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Topology and Geometry in Computation: A Comprehensive Review of Methods and Applications

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Abstract: Topology and geometry provide mathematical foundations for understanding the structure, connectivity, and spatial relationships of computational systems. This paper presents a narrative review of research applying these concepts across distributed networks, multi-agent systems, engineering design, robotics, medical imaging, computational geometry, and 3D point-cloud processing. The reviewed studies employ techniques such as graph theory, topology optimization, geometry projection, persistent homology, Morse-Smale complexes, and numerical optimization. The paper compares the reported methods, application areas, outcomes, and challenges to highlight how topological and geometric reasoning can support connectivity, structural robustness, design optimization, and geometric accuracy. The review also discusses recurring limitations, including computational cost, scalability, and the handling of complex structures.

Keywords: Topology, Distributed Networks, Multi-Agent Systems, Fault-Tolerance, Optimization, Autonomous Systems

I. INTRODUCTION

The study of topology and geometry in computation tells us about the structural characteristics of computational systems, seeing how states are connected, how data flows, and how components interact in complex environments. By applying mathematical concepts from topology and geometry, researchers can model systems such as distributed networks, neural networks, and separate platforms as geometric or topological spaces. This viewpoint enables us to analyse the important properties like ease of use, resilience, faulttolerance, energy efficiency, etc. which are becoming increasingly important as computational systems grow more interlinked and complex. In modern distributed systems, such as drones, sensor networks, maintaining proper communication and stable cooperation is a challenge nowadays. These systems often work in environments subject to unpredictable interference, limited energy resources, bandwidth restrictions, and changes. Traditional methods typically focus on algorithmic improvements for tasks like consensus or formation control, but it is sometimes overlooked how the system's structural organization affects performance. In many cases, when communication links fail or the topology changes unexpectedly, the system becomes unstable or ineffective, which could lead to mission failure. Topology and geometry provide a powerful approach by allowing systems to be analyzed and designed as networks of connected nodes with spatial relationships. Topological concepts, such as rigidity and connectivity, ensure that the structure of the network remains stable even under faults or environmental changes. Geometric methods help in precisely measuring distances, optimizing spatial layouts, and reducing energy consumption. This paper tells us the importance of solving the problems of link quality, energy consumption, and reducing network complexity while making sure of smooth running. It offers a fault-tolerant control framework that immediately makes rigid topology in 3D space. Through decisions and edge removal operations put up by mathematical theories, the system reconstructs itself to maintain connectivity and formation, even in the presence of problems.The effectiveness of this approach can be seen through simulations, showing improved robustness, fault tolerance, and energy efficiency in multiagent systems operating in complex, real-world environments.[F1.1]

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II. REVIEW METHODOLOGY

This paper follows a narrative literature-review approach. The review is based on the 25 research works cited in the reference list and discussed in the paper. The studies are examined thematically according to the computational and engineering applications described in the source material, including topology and geometry projection, network and multi-agent systems, medical imaging, computational geometry, shape modelling, optimization, and dynamic topologies. For each study, the discussion considers the method reported, its application or stated outcome, the challenge addressed, and the limitation or mitigation described. The findings are then compared to identify recurring benefits and open challenges across application areas. The source manuscript does not report the databases searched, search dates, or formal inclusion and exclusion criteria; accordingly, this work is presented as a narrative review rather than a systematic review.

III. TOPOLOGY AND GEOMETRY PROJECTION METHODS IN MODERN ENGINEERING APPLICATIONS

Researchers used a computer-based approach to create a new method for designing microstrip bandpass filters by applying topology enhancement with the geometry projection method. This method models thin stubs and air gaps, which are important for achieving accurate frequency responses. A computer algorithm, CMA-ES, is applied to determine the best conductor shapes. The optimized design includes a thin stub that greatly improves filter performance, while its removal reduces effectiveness. Overall, this method creates smaller and more efficient filters which makes them highly suitable for modern microwave and communication devices. [1] Morse-Smale complexes are powerful tools for analyzing complex data in domains like material science, computer graphics and fluid dynamics. Traditional methods such as the steepest descent approach that is used to compute these complexes usually cause shape distortions or disconnect points. This issue can be solved by replacing square grids with precisely constructed triangular grids. With this modification, the steepest descent method maintains both topological consistency and geometric accuracy without changing the primary algorithm. As a result, the reliability of Morse-Smale complexes is enhanced [2]. Topology optimization for designing a magnetic actuator can be done using gradient-based solvers such as the Method of Moving Asymptotes (MMA), Interior Point Optimizer (IPOPT), and Sparse Nonlinear Optimizer (SNOPT). The goal is to maximize the attractive magnetic force while minimizing material usage. All solvers achieve similar forces and designs but their efficiency differs. SNOPT is the best for large-scale problems because it is fast and efficient. MMA also gives good results but it takes more time. IPOPT is the least effective because it is slow and produces too many unwanted intermediate materials. The choice of solution affects the efficiency. [3] Topology optimization (TO) can significantly improve the design of switched reluctance motor rotors, especially by improving torque at certain positions and creating smoother torque profiles, but reducing mass lowers performance, creating a trade-off with efficiency of the motor rotor. Th results depend on setup choices such as mesh density, material models and initial conditions. Finer meshes refine geometry but do not always improve torque, while simplified material models make the designs faster to compute but less practical for real world use. The optimized designs are well-suited for additive manufacturing and modern 3D- printing [4]. The Boolean Geometry Projection (BGP) method optimizes magnet layouts in interior permanent magnet (IPM) motors. Unlike traditional parameterbased methods that restrict magnet shapes within fixed limits, BGP allows free modification of magnet configuration without such constraints, enabling the creation of manufacturable designs. The method uses the CMA-ES algorithm to enhance magnet placement with the goal of maximizing average torque while minimizing torque ripple. BGP produces diverse and effective magnet arrangements, including V-shaped, U-shaped, and delta-shaped structures without prior assumptions. These optimized designs significantly improve torque performance and reduce torque ripple compared to conventional motors. BGP method is a promising approach for advancing IPM motor design, particularly for applications in electric vehicles and modern electrical systems that demand high efficiency and reliability. [5]

IV. TOPOLOGY AND GEOMETRY ACROSS DISCIPLINES: FROM ENGINEERING TO MEDICINE

It highlights a multi-objective topology optimization approach for synchronous reluctance machines that affirms manufacturable rotor designs while accounting for material degradation due to cutting. It identifies Pareto-optimal tradeoffs among efficiency, torque, torque ripple, and power factor, providing insights into optimal machine designs for practical applications [6]. This paper explores how algebraic topology and differential geometry can enhance radiomics by providing powerful tools for analysing medical images. These methods enable robust shape and structural analysis. This paper also highlights how persistent homology and persistence landscapes can extract stable, multiscale topological features from medical images and histopathology slides. [7] This paper surveys computational topology methods in hand-drawn animation, focusing on frame deformation, feature correspondence, and volumetric modelling. Stroke graph isomorphism, matching, and region adjacency graph (RAG) methods tackle stroke/region correspondence

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in hand-drawn animation, balancing topology preservation with flexibility for artistic motion. Meshes and stroke complexes enable flexible, topology-aware frame deformation and correspondence in hand-drawn animation, balancing mathematical rigor with artistic expressivity. While they preserve features and support articulation, limitations like stroke degeneration, manual intervention, and lack of volumetric modelling challenge practical adoption in studios. Volumetric modelling builds 2.5D/3D character forms via stroke depth ordering, skeleton fitting, and inflation, but struggles with symbolic geometry, occlusion, and complex depth relationships. The goal is to let animators sketch volumetric characters directly using construction curves and Challenge Depth ambiguity when projecting 3D curves onto 2D drawings. [8] This paper proposes MVMRL, a multi-view self-supervised framework that integrates 2D topological and 3D geometric information for molecular representation learning. Through hierarchical pre-training and motif-level cross-view attention, it achieves superior performance in molecular property prediction. [9] Tetra-Spark is a Spark-based distributed framework for compactly representing and analysing large tetrahedral meshes. By leveraging simplicial complexes, efficient connectivity relations, and Spark Data Frames, it enables scalable storage, fast queries, and efficient geometric/topological analysis on massive 3D datasets. [10]

V. TOPOLOGY-DRIVEN APPROACHES IN COMPUTATIONAL GEOMETRY, IMAGING, OPTIMIZATION, AND NETWORKED SYSTEMS

This article has shown how homology, manifolds, and other topological tools have affected computational graphics and geometry, and hopes to encourage more utilization of topology in optimization, TDA, as well as the development of improved real-world algorithms [11]. This paper introduces a method for designing complex Shape Memory Alloy (SMA) compliant actuators using topology optimization for elastic materials. The resulting benchmark mechanisms are true to finite element analysis and show shape memory effect with strain retention percentages of 79.9 percent, sufficient for practical applications. The entire process is able to avoid directly modelling the complex thermomechanical behavior of SMAs when designing SMA-compliant actuators, which makes the whole process simpler. This work proves that complex shapes with complex geometries have the potential to utilise the shape memory effect, which allows them to create highly compact and highly reliable actuators [12]. This paper describes the high-bandwidth honeycomb topology (HHCT), a network-onchip with single-hop inter-cluster links and reduces the latency, response time, and power. Simulations show that the HHCT prototype shows substantial improvement than a regular mesh, with the same packet loss reported [13]. This paper provides a topology optimization framework for the SMA-based actuators using finite element analysis on three benchmarks due to which it can achieve increased strain retention of 69 - 80 percent among the prototypes. The results promises about its potential towards the next generation of compliant actuators [14]. NeCGS compresses multiple sets of 3D meshes by 900x by utilizing a unique TSDF-Def representation that compresses irregular meshes into a uniform 4D tensor. Using an autodecoder network, NeCGS learns compact features and shared parameters to allow for high-accuracy decompression while maintaining visual details. NeCGS also allows the user to add dynamic models and results suggest that it outperforms current standards such as MPEG and Draco in terms of their ratedistortion performance. The experiments confirms that NeCGS is able to achieve better quality in terms of visual perception across multiple datasets [15].

VI. ADVANCEMENTS IN TOPOLOGY FOR OPTIMIZATION IN SHAPE MODELING AND NETWORK DESIGN

Drones and robots remain connected and work together in a 3D space, even when communication links fail, due to the application of rigid graph theory to efficient connection patterns that reduce usage and improve link quality. The tests show it works well, keeping the formation steady even when parts break [16]. Optimal tool diameter selection enhances machining speed and access by utilizing an algorithm that analyzes the axial and radial cavity topography in detail. This technology identifies the largest suitable tool for each layer and also conducts a minimum radial analysis to ensure maximum efficiency and accuracy in the machining process. By keeping in mind these factors, the selection process becomes accurate and effective, which leads to improved performance in manufacturing. [17]. Connecting customers and maximizing profit through pipe routing are the main goals of district heating network design. Significant techniques include fast graph methods that require all consumers to be connected, flexible but slow heuristics, and MILP/MINLP/NLP for optimal but complex solutions. The Price-Collecting Steiner Trees (PCST) model chooses customers through an approximation algorithm, by constructing the graph, allocating weights, and computing heat flow, However, it ignores uncertainties in the real world by assuming just one source and unlimited capacity [18]. The increasing need for electricity and the push for using more renewable energy sources have led to new patterns of congestion in the power grid. Because expanding transmission lines can be slow and expensive, we use a technique called NTO (Network Topology Optimization) to rearrange the system through line and bus-bar switching. To improve this process, we introduce a new model called the Node-Breaker model, which uses something known as the Sparse Tableau Formulation (PVSTF). This approach helps reduce the number of variables and constraints in our calculations,

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making it easier and faster to find solutions. While this method is good at managing the switching of connections and provides better relief from congestion, it still faces challenges with high computational costs, especially in larger grids and when generator dispatch is fixed. Additionally, we've developed an algorithm for addressing LTL (Linear Temporal Logic) planning problems. Continuous planning can be enhanced by considering the layout of the network, which leads to smarter decision-making. The complexity of the topology can also help in finding more efficient paths when planning how to manage power flow in the grid. [19], [20].

VII. MODERN COMPUTATIONAL TECHNIQUES FOR ALGEBRAIC SYSTEMS, ELECTROMAGNETIC DESIGN, AND DYNAMIC TOPOLOGIES

The paper presents symbolic computation for algebra, geometry, and algebraic differential equations (ADEs) while emphasizing exact, formula-based methods over numerical approximations. Resultants and Gr¨obner bases are used to enable elimination and parametrization of algebraic varieties. Only irreducible genus 0 curves are rationally parametrizable, illustrated with cubic curves, cardioids, and tacnodes. The algebraic geometric method links ADEs to algebraic solution varieties, parametrizes them, and derives general solutions. Decision algorithms can confirm the existence of strong rational general solutions, which are particularly effective for first-order algebraic ODEs [21]. A reluctance network analysis (RNA) based topology optimization is developed for the middle rotors of coaxial magnetic gear to maximize torque density and reduce ripple. The design uses continuous density variables, RAMP interpolation, adjoint sensitivity analysis, and MMA optimization under volume and ripple constraints. Results show torque density gains and significant ripple reduction. RNA matches FEM accuracy while being simpler to implement, offering new CMG design opportunities [22]. A two-stage SIMP-based topology optimization designs ferrite structures in IPT pads to boost mutual inductance and reduce leakage fields under a volume constraint. Stage one yields high-performance layouts, while stage two simplifies them for manufacturability while retaining key flux guiding features. Prototypes show a 22.2 percent mutual inductance improvement over benchmarks under misalignment. The method can be adapted to high-power, multi-phase IPT systems. [23]. A fusion of SNMP and LLDP to accurately map industrial network topologies is proposed. By extracting routing and adjacency data from MIB tables and using an iterative IPbased search queue, the method captures both logical and physical connections. It reconstructed star and ring topologies with 100 percent accuracy and minimal time cost on Huawei's eNSP simulator. It addresses single-protocol shortcomings like device omissions and link errors through multi-source fusion, iterative mapping, and front-end visualization, offering a scalable, efficient, and reliable approach for industrial control network monitoring [24]. Table I reviews the existing literature.

A registration pipeline handles topological changes in 3D point clouds using bidirectional warp hypotheses. An embedded deformation graph estimates an initial warp; post processing detects stretching/compression, classifies events, and blends warp fields with RBF kernels. Experiments on MPI Sintel and custom datasets show great accuracy and robust motion boundary preservation in dynamic scenes. [25].

VIII. COMPARATIVE RESULTS AND DISCUSSION

The reviewed studies show that topology- and geometry-based methods address different but complementary computational requirements. Graph-based and rigidity-based approaches focus on maintaining connectivity and formation stability in networked or multi-agent systems. Topology optimization and geometry projection are used in engineering design problems where structural performance and geometric accuracy must be considered together. Persistent homology and related topological data-analysis methods are discussed for extracting stable features from medical and image data, while computational geometry and point-cloud registration methods address shape representation and geometric correspondence. The comparison in Table I summarizes the methods, reported outcomes, challenges, and approaches to those challenges across the reviewed studies. Across these areas, recurring concerns include computational expense, scalability, sensitivity to complex or changing structures, and the need to preserve accuracy while optimizing performance. Because this is a literature review, the outcomes summarized here are those reported by the cited studies; no new experiments or independent performance measurements are claimed in this paper.

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TABLE I COMPARATIVE SUMMARY OF REVIEWED STUDIES

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COMPARATIVE SUMMARY OF REVIEWED STUDIES

References, Year	Methodology and Result	Challenges	Tackle to Challenges
[1],2024	Geometry Projection, Designed thin stubs/gaps; achieved desired passband.	TO fails with thin stubs/gaps, Gradient methods unsuitable	Projection models thin parts, CMA-ES improves placement
[2],2024	Geometry for Morse-Smale complexes in TDA. Improved accuracy and consistency vs. older methods.	Descent causes errors, Probabilistic methods are inconsistent,	Special triangle grids, Hybrid descent with accuracy.
[3],2025	Gradient-based solvers (MMA, IPOPT, SNOPT) for actuator TO. SNOPT fastest; MMA stable; IPOPT inefficient.	High computation time (esp. IPOPT), Efficiency varies	SNOPT for large scale, MMA converges slower, IPOPT unsuitable.
[4],2019	TO of SRM rotors using GCMMA with SIMP. Balanced torque and weight; mesh density affected torque.	Sensitive to mesh/materials, Less torque with reduced mass	Tested different meshes, Reformulated TO, Balanced torque vs. weight.
[5],2022	BGP for IPM motor magnets. Higher torque, less ripple, and a feasible novel shape.	Parameter limits, Hard complex shapes, Risk of unmanufacturable designs	Free shape changes, Boolean ops ensure feasibility, better torque/ripple.
[6],2020	TO with manufacturability and degradation → 92 percent efficiency, 11 Nm torque, 15 percent ripple.	Conflicting objectives, high design space complexity.	Gaussian network + surrogate models.
[7],2024	Motor FEA Study FEA in ANSYS Maxwell → improved torque, efficiency, and stability. High computation demand, accuracy limits.	High computation demand, accuracy limits.	Mesh optimization + parameter tuning
[8],2025	Computational topology of animation → advances in deformation, correspondence, volumetric modeling.	Stroke variability, occlusion, depth ambiguity.	Spectral/topological cues + ML + animator input.
[9],2025	Self-supervised 2D topology + 3D geometry → better MoleculeNet and QM9 performance.	Single-level tasks and unstable 3D conformations	Multi-view tasks + cross-view attention.
[10],2022	Apache Spark VT-based mesh encoding → 78× faster, 80 percent less memory.	High memory use and cluster communication overhead.	Minimal encoding + DataFrames + local UDFs.
[11],2024	A review of existing topological concepts. Provides tools for robust shape analysis.	Scalability, robustness to noise	Developing efficient algorithms to ensure robustness against noisy data
[12],2015	Survey of digital topology and geometry methods. It enhances medical image analysis.	Maintaining topological consistency, handling noisy.	Adapting continuous mathematical methods.
[13],2015	Clustering core built on communication pattern.A clustered NoC topology to reduce latency.	High latency, congestion, packet loss probability, and energy consumption.	Redesigning mesh into HHCT
[14],2020	Topology optimization for compliant mechanisms .Topology-optimized SMA mechanisms achieve up to 80 percent strain retention.	Modelling and designing complex SMA-based compliant mechanisms.	Using topology optimization with elastic materials.
[15],2025	NeCGS compresses 3D geometry sets. Up to 900x compression while retaining high fidelity.	Digitization can distort or fail to preserve object topology.	Defining digitization constraints and convexity features, proper resolution, and camera distance.
[16],2023	Builds and repairs efficient 3D networks.	Link failures, limited energy, and difficulty obtaining real-time global information	Rebuilds the network using local info and deletes weak links.
[17],2021	Optimizing tool diameters, reducing machining time	Excessive tool changes and subjective tool selection	The 'worth time' variable minimizes tool changes and automates optimal tool selection.
[18],2025	PCST graph algorithms enable efficient district heating design	Suboptimal solutions and simplified thermal modeling	Validates the minimal impact of simplifications.
[19],2025	A PV-STF-NTO was developed for efficient network topology optimization	Requires high computational time for large networks.	An iterative MILP+NLP approach with linearization and integer cuts to achieve feasible topologies.
[20],2025	Developed a simplified nerve complex for topology-aware LTL planning.	Unrealized simplices break path validity.	This algorithm removes them by preserving homotopy and enabling correct planning.
[21],2025	Used elimination and parametrization to solve ADEs; Achieved exact solutions for first-order cases.	Higher-order complexity	Symbolic numeric extensions and curve invariants.
[22],2025	Optimized middle rotor via RNA and RAMP; Boosted torque density and cut ripple ¿90 percent.	Flux leakage and grey zones.	Flux-guiding shapes and symmetry reuse.
[23],2025	Applied SIMP-based TO to both pad sides; Improved mutual inductance by 22.2 percent.	Ease of manufacture and flux crowding	Two-stage simplification and geometric tweaks.
[24],2025	Combined SNMP and LLDP protocols, discovered network and link layer connections; 100 percent topology accuracy in simulations.	Single-protocol omissions and scalability.	MIB-based IP queue iteration and front-end visualization.
[25],2025	Estimated warp fields with bidirectional hypotheses; Improved motion accuracy and boundary handling.	Over-smoothing and subtle event detection.	Local deformation cues and RBF blending.

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IX. REVIEW LIMITATIONS

This review is limited to the studies and details available in the cited source material. The manuscript does not document a reproducible database-search protocol, publication-year cut-off, or formal study-selection criteria. In addition, the reviewed studies address diverse application domains and use different evaluation settings, so their reported outcomes should not be interpreted as directly comparable numerical performance measures. These limitations should be considered when interpreting the comparative discussion.

X. CONCLUSION

To sum it up, studying topology and geometry in computing is really important for helping us design and understand computer systems better. These fields focus on how different parts of a system fit together and connect rather than just getting caught up in algorithms. When researchers use concepts from topology and geometry, they can design systems that not only work well but also adapt smoothly to changes around them. These ideas are valuable in a variety of areas. For example, they play a big role in designing networks, improving robotics, enhancing medical imaging technologies, and creating smart devices that we rely on in our everyday lives. One good example is how topology helps engineers create better microwave designs, while geometric methods make it easier to analyze complex data. However, there are still some challenges that we need to tackle. For instance, managing complicated calculations, ensuring that designs can be easily produced, and dealing with messy or incomplete data can all be quite tricky. Thankfully, there are specialized techniques available that can help with these issues. In systems where many different components need to work together, using topology and geometry allows for designs that stay stable even if some connections fail or when energy gets low. Techniques like Boolean Geometry Projection are particularly helpful because they can improve how we manage resources, boost accuracy, and save energy. As computing continues to intertwine with our lives—like in smart homes or health monitoring devices—the importance of topology and geometry becomes even clearer. They offer essential tools for managing complexity, ensuring effective communication between system parts, and helping systems adapt, which keeps everything running smoothly. Looking to the future, it's crucial to invest more time into research that links these methods with exciting developments in machine learning. We also need to focus on creating better algorithms and making these techniques easier for various industries. By blending different mathematical concepts with computing, we have a great chance to enhance the performance and energy efficiency of complex systems, opening the door to innovative advancements in many fields.

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