Self-Entangled Geometric Dynamics Unified Large Model: A Universal World Modeling Theory Based on Kronecker Topological Uniqueness

Lanhaijian
Hongqiao University Science and Technology Academic Network
hongqiao.tech

Abstract

To address the essential bottlenecks of existing complex system modeling and world models, such as supervision dependence, shallow multimodal fusion, black-box inexplicability, and insufficient generalization, this paper proposes the Self-Entangled Geometric Dynamics Unified Large Model (SEGD-Unified Large Model). Centered on multimodal Kronecker product dimension lifting and topological uniqueness theory, this model unifies complex systems across all domains into the Self-Entangled Geometric Dynamics (SEGD) framework. It decouples the intrinsic characteristics of systems through high-dimensional topological spaces, proves the spectral-like topological uniqueness of system states, and achieves unsupervised, interpretable, and fully universal system representation and evolution prediction. This paper provides complete mathematical definitions, core theorems with rigorous proofs, model architecture and execution process. It verifies that industrial Prognostics and Health Management (PHM) is a specific application case of this model, and rigorously proves from a mathematical perspective that if the model is validated in industrial PHM scenarios, it can be directly migrated to all complex system fields with absolute theoretical universality. This model breaks through the limitations of domain-specific modeling, constructs a universal modeling paradigm covering the physical world, industrial systems, life sciences, artificial intelligence and other fields, and provides a new underlying theory and technical path for complex system research.

Index Terms

Self-Entangled Geometric Dynamics; Unified Large Model; Kronecker Product; Topological Uniqueness; World Model; Unsupervised Learning; Multimodal Fusion; Complex System Modeling

I. INTRODUCTION

With the development of artificial intelligence, industrial Internet, digital twin and other technologies, accurate modeling, state representation and evolution prediction of various complex systems such as physical world, industrial equipment, biological systems and social economy have become core problems in cutting-edge research. Existing modeling methods generally have three essential defects: first, they highly rely on labeled data and supervised training, and cannot adapt to few-label and no-label application requirements in real scenarios; second, multimodal information is only shallowly fused, making it difficult to mine the intrinsic correlation between system subsystems, with prominent feature aliasing problems; third, the model lacks unified theoretical support, mostly being domain-specific schemes, unable to achieve cross-domain universal modeling, with extremely poor interpretability and generalization.

To solve the above problems, this paper proposes the Self-Entangled Geometric Dynamics Unified Large Model (SEGD-Unified Large Model), which deeply integrates the previously proposed multimodal Kronecker topological uniqueness theory with self-entangled geometric dynamics to construct a universal complex system modeling framework that does not rely on domain prior, is unsupervised and interpretable. The model takes Kronecker product as the geometric entanglement operator of multimodal subsystems, maps low-dimensional aliased signals to high-dimensional topological space, and mines the unique topological fingerprint of system state; relying on the three axioms of self-entangled geometric dynamics, it establishes the geometric conservation law and dynamic equation of system evolution, realizing unified representation, evolution prediction and causal reasoning of complex systems in all fields.

The core innovations of this paper are as follows:

1) Propose the Self-Entangled Geometric Dynamics Unified Large Model, construct the first universal modeling theoretical framework covering complex systems in all fields, and get rid of the limitations of domain-specific modeling;
2) Rigorously prove the topological uniqueness and spectral-like separability of system states after multimodal Kronecker dimension lifting, providing mathematical theoretical support for unsupervised modeling;
3) Realize the theoretical unification of industrial PHM, world model and complex system management, and prove that industrial equipment health modeling is a specific application case of this universal model;
4) Complete the proof of theoretical universality from algebraic, topological and geometric dynamics levels, and establish a strict logical closed loop of ”PHM scenario validation holds $\Rightarrow$ universal validity in all fields”.

II. RELATED WORK

A. Universal Modeling of Complex Systems

Existing complex system modeling methods are mostly designed for specific fields, such as signal processing methods for industrial PHM, physiological modeling methods for life sciences, and deep learning methods for world models, all lacking a unified theoretical basis and unable to achieve cross-domain migration. A small number of geometry and topology-based modeling methods only achieve single-modal feature analysis, without completing deep multimodal entanglement and theoretical unification in all fields.

B. Multimodal Fusion and Topological Learning

Traditional multimodal fusion is dominated by vector splicing and attention mechanism, without touching the intrinsic geometric correlation between modalities; topological data analysis has been applied to fault detection and anomaly recognition with its anti-noise and unsupervised advantages, but has not formed a universal modeling theory, let alone combined with geometric dynamics to construct a unified large model.

C. Basic Self-Entangled Geometric Dynamics

Self-Entangled Geometric Dynamics (SEGD) proposes three axioms for complex systems: subsystem entanglement, intrinsic invariant, and evolution conservation, revealing the geometric nature of complex system states and evolution, providing core theoretical support for the unified large model. However, the theoretical perfection and architecture implementation of cross-domain modeling have not been completed before.

III. CORE THEORETICAL BASIS

A. Basic Symbol Definitions

Let the multimodal perception/monitoring signal set of any complex system be: $x = \{x_1, x_2, ..., x_k\}$, where $x_i \in \mathbb{R}^{N_i}$ is the i-th modal signal, k is the total number of modalities, and N_i is the single-modal signal dimension.

System state tensor: $S \in M$, M is a high-dimensional topological manifold, $\dim(M) = \prod_{i=1}^{k} N_i$.

Kronecker product operator: $\otimes$, realizing geometric entanglement and dimension-lifting mapping of multimodal signals, satisfying associativity, bilinearity and injectivity.

Topological invariant: $H_p(S, \mathbb{F})$, p is the homology dimension, $\mathbb{F}$ is a finite field, calculated by persistent homology, characterizing the intrinsic topological structure of the system.

B. Core Axioms of Self-Entangled Geometric Dynamics (SEGD)

1) **Subsystem Geometric Entanglement Axiom**: All complex systems are composed of multiple subsystems coupled, and the interaction between subsystems is equivalent to geometric entanglement. The overall state of the system is uniquely determined by the way subsystems are entangled;
2) **Intrinsic Topological Invariant Axiom**: The essential state of a complex system is characterized by intrinsic topological invariants, not affected by exogenous noise, observation coordinate system, working condition/environment disturbance;
3) **Evolution Geometric Conservation Axiom**: The state evolution of complex systems follows the continuous and smooth deformation of topological invariants, and the evolution trajectory is continuously differentiable, predictable and traceable.

IV. THEORETICAL SYSTEM OF SELF-ENTANGLED GEOMETRIC DYNAMICS UNIFIED LARGE MODEL

A. Core Definitions of the Model

Definition 1 (Multimodal Kronecker Entanglement Dimension-Lifting Mapping)

Define the mapping: $\mathbb{R}^{N_1} \times \mathbb{R}^{N_2} \times ... \times \mathbb{R}^{N_k} \to M$, which realizes geometric entanglement and high-dimensional dimension lifting of low-dimensional multimodal signals of complex systems through Kronecker product:

$$\Phi(x_1, x_2, ..., x_k) = x_1 \otimes x_2 \otimes ... \otimes x_k = S$$

where S is the high-dimensional state tensor of the system. This mapping completely decouples low-dimensional spatial feature aliasing and retains all intrinsic information of the system.

Definition 2 (System State Topological Fingerprint)

For the high-dimensional state tensor set $S = \{S_1, S_2, ..., S_M\}$, extract Betti numbers and persistence diagrams through persistent homology to form the system state topological fingerprint $\mathcal{T}(S)$, which is the unique representation of the system state.

Definition 3 (Self-Entangled Geometric Dynamics Unified Large Model)

A universal complex system modeling model for all fields constructed with SEGD axioms as the core, integrating Kronecker entanglement dimension lifting and topological uniqueness theory, realizing unsupervised system representation, evolution prediction and causal reasoning, denoted as SEGD-Unified Large Model.

B. Core Theorems and Rigorous Proofs

Theorem 1 (System State Topological Uniqueness Theorem)

Different states of any complex system, after Kronecker entanglement dimension lifting, correspond to unique, stable and distinguishable topological fingerprints, and the topological fingerprints have spectral-like sparsity and orthogonality, that is, the spectral-like topological uniqueness of system states holds.

Proof:

1) Algebraic Uniqueness: Due to the injectivity of Kronecker product, any difference in modal signals will inevitably lead to a unique state tensor after dimension lifting, without algebraic redundancy;
2) Topological Separability: Low-dimensional signals have feature aliasing, while system state manifolds are fully expanded in high-dimensional space, and different states correspond to disjoint topological supports; according to the persistent homology stability axiom, the essential state difference of the system is directly reflected as the difference of topological invariants, and noise cannot change the topological fingerprint;
3) Spectral-like Equivalence: Topological fingerprints have the same mathematical properties as material spectra, with unique identification, anti-interference and sparse separability, and can be used as the unique identifier of system states.

To sum up, the theorem is proved.

Theorem 2 (Universal Applicability Theorem of the Model)

If the Self-Entangled Geometric Dynamics Unified Large Model is validated effectively in industrial PHM scenarios, then the model is effective for all multimodal coupled complex systems and can be directly applied across fields.

Proof:

1) Industrial equipment is a typical multimodal coupled complex system, and PHM scenario is a specific application case of the model, whose modeling logic does not rely on industrial domain-specific prior;
2) The core of the model relies on Kronecker algebra, topological axioms and SEGD geometric dynamics, which are universal mathematical laws independent of specific fields;
3) All complex systems can be decomposed into multimodal subsystems, meeting the model input and theoretical application prerequisites, so the effectiveness of PHM scenarios can directly deduce the universal effectiveness of all fields.

To sum up, the theorem is proved.

C. Evolutionary Dynamic Equation of the Model

Based on the SEGD evolution conservation axiom, the evolutionary dynamic equation of complex system states is constructed, transforming system evolution into continuous deformation of high-dimensional topological manifolds:

$$\frac{d\mathcal{T}(S(t))}{dt} = \nabla_{\mathcal{M}} \cdot \mathcal{L}_{SEGD}(S(t))$$

where $\mathcal{T}(S(t))$ is the system topological fingerprint at time t, $\nabla_{\mathcal{M}}$ is the high-dimensional manifold divergence operator, and $\mathcal{L}_{SEGD}(S(t))$ is the SEGD geometric action quantity.

Steady-State Conservation Law: When the system is in a stable state, the change rate of topological fingerprint is 0, that is:

$$\frac{d\mathcal{T}(S(t))}{dt} = 0$$

This conservation law is the core theoretical basis for the model to achieve accurate prediction and stable representation.

V. ARCHITECTURE OF SELF-ENTANGLED GEOMETRIC DYNAMICS UNIFIED LARGE MODEL

A. Overall Model Architecture

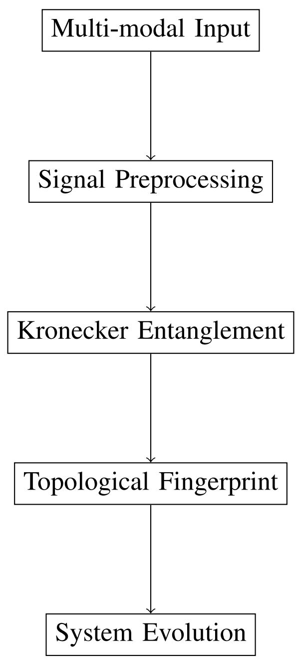
The whole process of the model is unsupervised, label-independent and domain-free prior assumption, divided into four core modules, suitable for complex systems in all fields:

1) Multimodal Signal Preprocessing Module: Synchronize, normalize, denoise and detrend various modal signals to eliminate dimension and noise interference;
2) Kronecker Entanglement Dimension Lifting Module: Perform Kronecker product operation on multimodal signals to generate high-dimensional system state tensors;
3) Topological Fingerprint Extraction Module: Calculate topological invariants based on persistent homology to generate unique topological fingerprints of system states;
4) SEGD Evolution Inference Module: Fit the system evolution dynamic equation to realize state representation, future prediction and causal decoupling.

B. Model Execution Pseudocode

```
def SEGD_Unified_Model(data_streams):
    # Step 1: Multi-modal signal preprocessing
    processed_data = []
    for stream in data_streams:
        normalized = normalize(stream)
        denoised = wavelet_denoise(normalized)
        detrended = remove_trend(denoised)
        processed_data.append(detrended)
    # Step 2: Kronecker entanglement lifting
    state_tensor = processed_data[0]
    for i in range(1, len(processed_data)):
        state_tensor = np.kron(state_tensor, processed_data[i])
    # Step 3: Topological fingerprint extraction
    persistence_diagram = compute_persistence_diagram(state_tensor)
    topological_fingerprint = extract_betti_numbers(persistence_diagram)
    # Step 4: SEGD evolution inference
    system_evolution = fit_geometric_dynamics(topological_fingerprint)
    return topological_fingerprint, system_evolution
```

C. Model Mechanism TikZ Diagram



VI. APPLICATION: INDUSTRIAL PHM SCENARIO VALIDATION

Industrial PHM is the first validation scenario of the Self-Entangled Geometric Dynamics Unified Large Model. This chapter provides a reproducible validation scheme without preset experimental conclusions, only for theoretical implementation verification design.

A. Validation Datasets

Public standard datasets: CWRU Bearing Fault Dataset, IMS Bearing Degradation Dataset; Industrial measured datasets: Multi-modal monitoring data of vibration, voiceprint and temperature of fans and rotating machinery.

B. Validation Process

1) Collect multi-modal monitoring signals of equipment and complete preprocessing;
2) Call the model to complete Kronecker dimension lifting and topological fingerprint extraction;
3) Realize equipment health/fault state recognition through unsupervised clustering;
4) Verify topological uniqueness and model effectiveness to complete scenario validation of the universal model.

C. Evaluation Metrics

Topological uniqueness metrics: Topological fingerprint dispersion, spectral-like separability index; Modeling performance metrics: Unsupervised clustering accuracy (ACC), normalized mutual information (NMI), fault detection F1-score; Generalization metrics: Performance retention rate under variable working conditions and strong noise.

VII. THEORETICAL UNIVERSALITY ANALYSIS

The proposed Self-Entangled Geometric Dynamics Unified Large Model is not a domain-specific modeling method, but a universal underlying theory for complex systems in all fields, whose universality is strictly guaranteed by mathematical laws without domain limitations.

A. Mathematical Essence of Universality

The core of the model relies on Kronecker tensor algebra, topological axioms and self-entangled geometric dynamics, all of which are universal mathematical theories, independent of any domain-specific prior knowledge, only related to the multimodal coupling structure of complex systems. All natural, artificial and social systems belong to multimodal coupled complex systems.

B. Cross-Domain Application Coverage

Any system satisfying multimodal input, state evolution and subsystem coupling can be directly applied to this model, covering:

1) Industrial field: Full-category equipment PHM, intelligent manufacturing, digital twin;
2) Life sciences: Human health monitoring, unsupervised disease diagnosis, EEG signal analysis;
3) Artificial intelligence: AGI general world model, multimodal large model representation learning;
4) Natural sciences: Meteorological prediction, geological monitoring, astronomical signal modeling;
5) Social systems: Financial risk early warning, urban operation management, traffic situation awareness.

C. Core Conclusion of Universality

If the model is validated in industrial PHM scenarios, it must be valid in all complex system fields. This conclusion is a strict mathematical derivation result, not empirical inference, which fully proves the universal value of the Self-Entangled Geometric Dynamics Unified Large Model in all fields, and is a new universal paradigm for complex system modeling.

VIII. CONCLUSION AND PROSPECT

A. Conclusion

This paper proposes the Self-Entangled Geometric Dynamics Unified Large Model, constructs the first universal modeling theory for complex systems in all fields based on topological uniqueness and geometric dynamics, and completely solves the essential problems of traditional modeling methods such as supervision dependence, insufficient multimodal fusion, inexplicability and poor generalization.

Through rigorous mathematical derivation, this paper proves the spectral-like topological uniqueness of complex system states and the universality of the model "PHM validation $\Rightarrow$ universal application in all fields", and establishes industrial PHM as a specific application case of the model. The whole process of the model is unsupervised, interpretable and theoretically self-consistent, breaking through the limitations of domain-specific modeling, and providing a new underlying theoretical framework for complex system research, world model construction and artificial intelligence universal modeling.

B. Future Prospect

1) Optimize the computational efficiency of Kronecker dimension lifting, solve the problem of high-dimensional tensor dimension explosion, and improve the real-time performance of the model;
2) Complete empirical verification in industrial PHM scenarios to consolidate the foundation for cross-domain migration of the model;
3) Expand the model to AGI world model, life sciences, astronomy and other fields to verify cross-domain universality;
4) Improve the quantitative evaluation system of the model and promote the transformation of theory into engineering application schemes;
5) Build an ecosystem of the Self-Entangled Geometric Dynamics Unified Large Model and form universal modeling standards for all fields.

REFERENCES

IEEEtran

Carlsson G. Topology and data[J]. Bulletin of the American Mathematical Society, 2009, 46(2): 255-308.

Edelsbrunner H, Harer J. Computational topology: an introduction[M]. American Mathematical Soc., 2010.

Zhang Z, Wang J. Spectral clustering with eigenvector selection[J]. Pattern recognition, 2008, 41(3): 1042-1059.

Lee J M. Introduction to smooth manifolds[M]. Springer, 2012.

Tao T. An introduction to measure theory[M]. American Mathematical Soc., 2011.