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A Spatiotemporal Hypercube-Based Framework for Integrated Battlefield Modeling and Analysis

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Abstract

Traditional spatiotemporal data systems often suffer from fragmentation and insufficient integration of temporal-spatial dimensions. To address these limitations, this study proposes a novel framework leveraging elastic, multi-scale spatiotemporal grids to systematically correlate operational elements across land, sea, air, space, cyberspace, and electromagnetic domains. The framework synthesizes five-dimensional information—Ontology, Spatial, Informational, Operational, and Temporal Dimensions—to construct unified battlefield "pixel" units through grid encoding. The Spatiotemporal Hypercube extends the static/dynamic attribute representation of conventional spatiotemporal cubes. It overcomes the limitation of traditional models by adopting a "node-link" paradigm to characterize heterogeneous spatial features, enabling dynamic encoding of multidimensional battlefield elements. Through modular assembly and building-block-like integration, the hypercube framework supports rapid generation of digital battlefield environments with adaptive scalability. Compared to conventional approaches, the Spatiotemporal Hypercube framework demonstrates five key advancements: finer modeling granularity, comprehensive relational expressiveness, dynamic grid encoding, scalable dimensionality, intelligent analytics integration. This framework establishes a paradigm shift in battlefield digitization by transforming fragmented physical-domain data into structured, analyzable hypercube units. Its multidimensional fusion mechanism and dynamic encoding architecture provide theoretical and technical foundations for next-generation command and control systems.

1. Introduction

1.1 Research Background and Significance

In modern warfare, the battlefield environment is complex and changeable, the combat forces are diversified and integrated, and the rhythm of combat operations is fast, which puts forward high requirements for battlefield modeling. Accurate and efficient battlefield modeling is the key foundation to realize the scientific, accurate and real-time decision-making of combat command, which can provide strong support for combat operations and improve combat effectiveness. The traditional battlefield modeling method has gradually exposed many limitations in the face of such complex combat requirements, and it is difficult to meet the requirements of modern warfare for comprehensive, real-time and accurate perception of battlefield situation. For example, when dealing with massive, multi-source and heterogeneous battlefield data, traditional methods often have problems such as difficult data integration and low analysis efficiency, and cannot reflect the dynamic changes of battlefield situation in a timely and accurate manner.

As a new battlefield modeling method, the Spatiotemporal Hypercube modeling architecture provides a new method to solve the problem of modern warfare battlefield modeling with its unique spatio-temporal dimension fusion and data processing method. Through the organic integration of time and space dimensions, the Spatiotemporal Hypercube can describe the dynamic changes of battlefield elements more comprehensively and accurately, and realize the refined modeling of battlefield situation. When analyzing the deployment and maneuver of combat forces, the Spatiotemporal Hypercube can clearly show the spatial position and action trajectory of different combat units at different time points, and provide intuitive and accurate information support for combat command decision-making. In addition, the Spatiotemporal Hypercube modeling architecture can also effectively integrate multi-source battlefield data and mine the potential correlation between data, so as to provide more in-depth and extensive intelligence support for operational command decision-making. When processing intelligence data, the Spatiotemporal Hypercube can find the operational intention and action law hidden behind the data by analyzing the spatio-temporal correlation of intelligence from different sources, and provide a strong basis for commanders to formulate scientific and reasonable operational plans. Therefore, in-depth study of the battlefield modeling architecture based on Spatiotemporal Hypercube is of great practical significance for improving the level of command and decision-making in modern warfare and enhancing the combat effectiveness of the army.

1.2 Overseas and Domestic Research Status

In foreign countries, the research on spatio-temporal hypercube in the field of battlefield modeling started earlier and achieved a series of representative results. The United States is in a leading position in this field, and its military and scientific research institutions have invested a lot of resources and carried out a number of related projects. For example, Langran aims to build a joint battlefield situation awareness system based on the grid, and realize real-time monitoring and prediction of battlefield situation by integrating multi-source intelligence data. The project has made important breakthroughs in spatio-temporal data fusion and situation analysis algorithms, and can provide more accurate battlefield situation information for combat command. Some European countries are also actively carrying out relevant research. Peuquet focuses on the application of spatiotemporal grid in land battlefield modeling. Through spatio-temporal modeling of terrain, force deployment and other elements, the authenticity and accuracy of land warfare simulation are improved. However, foreign research still has shortcomings in cross-domain combat modeling, and spatio-temporal data fusion and collaborative modeling between different combat domains still face many technical problems.

Domestic research on Spatiotemporal Hypercube in the field of battlefield modeling has also made remarkable progress in recent years. Domestic scholars have made in-depth explorations in spatio-temporal data models and modeling algorithms, and put forward some innovative theories and methods[4-7]. Li's group proposes a battlefield target tracking model based on improved spatiotemporal grid. By optimizing the division of spatio-temporal dimension and data association algorithm, the accuracy and stability of target tracking are improved. Feng's group studied the application of spatio-temporal grid in naval warfare battlefield modeling, and constructed a naval warfare situation assessment model based on spatio-temporal grid which provided effective support for naval warfare command decision-making. Although domestic research has achieved certain results in some aspects, compared with foreign countries, the versatility and practicability of the model still need to be further improved, and some research results still have a certain gap in practical combat applications.

1.3 Subject and Method

The main research content of this paper focuses on the application of Spatiotemporal Hypercube in battlefield modeling, including the following aspects:

(1) The concept and theoretical basis of Spatiotemporal Hypercube. The concept connotation of Spatiotemporal Hypercube is deeply analyzed, and its mathematical model and theoretical basis are elaborated in detail. The fusion method of time and space dimensions in Spatiotemporal Hypercube is studied, and how to realize the comprehensive and accurate expression of battlefield information through this fusion is studied. The characteristics of Spatiotemporal Hypercube are analyzed in depth, including its high-dimensionality, dynamics, relevance, etc., and the influence and advantages of these characteristics on battlefield modeling are discussed.

(2) Design of battlefield modeling architecture based on Spatiotemporal Hypercube. The battlefield modeling architecture based on Spatiotemporal Hypercube is constructed, and the components and functions of each part of the architecture are clarified. The expression method of battlefield elements in Spatiotemporal Hypercube is studied in depth, including the s patio-temporal modeling of combat entities, combat operations, battlefield environment and other elements. The operation mechanism of the modeling architecture is analyzed, and how to realize real-time perception, analysis and prediction of battlefield situation and how to provide effective support for military decision-making are discussed.

(3) Research on key technologies of Spatiotemporal Hypercube battlefield modeling. The key technologies involved in the battlefield modeling process based on Spatiotemporal Hypercube are studied in depth, such as the acquisition and preprocessing technology of spatio-temporal data. How to obtain accurate battlefield spatio-temporal data from multi-source heterogeneous data and clean, transform and integrate it is studied. The storage and management technology of spatio-temporal data, explores the storage structure and management method suitable for the characteristics of Spatiotemporal Hypercube data, in order to improve the storage efficiency and query performance of data ; spatio-temporal data analysis and mining technology studies how to use data mining, machine learning and other methods to extract valuable information from massive spatio-temporal data to provide support for battlefield situation analysis and prediction.

2. Theoretical Basis of Spatiotemporal Hypercube

2.1 Concept and Composition

Based on the elastic and multi-scale spatio-temporal grid, the Spatiotemporal Hypercube is related to the battlefield elements of land, sea, air, fire, network and sky. The five-dimensional information of 'ontology dimension, space dimension, information dimension, combat dimension and time dimension' is comprehensively characterized to form the battlefield ' pixel ' unit. Through modular combination and building blocks, the digital battlefield is quickly formed. It is a high-dimensional data structure based on spatio-temporal unified modeling. It maps the entities, events and their interactions in the physical space into nodes and relationships in the spatio-temporal coordinate space. The core goal is to solve the fragmentation problem of traditional spatio-temporal data (real-time sea and air situation, etc.) and realize the deep integration of spatio-temporal dimension, semantics and attributes.

The Spatiotemporal Hypercube mainly includes five dimensions: ontology dimension, space dimension, information dimension, combat dimension and time dimension, as shown in Figure 1. The organic integration of time and space dimensions constructs a high-dimensional spatio-temporal framework. In this structure, each point represents the spatial position at a specific time and various attribute information related to it.

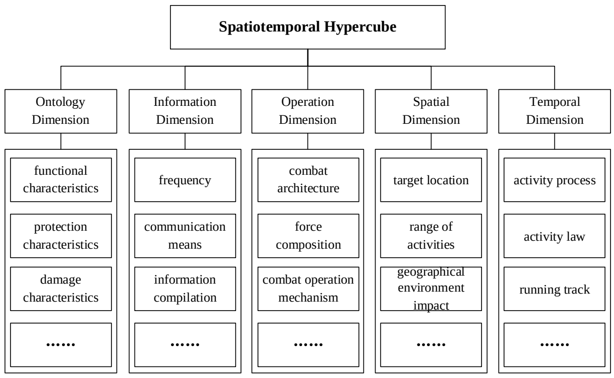

Figure 1. Composition of spatiotemporal hypercube.

The ontology dimension is mainly composed of the physical characteristics, functional characteristics, protection characteristics, damage characteristics, weapon mounting, tactical and technical performance of the space entity, which is mainly used to characterize the intrinsic attribute information of the entity in the battlefield space. The information dimension is mainly composed of frequency, communication means and information compilation, which is mainly used to characterize the information interaction attributes of battlefield space entities. The operation dimension is mainly composed of combat architecture, force composition, combat operation mechanism, combat system capability analysis (including combat system capability, failure mechanism, recovery mechanism, target value, strong and weak points, key nodes, etc.), threat analysis, damage analysis, capability analysis (including maneuverability, reconnaissance capability, strike capability, communication capability, etc.), which is mainly used to characterize the attributes related to the combat capability of battlefield space entities. The spatial dimension is mainly composed of information such as target location, target composition, range of

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activities, geographical environment impact, meteorological conditions impact, spatial distribution of limited avoidance strikes, and spatial networking association. It is mainly used to characterize the affected situation of battlefield entities. The temporal dimension is mainly composed of activity process, activity law, running track and other information, which is mainly used to characterize the battlefield entity attributes related to time.

2.2 Basic Characteristic

The Spatiotemporal Hypercube is high-dimensional, which can integrate multi-dimensional information and comprehensively describe the battlefield situation. In modern warfare, the battlefield situation involves many elements, including the location, type, quantity, action time, combat capability and so on. These elements are interrelated and influence each other. The high dimension of Spatiotemporal Hypercube makes it possible to incorporate these elements into a unified framework for analysis and mining the potential relationship between elements. Through the comprehensive analysis of the information of different combat units in multiple dimensions, the overall effectiveness of the combat system can be evaluated more accurately, the weak links in the combat system can be found, and the basis for optimizing the combat system can be provided.

The Spatiotemporal Hypercube has continuity and can smoothly describe the change process of battlefield elements with time and space. Various phenomena and events in the battlefield are continuously changing, and traditional models may have intermittent or inaccurate situations when dealing with these changes. The Spatiotemporal Hypercube can accurately capture the subtle changes of battlefield elements in the spatio-temporal dimension through its continuous spatio-temporal expression. When describing the maneuvering process of combat troops, the Spatiotemporal Hypercube can accurately show the position changes of the troops at different time points, as well as the changes of dynamic parameters such as speed and acceleration, and provide real-time and accurate intelligence support for combat command.

The Spatiotemporal Hypercube is also dynamic and can reflect the change of battlefield situation in real time. The battlefield situation of modern warfare is changing rapidly. Combat command needs to grasp the battlefield dynamics in time and make correct decisions. The Spatiotemporal Hypercube can receive and process battlefield data in real time, and update the model in real time according to the change of data, so as to quickly and accurately reflect the latest changes of battlefield situation. When the deployment of combat troops is adjusted, the Spatiotemporal Hypercube can quickly incorporate these changes into the model, provide commanders with the latest battlefield situation map, and help commanders adjust their combat plans in time to adapt to battlefield changes.

3. Design of Battlefield Modeling Architecture Based on Spatiotemporal Hypercube

3.1 Technical Framework

The battlefield modeling architecture based on Spatiotemporal Hypercube is mainly composed of data layer, model layer and application layer, as shown in Figure 2. Each part cooperates closely to realize the function of battlefield modeling.

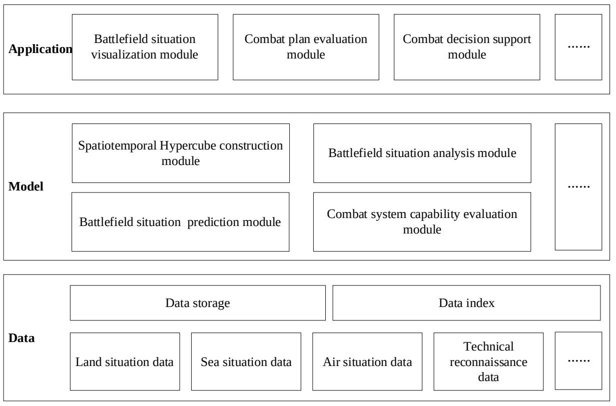

Figure 2. Technical framework of spatiotemporal hypercube.

The data layer is the basis of the whole architecture, which is responsible for collecting, storing and managing massive battlefield spatio-temporal data. It covers multi-source heterogeneous data sources, including battlefield situation data obtained from satellite reconnaissance, radar detection, intelligence personnel reports, etc., as well as environmental data such as terrain and meteorology. These data have different formats, accuracy and time frequency, and are integrated into the data layer through the data acquisition interface. The data layer uses distributed storage technologies, such as Hadoop Distributed File System (HDFS)[11-12], to ensure data reliability and efficient storage. At the same time, in order to improve the efficiency of data query and access, a spatio-temporal index, such as R-tree index[13-14], is also constructed to quickly locate and retrieve data in a specific spatio-temporal range.

The model layer is the core of the architecture, which is constructed based on the Spatiotemporal Hypercube model. It mainly includes Spatiotemporal Hypercube construction module, battlefield situation analysis and prediction module and combat system capability evaluation module. The Spatiotemporal Hypercube construction module is responsible for processing and converting the original data in the data layer to construct a Spatiotemporal Hypercube structure, which provides a unified data model for subsequent analysis and application. The battlefield situation analysis and prediction module is based on Spatiotemporal Hypercube, and uses data mining, machine learning and other algorithms to analyze and predict the battlefield situation in real time, mine the potential patterns and laws in the battlefield data, and provide decision-making basis for combat command. The combat system capability evaluation module evaluates the overall capability of the combat system and finds the advantages and disadvantages of the combat system by analyzing the elements of combat power and combat resources in the Spatiotemporal Hypercube.

The application layer provides intuitive and easy-to-use battlefield modeling application services for combat commanders and related decision-making departments. It includes battlefield situation visualization module, combat plan evaluation module and combat decision support module. The battlefield situation visualization module displays the results of model layer analysis and prediction in the form of intuitive graphics, charts, etc., such as three-dimensional battlefield situation map, dynamic trajectory map, etc., so that combat commanders can quickly and accurately understand the battlefield situation. The combat plan evaluation module simulates and evaluates different combat plans according to the data and models in the Spatiotemporal Hypercube, compares the advantages and disadvantages of each plan, and provides a reference for combat commanders to choose the best combat plan. The operational decision support module is based on the results of battlefield situation analysis and operational plan evaluation, combined with operational experience and expert knowledge, to provide decision-making suggestions and action plans for combat commanders, and assist them to make scientific and reasonable operational decisions.

3.2 Analysis of the Relationship between Layers

The data layer provides the original data support for the model layer. After the model layer obtains the data from the data layer, it processes and analyzes the data to generate the battlefield situation analysis results and prediction information. The application layer provides various application services for combat commanders based on the output of the model layer. The data flow and information interaction between different levels are closely related, forming an organic whole.

In terms of data flow, data flows from the data layer to the model layer, and then flows to the application layer after processing and analysis of the model layer. The original data in the data layer is processed by the Spatiotemporal Hypercube construction module and converted into the data of the Spatiotemporal Hypercube structure, which provides the data basis for the battlefield situation analysis and prediction module and the combat system capability evaluation module. The battlefield situation analysis and prediction module and the combat system capability evaluation module analyze and calculate the Spatiotemporal Hypercube data to generate battlefield situation analysis results, prediction information and combat system capability evaluation reports. These results are transmitted to the application layer to provide decision support for combat commanders.

In terms of information interaction, there is a two-way information interaction between the various levels. The application layer can send query and analysis requests to the model layer according to the needs of combat commanders. The model layer obtains the corresponding data from the data layer for processing and analysis according to the request, and returns the results to the application layer. When processing data and analyzing battlefield situation, the model layer may also need to request more data or update data from the data layer to ensure the accuracy and timeliness of the analysis results. The data layer manages and maintains the data according to the requirements of the model layer and the application layer, and updates and supplements the data in time to ensure the normal operation of the entire architecture. Through this kind of data flow and information interaction between levels, the battlefield modeling architecture based on Spatiotemporal Hypercube can achieve efficient and accurate battlefield modeling, provide strong support for operational command decision-making, and improve operational effectiveness.

3.3 Key Points of Battlefield Representation based on Spatiotemporal Hypercube

The Spatiotemporal Hypercube battlefield modeling architecture has unique points in the representation of space, time, and attribute relationships (including ontology, information, and Operation).

In terms of spatial representation, it can accurately express the multi-dimensional characteristics of battlefield space. It can not only describe the traditional three-dimensional physical space (length, width, height), but also cover land, sea, air, sky, electricity, network, sky and other multi-dimensional combat space. In describing the scene of a joint naval and air combat, the Spatiotemporal Hypercube can simultaneously express the position of the ship in the ocean, the flight trajectory of the fighter in the air, the electronic countermeasure area in the electromagnetic space, and the information transmission path in the cyberspace. Through the subdivision and integration of spatial dimensions, the distribution and activities of combat elements at different spatial levels and fields can be accurately presented.

In terms of time representation, Spatiotemporal Hypercube can effectively deal with the dynamic changes in the combat process and achieve high-precision characterization of time. It can record the occurrence time, duration and time sequence of combat events, accurate to seconds or even milliseconds. When analyzing the process of a battle, you can clearly show the sequence and time interval of each combat action, such as the time of the attack, the duration of the fire support, etc. Through the detailed expression of the time dimension, we can deeply study the evolution law of the battlefield situation with time, and provide real-time time reference for combat decision-making.

In terms of attribute relationship representation, Spatiotemporal Hypercube can fully describe various attribute information of combat elements. For combat entities, it not only includes its basic attributes (such as model, quantity, performance parameters, etc.), but also covers its dynamic attributes (combat, standby, damage, etc., position change speed, etc.). For battlefield environmental elements, attribute characterization can include terrain slope, vegetation coverage, meteorological temperature, wind speed, precipitation, etc. Through the comprehensive recording and analysis of attribute information, we can more accurately understand the characteristics and status of combat elements, and provide rich data support for combat analysis. At the same time, the Spatiotemporal Hypercube can clearly express the complex relationship between combat elements, including the command relationship, coordination relationship and confrontation relationship between combat entities, the execution relationship between combat operations and combat entities, and the interaction relationship between combat operations and battlefield environment. In the analysis of a multi-army joint operation, the Spatiotemporal Hypercube can intuitively show the cooperative combat relationship between the army, the navy and the air force, as well as the obstacle or promotion relationship of the battlefield environment (such as bad weather) to the combat action. Through the accurate representation of the relationship, we can deeply understand the internal mechanism of the formation of battlefield situation and provide the basis for optimizing the combat system.

4. Comparative analysis with traditional grid modelling methods

To comprehensively and objectively evaluate the performance and advantages of the battle modeling architecture based on spatiotemporal hypercube, a comparative analysis was conducted with traditional grid modeling.

Traditional grid modeling is a relatively classic and widely applied method in battlefield modeling. It divides the battlefield space into regular grid units, assigns corresponding attributes and states to each grid unit, and describes the battlefield situation through the analysis and calculation of grid units. This method played a significant role in early battlefield modeling and has certain representativeness. When studying the impact of regional terrain on combat operations, traditional grid modeling can divide the terrain into grids, assess the impact of terrain on troop mobility and weapon range by analyzing terrain attributes (such as slope, altitude) of each grid. It has the characteristics of simple principle and easy implementation. Many military simulation systems initially adopted this modeling method, and related technologies and tools are relatively mature, with a large number of application cases available for reference.

The research conducts a detailed comparison of the spatiotemporal hypercube and traditional grid modeling methods across multiple critical dimensions, including modeling accuracy, computational efficiency, and adaptability.
Modeling accuracy is one of the key indicators to evaluate the quality of battlefield modeling methods, directly impacting the accurate description and analysis of the battlefield situation. The modeling method based on the spatiotemporal hypercube, with its high dimensionality and continuity, can more accurately express the spatiotemporal characteristics and dynamic changes of battlefield elements. When describing the maneuvering process of combat units, the spatiotemporal hypercube can precisely display the changes in parameters such as the unit's position, speed, acceleration at different time points, as well as the relative positional relationship between units, through multidimensional information. Traditional grid modeling, due to discretizing the battlefield space into fixed-sized grid cells, has certain limitations in describing continuous changes in the battlefield situation, potentially leading to information loss or significant errors.

Computational efficiency is an important factor that battlefield modeling methods need to consider in practical applications. Due to the involvement of high-dimensional data processing and complex mathematical operations, the spatiotemporal hypercube has relatively large computational requirements and demands higher computing resources. In handling large-scale battlefield data, the construction and updating of the spatiotemporal hypercube model may take a longer time. Traditional grid modeling, with a relatively simple model structure, mainly focuses on attribute calculations and state updates of grid cells during the computation process, achieving higher computational efficiency and capable of completing the generation and updating of the battlefield model within a shorter time frame.

Adaptability refers to the ability of battlefield modeling methods to accommodate different battlefield environments and operational needs. Due to its high dimensionality and dynamism, the spatiotemporal hypercube can adjust its model structure and parameters in real-time according to changes in battlefield data, accurately reflecting the dynamic changes in the battlefield situation. Traditional grid modeling is relatively weaker in terms of adaptability. Since its grid division is fixed, it is difficult to flexibly adjust the model to meet different operational needs, resulting in less accurate simulation of unit maneuvers and combat actions.

5. Conclusions

This paper focuses on the in-depth study of battlefield modeling architecture based on Spatiotemporal Hypercube, and has achieved a series of important theoretical and practical results. At the theoretical level, the concept core of Spatiotemporal Hypercube is deeply analyzed, its mathematical principles and characteristics are systematically expounded, and the unique advantages of Spatiotemporal Hypercube in battlefield modeling are clarified. Spatiotemporal Hypercube can express complex spatio-temporal information comprehensively and accurately by integrating time and space dimensions to construct a high-dimensional spatio-temporal framework, which provides a solid theoretical basis for battlefield modeling. In terms of architecture design, the battlefield modeling architecture based on Spatiotemporal Hypercube is carefully constructed, and its overall framework design is elaborated in detail. In terms of comparative analysis, compared with the traditional grid modeling method, the Spatiotemporal Hypercube has obvious advantages in modeling accuracy and adaptability. It can describe the dynamic changes of battlefield situation more comprehensively and accurately, and better adapt to the complex and changeable battlefield environment and diversified operational requirements.

Although this paper has achieved some research results, some shortcomings have been found in the research process. In the future research, one is to strengthen the research on battlefield spatio-temporal data acquisition technology, improve the accuracy and integrity of data acquisition, and improve data quality. Secondly, the optimization method of model calculation efficiency is studied in depth to improve the real-time performance of the model. The third is to combine artificial intelligence and big data technology to further explore the potential value of battlefield data, improve the intelligent level of battlefield modeling, and provide more forward-looking and targeted support for operational command decision-making.

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