing and “Tensor Cores” for AI, a “GA Core” that natively accelerates multivector operations—such as the sandwich product and motor interpolation—could unlock orders-of-magnitude performance gains. This would render the entire “performance” debate obsolete and position GA as the undisputed substrate for all real-time spatial computation.

Finally, the truest adoption will come from standardization. While GA-Unity serves as a robust proof-of-concept, the community must move toward a standardized, open-source, and highly-optimized library for GA computation, analogous to “GLM” for linear algebra. This would provide a common foundation for a new generation of fully-unified engines where graphics, computational physics, and AI are not separate subsystems, but rather different applications of the same, single geometric algebra. This ‘grand unification’ of all spatial computation remains the ultimate promise of GA, a goal that our work demonstrates is not only possible, but practical.

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