# Measurement Data Management System Based on Graph Computing

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**Abstract: Metering refers to activities carried out for achieving uniform unit, accurate and reliable measurement values. This study intends to explore the key technologies of a measurement data storage system based on graph computing, so as to address the challenges faced by traditional structured data architectures when processing massive, multi-dimensional, and diverse-format measurement data. The core contents of the study include: analyzing the quantity traceability system and the requirements of different measurement activity scenarios, researching and establishing a graph storage architecture for measurement data, and designing a GAS graph storage programming model with balanced computing load. Based on the measurement and testing data, measurement primary and standard data of our institute, research and design work such as data dictionary modeling, database scripting, and graphical user interface (GUI) development are carried out, and a digital interaction method for measurement data graph storage is formed. In addition, this report extracts a general data storage method suitable for thermal radiation measurement data and data storage during experiments, according to the data and structures defined in the existing technical specifications of the thermal radiation field. It also establishes a knowledge graph based on experimental data in the thermal radiation field, which is applicable to thermal radiation institutions for knowledge management and query during experimental work.**

**Keywords: Measurement Data; Storage System; Knowledge Graph Construction; Graph Visualization**

## 1. Introduction

Metering refers to activities carried out for achieving uniform unit, accurate and reliable measurement values. It serves as a crucial technical foundation for economic and social development, and an important support for building an integrated national strategic system and capacity. The data generated by these activities is massive, multi-dimensional and in diverse formats. With the transformation toward the quantization of the unit of measurement system and the flattening of quantity value transmission, digital transformations have also emerged in areas such as measurement standards, reference materials, digital maps of equipment, electronic original records, and digital certificates. Consequently, the output and accumulation of metrological data are showing a large-scale upward trend. However, the research and application in the informatization construction of China's metrological system still mainly rely on structured (SQL) data architecture as the underlying database. This leads to problems such as great difficulty and high cost in the management, cleaning, desensitization, and mining analysis of massive data, as well as widespread data isolation and low value of data utilization.[1]

This study analyzes the functional requirements of metrological traceability system and various metrological scenarios, and designs a graph-based structure for metrological data. Through the research on data partitioning, node identification and corresponding iterative functions, a GAS (Gather-Apply-Scatter) programming model is developed to achieve load balancing in graph computing. Based on the metrological testing data, metrological standard data, and metrological information data of our institute in the past five years, we have conducted research and design in areas such as data dictionary modeling, interactive response mechanisms, database scripts, and graphical user interfaces(GUI). This leads to the formation of a digital interaction method for metrological data graph storage that conforms to the quantity traceability system and quality management system, eliminating dependence on third-party software such as Excel. By establishing a new underlying metrological data storage system, this study provides a new approach and new ideas for solving problems in traditional structured storage modes of metrological data, such as high costs of analysis and mining, low efficiency of data collaboration, and difficulties in cross-industry applications.

With the development of experimental techniques, the types and quantities of experimental data on thermal radiation are rapidly increasing. However, effectively managing and analyzing these large-scale and complex experimental data has become a major challenge for researchers.

As an emerging data management and analysis tool, knowledge graphs offer a systematic and structured way of representing and processing complex knowledge systems.[2, 3]Using nodes and edges, knowledge graphs connect different entities (such as experimental equipment, materials, measurement parameters, etc.) and their relationships (such as data dependency relationships, etc.) to form a network structure. This representation not only enables the integration and management of multi-source heterogeneous data but also supports reasoning through relationships and attributes within the graph, thereby uncovering implicit knowledge and patterns.

In the field of thermal radiation, the construction of knowledge graphs can significantly improve the utilization efficiency and analytical capabilities of experimental data. Firstly, knowledge graphs can help researchers systematically organize and summarize experimental data, integrating scattered data points into a single graph for easier retrieval and querying. Secondly, by defining various entities and their relationships in experiments, knowledge graphs can clearly describe the experimental process and the semantics of data, making the meaning of data more explicit. Furthermore, knowledge graphs can also support knowledge-based reasoning and analysis, inferring new insights from existing data and relationships to uncover potential associations among data.

The purpose of this study is to construct a systematic knowledge graph based on experimental data in the field of thermal radiation, aiming to assist relevant research institutions in managing and analyzing experimental data more efficiently. To this end, we will provide specific implementation methods and technical solutions focusing on key steps such as entity recognition and relationship extraction, data integration, graph construction, storage, and visualization. Through the construction of the knowledge graph, we aim to significantly improve the level of experimental data management in the field of thermal radiation, promote data sharing and reuse, and enhance the efficiency and quality of research work. By constructing a knowledge graph based on experimental data in the field of thermal radiation, this report offers a new idea and method for research in related fields. We believe that the application of knowledge graph technology can effectively improve the ability to manage and analyze experimental data, and promote scientific research and technological progress in the field of thermal radiation.

The main contributions of this study are as follows:

(1) We develop a underlying management architecture for metrological data based on graph data structures, which aligns with both the measurement traceability and metrological work requirements.

(2) Based on metrological calibration scenarios, we design a graph-structured data interaction model and developed dedicated data interface tools, thereby eliminating reliance on third-party software.

## 2. Architecture Design of Metrological Data using Graph

### 2.1 Overview

2.1.1 Overall framework of the graph based metrological data

This paper analyzes the functional requirements of the quantity traceability system and different metrological activity scenarios, as well as the structural storage characteristics of the metrological data graph. Quantity traceability management requires managing the continuity and consistency of metrological standards to ensure the accuracy and reliability of quantity transmission; conducting regular or irregular stability assessments on metrological equipment to ensure the equipment maintains a stable working state for a long time; performing regular comparison work between metrological standards to verify the consistency and accuracy of the standards[4]; and formulating detailed verification procedures and calibration methods to ensure the accuracy of measuring instruments meets specified requirements.

Metrological data often involves multi-dimensional information, characterized by large volume and complex structure. Moreover, the relationships between different metrological activities can be represented by vectors, reflecting the interdependence and mutual influence among different activities. Different relationships vary in importance and need to be assigned different weights in the graph storage architecture to facilitate subsequent data analysis and mining. Considering the complexity of metrological testing data, in practical work, we need to classify, organize, and store the data. This includes managing original records to ensure the authenticity and integrity of the data; conducting structured processing on metrological data and constructing a data dictionary to support subsequent data analysis and mining work; developing a graphical user interface (GUI) to realize the direct mapping between user-input data and the underlying graph architecture database, simplifying the data entry process and improving work efficiency; and researching and writing database scripts to achieve persistent data storage and ensure data security and reliability.

To validate the advantages of the graph data storage structure, this study quantified I/O resource consumption, efficiency execution, and the time/space complexity of algorithms through theoretical analysis and code testing. We use theoretical models to predict the number and frequency of I/O operations and evaluate the impact of the graph data storage structure on disk reading/writing, memory access, and other aspects. Based on algorithm theory, we calculate the time complexity and space complexity of typical operations (such as query, insertion, and deletion) in the graph storage structure to assess its efficiency. We develop a test program to simulate graph data operations in real-world environments, including data loading, querying, and updating, while recording execution time and resource consumption. We collect data during the operation of the test program, and compare performance differences under different storage structures to evaluate the practical efficiency of the graph data storage structure.

To address the characteristics of metrological data, such as high concentration, vector-based node relationships, and significant differences in relationship weights, this study decomposed and abstracted the functional requirements of metrological calibration activity scenarios into a series of related data objects, including but not limited to metrological standards, reference materials, equipment, original records, and digital certificates firstly. This study adopted the RUP (Rational Unified Process) architecture and used the UML (Unified Modeling Language) to construct a logical view, so as to clarify the functional requirements of metrological calibration activities and improve the maintainability and scalability of the system. We adopt a distributed deployment strategy to study the impact of factors such as hardware and network on the reliability and scalability of the software architecture and draw a physical view and complete the RUP architecture design for metrological data graph storage , as shown in Figure 1.

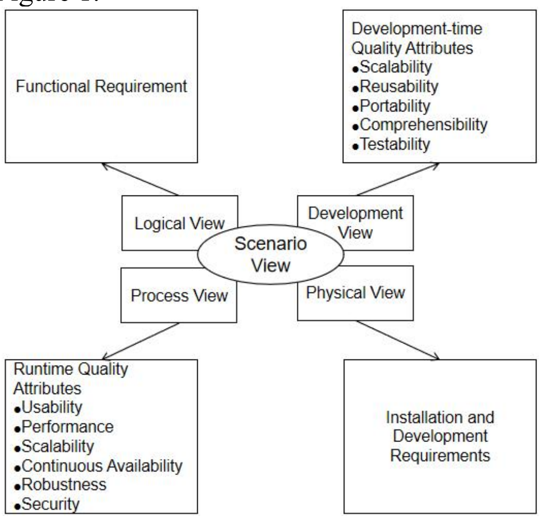


**Figure 1. Architecture View Model**

Centering on data carriers (original records), this study adopts a step-by-step expansion approach for conceptual structure design, abstracting the logic of metrological testing scenarios into a conceptual model independent of specific DBMS (Database Management Systems). By analyzing development-phase quality attributes of the model, such as scalability, reusability, and portability, we construct a development view to facilitate business logic invocation. Examples of such attribute analysis include: whether the model can easily add new metrological data types or new metrological activity scenarios, whether it can be used multiple times or reused across different metrological activities, and whether it can run on different hardware environments or operating systems.

This study analyzes the node attributes and weight assignment of metrological data in the graph storage architecture, examines operational characteristics of the data model such as usability, continuous availability, extensibility, and scalability, and conducts research to construct a processing view to support system integration testing. The research results show that a user-friendly interface and intuitive data presentation method improves the user experience; research on the distributed deployment strategy of the data storage architecture enhances the system's reliability and continuous availability. Through modular design and well-defined interfaces, the system can easily integrate new functions or services, supporting the system's extensibility. Through theoretical analysis and code testing, I/O resource consumption, efficiency execution, and the time/space complexity of algorithms are quantified, verifying the advancement of the graph data storage structure. These findings indicate that the designed data model and storage architecture possess excellent operational characteristics, which can adapt to data processing needs of different scales while ensuring the system's reliability and usability.

The knowledge graph processes data into knowledge. The overall framework of the data storage knowledge graph based on experimental data in the thermal radiation field is shown in Figure 2.

The data storage architecture, organized according to the data flow direction from bottom to top, consists of four layers: the Data Source Layer, the Knowledge Management Layer, the Knowledge Mining and Analysis Layer, and the Business Interaction Layer.

The data source layer is the initial source of data required for knowledge graph construction. It mainly consists of process data and result data recorded in industrial experiments in the thermal radiation field, where the data form is primarily structured data.

The knowledge management layer takes the data obtained from experiments as input and realizes effective management and efficient access to knowledge graph presentation results through modular processing such as graph data storage, data search, and metadata configuration management.

The knowledge mining and analysis layer uses technologies such as graph analysis, graph algorithms, and graph machine learning to form standardized graph analysis and mining conclusions with specific patterns, serving the subsequent construction of the business interaction layer.

The business interaction layer standardizes the results and processing formed by the knowledge mining and analysis layer into services that can be used by various terminals or other related systems, realizing the openness of measurement data storage and retrieval methods and technologies in the thermal engineering field.

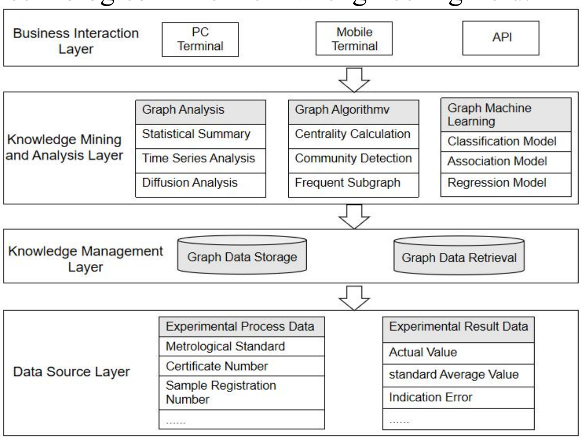


**Figure 2. Overall Framework of the Knowledge Graph for Data Storage**

2.1.2 Data storage process

A top-down approach is adopted to construct the data storage system for the thermal radiation metrology field, with specific steps shown in Figure 3.

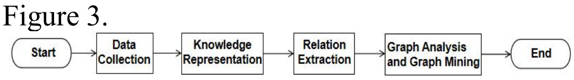


**Figure 3. Data Storage Flowchart**

Data files from paper forms, electronic forms, and databases are collected.[5] These files may contain various types of information, including serial numbers, metrological data, and instrument parameters. The primary goal of knowledge representation is to define the attributes of entities and the storage structure of data. It represents knowledge information in the thermal engineering field in a structured manner, making it suitable for the knowledge graph model. The goal of relationship extraction is to identify relationships between entities from data, establish connections between entities based on the associative relationships among data, and map these relationships to the knowledge graph model. Graph analysis and mining build analytical models and algorithmic mining models based on knowledge graph modeling and reasoning technologies.[6] It conducts in-depth mining of the knowledge graph, generates analytical and mining results, and supports the subsequent scenario construction in the thermal radiation metrology field.

2.1.3 Knowledge representation

Knowledge representation defines the entity types and relationship types included in the storage system for the field of thermal radiation metrology, specifies the attribute names required for various entities, and establishes constraints and rules. This data storage system comprises 6 entity types—inspection item, verification certificate, procedure, standard instrument, metrological standard, and detailed data, and 5 relationships: The procedures used, the standard instrument used, metrological standard used, inclusion, and detailed data relationship.

The inspection item entity includes attributes such as item name, identifier, procedure number, and metrological method. The identifier is used to uniquely identify an entity; the procedure number is used to establish a relationship with a procedure; and the metrological method is used to distinguish the type of verification certificate.

The verification certificate entity includes header information (e.g., inspection record name, verification location, ambient temperature, atmospheric pressure) and verification results. The verification results are stored in different fields depending on the inspection item. For example, when calibrating a radiation thermometer, the verification results include fields such as standard instrument average value, measured average value, indication error, and expanded uncertainty. This electronic certificate can replace traditional paper certificates, facilitating storage, transmission, and data utilization.

The procedure entity includes attributes such as procedure name, procedure number, implementation date, and revocation date.

The standard instrument entity includes attributes such as standard instrument name, identifier, equipment number, factory number, and model specification. The equipment number and factory number together uniquely identify a standard instrument.

The metrological standard entity includes attributes such as metrological standard name, metrological standard number, and metrological standard code. The metrological standard number and metrological standard code together uniquely identify a metrological standard.

The detailed data entity consists of process data and result data from item inspection, and can be used to guide production.

## 2.2 Processing of Graph based Metrological Data

2.2.1 Relationship extraction

This study utilizes E-R diagrams to transform connections between nodes (entities) into relational schemas. We analyze the attributes and weights of these relationship models, and design a data model supported by a graph-structured database. We also construct a processing view by analyzing indicators such as usability, performance, scalability, availability, and security. Meanwhile, we adopt a distributed deployment strategy for the metrological data graph architecture, examining the impact of hardware, network, and other factors on the reliability and scalability of the software architecture to form a physical view.[7]

The inspection item entity is associated with the procedure entity and the verification certificate entity. Among them, the verification certificate entity is associated with the standard instrument entity, the metrological standard entity, and the detailed data entity, as shown in Figure 4.

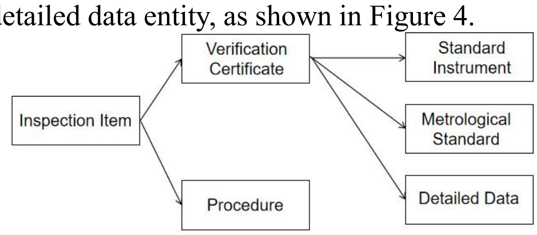


**Figure 4. Entity Relationship Diagram**

2.2.2 Data storage

Graph data storage includes entity data and relationship data; the storage method, whether distributed or single-machine shall be determined based on the scale of the data. The main factors to be considered for graph data storage are as follows:

(1) Logical division and physical storage isolation should be adopted for the database dimension;

(2) Each data shard have multiple replicas to ensure security, disaster recovery, and high availability requirements;

(3) The cluster data processing capability should be improved by upgrading the server hardware configuration or increasing the number of servers.

## 3. High-Performance Programming Model for Metrological Data Graph Storage

### 3.1 Using GAS Algorithm

3.1.1 GAS (Gather-Apply-Scatter) programming model

By classifying metrological activity scenarios and analyzing data structures, contents, and attributes, this study examines the relationships between nodes and edges and identifies the distribution patterns of the metrological data graph structure.[8]

This research adopts the vertex-centric programming model and integrates the design philosophy of "think like a graph" to analyze different metrological activity scenarios and their data utilization dimensions. This means that during the design process, the focus is not only on the behavior of individual nodes but also on the structure of the entire graph. Data partitioning is determined by understanding the overall characteristics of the graph, and master nodes and minor nodes for different partitions are designated. In practical applications, we design a GAS (Gather-Apply-Scatter) programming model for load balancing in metrological data graph computing to reduce the number of iterations required and the volume of messages generated during computation. The study identifies graph partitions, master nodes, and minor nodes in the vertex-cut graph. Based on the vertex-cut graph partitioning algorithm, intermediate results are computed using local partition information. Subsequently, all minor nodes send the intermediate results to the master node, which executes the iterative function and synchronizes the execution results back to the minor nodes. Finally, all master and minor nodes send their respective update results to the neighbor nodes within their partitions as shown in Figure 5.

```
def scatter(graph, node, message):
    for neighbor in graph.edges[node]:
        neighbor.receive_message(message)

def gather(node, message):
    node.messages.extend(message)

def apply(node):
    node.state = sum(node.messages)

messages = {}
for node in nodes:
    messages[node] = [random.randint(0,10) for _ in range(len(graph.edges[node.name]))]
    gather(node, messages[node])

for node in nodes:
    apply(node)
    print(f"Node {node.name} updated state to {node.state}")

for node in nodes:
    scatter(graph,node,node.state)
```

**Figure 5. Entity Relationship Diagram**

3.1.2 Centrality analysis

Centrality analysis aims to calculate and display the top K companies with the closest cooperation, the cities with the highest number of cooperations, and the top K technical bases and standard instruments in use. By analyzing the information of these companies, their needs and preferences can be better understood, thereby providing more targeted services in future cooperation.[9]At the same time, understanding the top K standard instruments used by these companies helps us grasp market trends and the popularization of technical standards. As key tools for quality control and measurement, the usage of standard instruments reflects the industry's acceptance and dependence on technical standards. By analyzing these data, current market demands can be evaluated, and product and service strategies can be adjusted to better meet customer needs as shown in Figure 6.

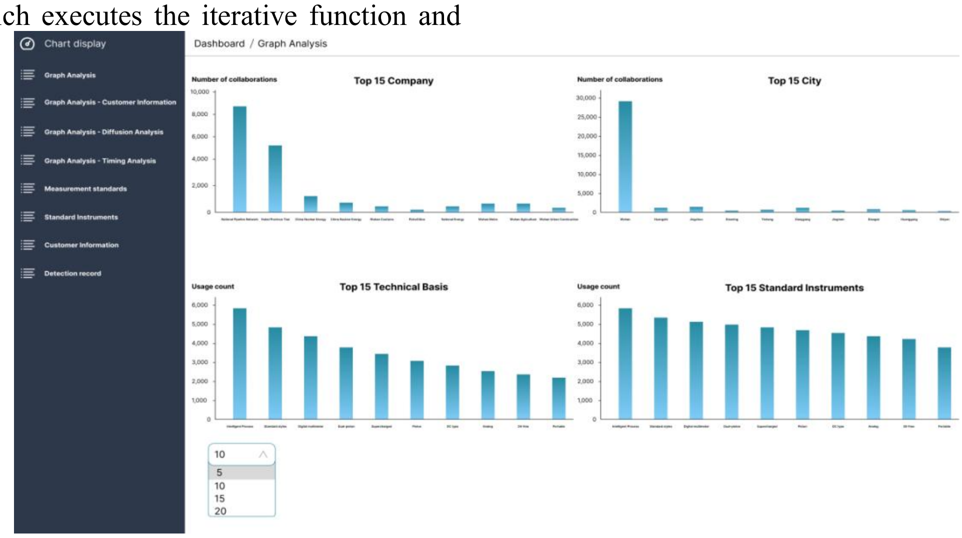


**Figure 6. TOP K companies**

3.1.3 Temporal analysis

Temporal analysis takes time as a sequence to statistically present the trends of certain data within a specific time period—for example, tracking the usage trends of standards over a period.[10] It also allows adjusting statistical results based on time and supports search by specified names.

Temporal analysis helps track the changing trends of data; through it, one can gain a comprehensive understanding of the dynamics of data changes over time as shown in Figure 7. Whether it is the usage frequency of standards, the number of corporate collaborations, or other key indicators, the statistical analysis and visualization of time series make it easy to clearly observe the fluctuations of these data across different periods. This is of great significance for analyzing market trends and predicting future developments. Time series analysis can identify seasonal changes and periodic fluctuations in data. For instance, the usage of certain standards may experience significant increases or decreases in specific seasons or years. Understanding these change patterns helps adjust market strategies and resource allocation at appropriate times to achieve optimal results.

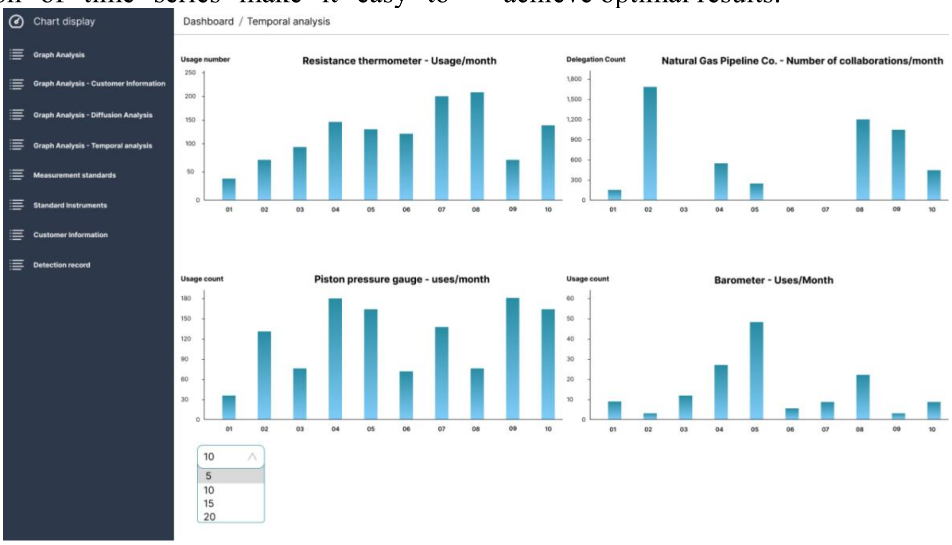


**Figure 7. Temporal Analysis**

## 3.2 Iterative Function Design for Optimization of Metrological Data

### 3.2.1 Iterative function design

In the point-centric model, messages sent by a node can only propagate to one-hop neighbors in a single iteration, which may result in a relatively large number of iterations required for the algorithm to reach a converged state. In each iteration of the subgraph-centric programming model, each node can utilize all graph structure information of the subgraph it belongs to and directly exchange information with all other nodes. A targeted iterative function (VertexProgram) is designed by combining the metrological business scenarios and the logic of the quantity traceability system. Through the iterative function, this study defines how nodes update their own states using received messages and send messages to other nodes to activate their computations. The computation reaches a converged state when all nodes stop sending messages.

### 3.2.2 Spatial analysis

Spatial analysis is used to display data distribution on maps, aiming to take space as a sequence to statistically present the trends of certain data in different regions. For data containing geographic location information in the database, summarized results are presented using heat maps to highlight variations across provinces.

Spatial analysis helps identify and analyze data differences across various regions, enabling a comprehensive understanding of the distribution and changes of data in different geographic areas.[11] This facilitates a better grasp of market demands and preferences in each region. For instance, there may be significant differences in the acceptance and usage frequency of certain standards among different regions. By analyzing data from different regions, more targeted regional market strategies can be formulated, and potential market opportunities and issues can be identified as shown in Figure 8. For example, understanding which regions use certain standards more frequently allows for concentrating resources on more in-depth marketing promotion and services in these areas; if the usage frequency of standards is low in some regions, it may indicate insufficient understanding of products or services in these regions, or the existence of other market barriers.

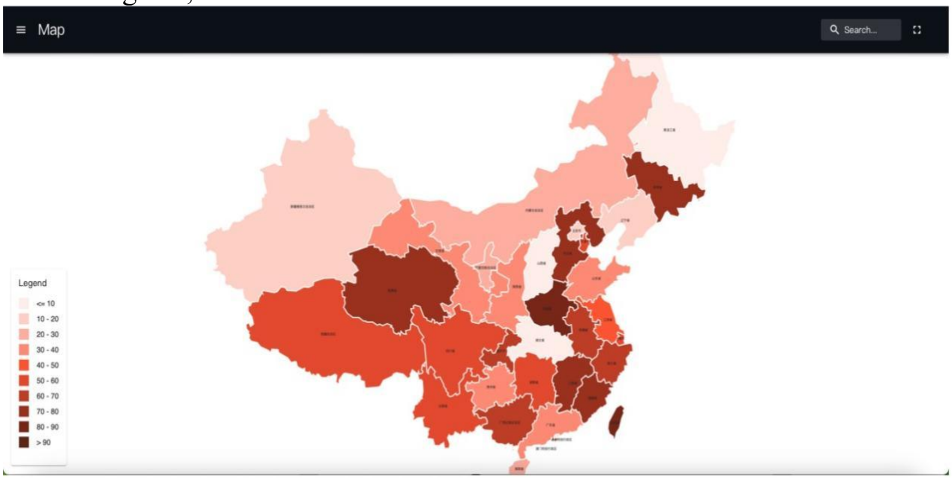


**Figure 8. Spatial Analysis**

## 4. Digital Interaction for Graph Based Metrological

### 4.1 Data Dictionary Modeling and Script Control

This study utilizes metrological testing data, reference standard data, and metrological information data from the past five years collected by the Hubei Institute of Measurement and Testing Technology, including original records generated during metrological testing processes and covering various types of metrological activities such as equipment calibration, reference material management, and data recording in testing processes. By analyzing the regularity and differences in the format and content of these original records, we extracts data features such as format consistency, data types, record integrity, and relational links.

In this study, the statistical data of original records is classified according to element attributes, and the controls are matched with the data dictionary definitions of the graph database to meet the format requirements of metrological testing data. We also design corresponding software drag-and-drop controls allowing users to select and place different controls on the interface as needed. we defined the mapping relationship between the controls and the data dictionary of the graph database, enabling user interactions on the interface to be directly mapped to the operations of the underlying graph database. Meanwhile, we design an intermediate container class and a layout manager to support the combined storage of controls and facilitate reuse.

Furthermore, A top-level container is designed to define the window framework and render the graphical interactive interface, providing users with a WYSIWYG (What You See Is What You Get) design effect. we designed an intermediate container class and a layout manager to store the controls created by users according to the original record format as a combined, reusable template. We also decoupled and isolated the controls from the data. This allows users to easily adjust the storage format and content of the graph database by modifying the original record controls, thereby addressing the issue of diverse and frequently changing original record formats. Finally, we define a response mechanism between window events and controls, and conduct UML modeling based on metrological testing business scenarios to draw class diagrams, sequence diagrams, collaboration diagrams, and more.

We use the Cypher language to write Database scripts, enabling the automatic writing of user-input data into the graph database. This hides the complexity of the data writing process and lowers the user operation threshold. Additionally, user control data is automatically written into the graph database, ensuring data accuracy and consistency. Through these steps, a data interaction method that complies with the quantity traceability system and quality management system is ultimately formed, allowing users to complete data entry and management without relying on third-party software such as Excel.

### 4.2 Experimental Data Management

The knowledge graph manages data in

 

experiments and enables create, read, update, and delete (CRUD) operations, thereby providing users with a comprehensive and flexible knowledge management tool. It plays an important role in fields such as data maintenance, information management and knowledge engineering.

Data management enables users to conveniently maintain and update the knowledge graph. Users can add new nodes and relationships, delete outdated or invalid data, and modify existing information as needed to maintain its accuracy and timeliness.[12] This flexibility ensures that the knowledge graph always reflects the latest knowledge and data, improving the efficiency and accuracy of information management. Data management supports a variety of complex operations to meet the needs of different scenarios. Users can perform batch data operations through a simple interface or API to realize large-scale knowledge graph construction and updates. For example, they can add multiple measurement standards, standard instruments, technical bases, and so on. In addition, the data query function allows users to quickly locate and obtain the required information. With efficient search and filtering tools, users can easily find specific nodes and relationships for in-depth analysis and application.

### 4.3 Knowledge Graph Visualization

The knowledge graph is presented in 3D. Through three-dimensional and interactive display, users can understand complex information networks more intuitively and comprehensively. Compared with traditional 2D graphs, the 3D representation spatializes nodes and relationships, making complex structures and connections more clearly visible. By rotating, zooming, and moving the graph, users can observe and analyze data from different perspectives, thereby gaining a deeper understanding.

The 3D knowledge graph enhances the interactivity of information. By clicking or hovering over specific nodes, users can view detailed information and related data; using the mouse wheel allows zooming, holding down a node enables dragging and dropping, and holding down an empty area allows panning of the image; clicking a node will highlight it and display detailed information about the node simultaneously. Various interaction methods make information presentation more dynamic and flexible, helping users discover new connections and knowledge points during exploration.

In addition, the system supports hierarchical visualization of data relationships by displaying modules in distinct colors according to their levels.[13] This allows users to easily examine nodes currently stored in the database, the connections between them, and concise node information, thereby facilitating a clear understanding of hierarchical relationships and structural organization within the data. There are four modes of the hierarchical structure diagram: top-down, left-to-right, radial structure, and ordinary 2D display structure, corresponding to Figures 9, 10, 11, and 12 respectively. With the continuous development and improvement of knowledge graph technology, we believe that its application in the thermal radiation field will become more extensive and deeper.[14]

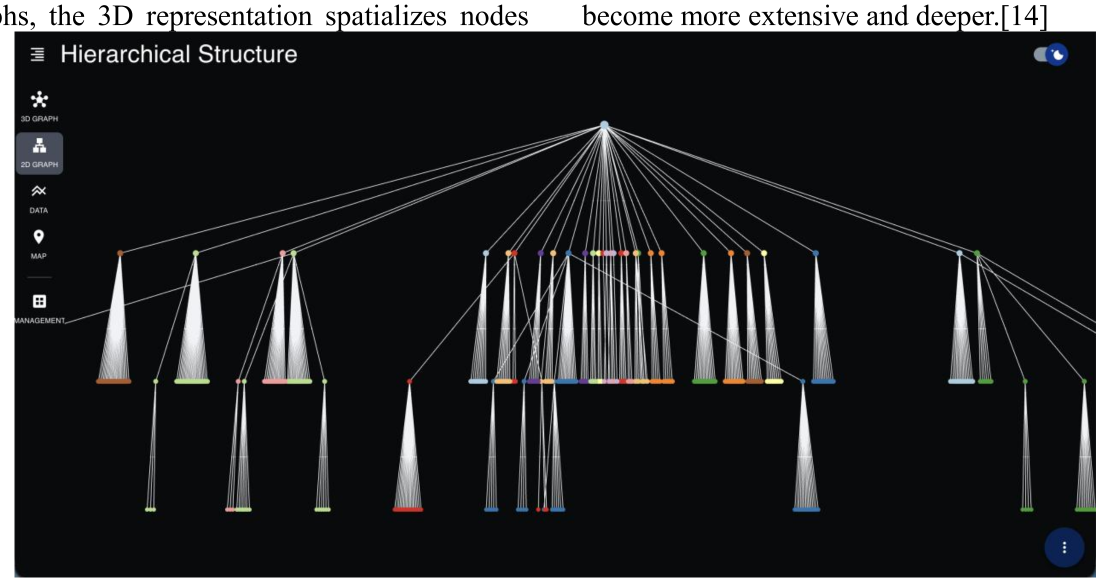


**Figure 9. Visualization Graph of Hierarchical Structure**

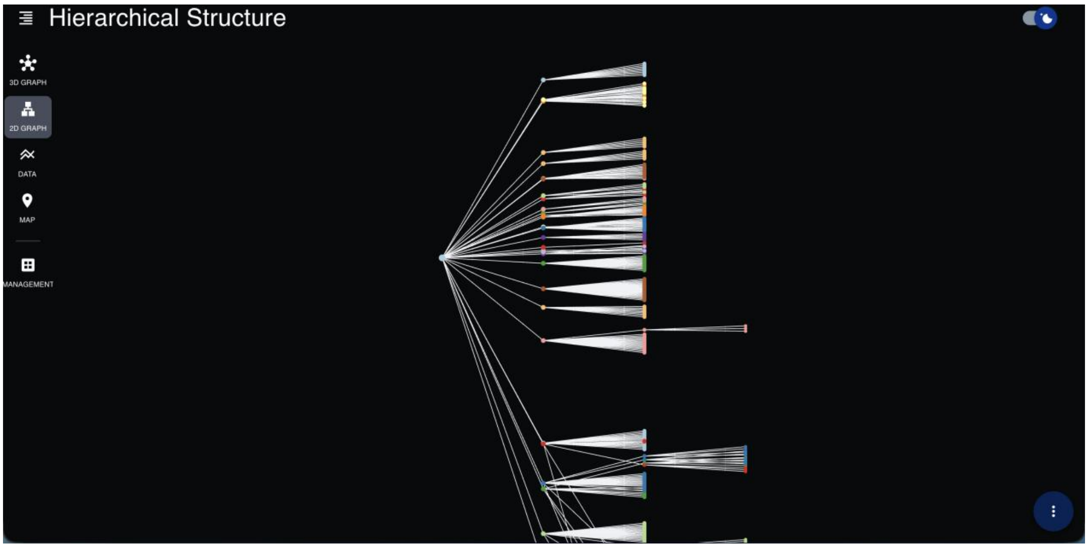


**Figure 10. Vertically Arranged Hierarchical Structure**

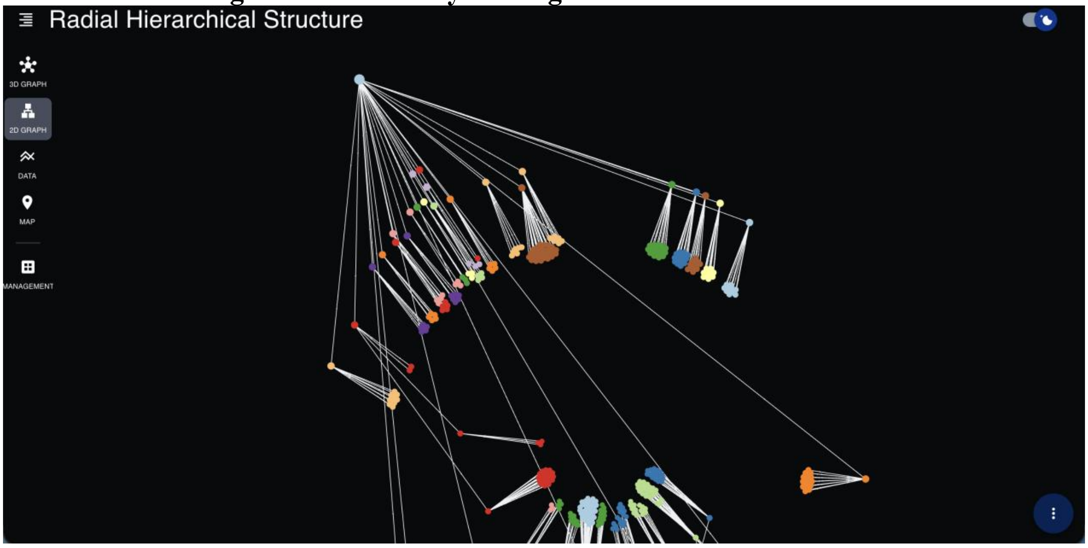


**Figure 11. Radial Hierarchical Structure**

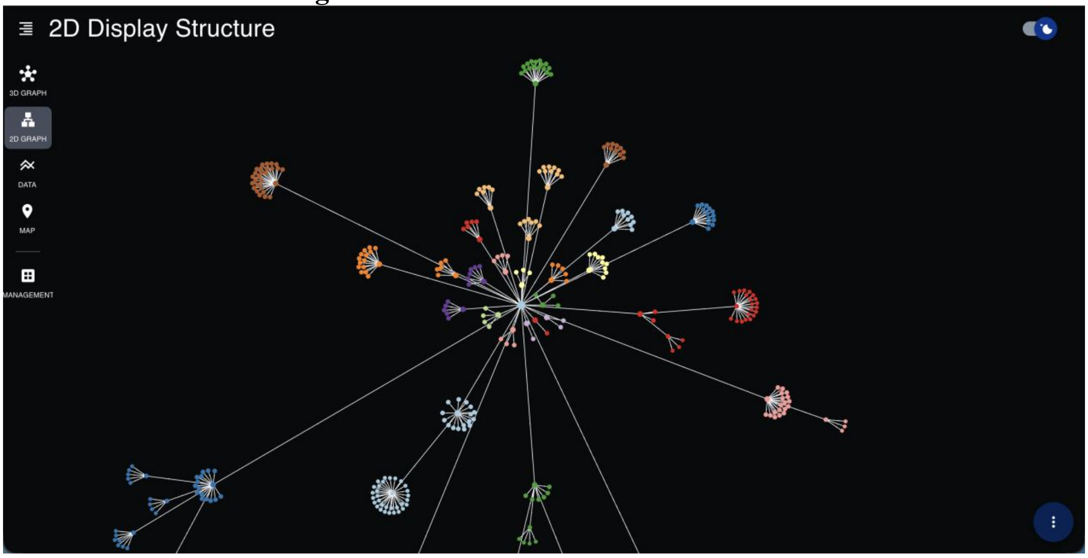


**Figure 12. 2D Display Structure**

## 5. Conclusion and Future Work

Based on the data and structures defined in the existing technical specifications for thermal radiation, this study systematically extracts and analyzes the general data storage methods applicable to thermal radiation metrological data and data storage during experimental processes, and successfully establish a knowledge graph based on experimental data in the thermal radiation field. Meanwhile, we implement knowledge graph visualization to assist researchers in efficiently conducting data query, analysis, and result presentation. Through a user-friendly interface, users can conveniently obtain the required experimental data and analysis results, which greatly improves work efficiency and research effectiveness.

This study demonstrates the application potential of knowledge graphs in the management and analysis of experimental data in the thermal radiation field. This achievement provides new ideas and methods for research in the thermal radiation field, and also serves as a reference for the construction of knowledge graphs in other similar fields. In the future, by continuously optimizing and expanding the knowledge graph, we can further improve the accuracy and efficiency of data management and analysis, and promote scientific research and technological progress in the thermal radiation field.

## References


[1] E. V. A. Martins, E. G. Machado, R. T. B. Gomes, W. S. Melo. Blockchain-based Architecture to Enhance Security in Distributed Measurement Systems. 2023 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE), Nadi, Fiji, 2023: 1-4. DOI:10.1109/CSDE59766.2023.10487656.

[2] Shaoxiong J, Shirui P, Erik C, Pekka M, Philip S Y, et al. A Survey on Knowledge Graphs: Representation, Acquisition and Applications, IEEE Transactions on Neural Networks and Learning Systems, 2022, 33(2): 494-514.

[3] Xuhui Jiang†, Chengjin Xu†, Yinghan Shen, Xun Sun, et al. On the Evolution of Knowledge Graphs: A Survey and Perspective. arXiv:2310.04835 [cs.AI], 2023 (submitted on 7 Oct 2023, last revised 21 May 2025, v3). https://doi.org/10.48550/arXiv.2310.04835.

[4] Hoffmann K, Kroke A, Klipstein-Grobusch K, Boeing H. Standardization of dietary intake measurements by nonlinear calibration using short-term reference data. Am J Epidemiol. 2002 Nov 1;156(9):862-70. doi: 10.1093/aje/kwf121. PMID: 12397005.

[5] Amanda A. Boatswain Jacques, Viacheslav I. Adamchuk, Jaesung Park, Guillaume Cloutier, James J. Clark, Connor Miller. Towards a Machine Vision-Based Yield Monitor for the Counting and Quality Mapping of Shallots. Frontiers in Robotics and AI (Front Robot AI), 2021, 8: 627067. DOI:10.3389/frobt.2021.627067.

[6] Penghe C, Yu L, Vincent W. Z, Xiyang C, Xiaoqing L. An automatic knowledge graph construction system for K-12 education. In Proceedings of the Fifth Annual ACM Conference on Learning at Scale (L@S '18), 2018, Article No.: 40, pp. 1-4. https://doi.org/10.1145/3231644.323169

[7] D. Menges, A. Rasheed, H. Martens, T. Pedersen. Real-Time Predictive Condition Monitoring Using Multivariate Data. IEEE Transactions on Image Processing, 2024, 33: 5703-5714. DOI:10.1109/TIP.2024.3468894.

[8] Andrea R, Denilson B, Donatella F, Antonio M, Paolo M, et al. Knowledge Graph Embedding for Link Prediction: A Comparative Analysis, ACM Transactions on Knowledge Discovery from Data, 2021, 15(2): 1-49.

[9] Qitian W, Hengrui Z, Xiaofeng G, Peng H, Paul W, Han G, Guihai C. Dual Graph Attention Networks for Deep Latent Representation of Multifaceted Social Effects in Recommender Systems. In Proceedings of The World Wide Web Conference (WWW '19), 2019, pp. 2091-2102. https://doi.org/10.1145/3308558.3313442

[10] F. Zhang, Z. Zhang, F. Zhuang, Y. Zhao, D. Wang, H. Zheng. Temporal Knowledge Graph Reasoning With Dynamic Memory Enhancement. IEEE Transactions on Knowledge and Data Engineering, 2024, 36 (11): 7115-7128. https://doi.org/10.1109/TKDE.2024.3390683

[11] Yuhao Y, Chao H, Lianghao X, Chenliang L, et al. Knowledge Graph Contrastive Learning for Recommendation, Annual International ACM SIGIR Conference on Research and Development in Information Retrieval, 2022

[12] Xiang W, Tinglin H, Dingxian W, Yancheng Y, Zhenguang L, Xiangnan H, Tat-Seng C, et al. Learning Intents behind Interactions with Knowledge Graph for

Recommendation, The Web Conference, 2021, abs/2102.07057: 878-887.

[13]Zongsheng C, Qianqian X, Zhiyong Y, Xiaochun C, Qingming H, et al. Dual Quaternion Knowledge Graph Embeddings, AAAI Conference on Artificial Intelligence, 2021, 35: 6894-6902.

[14]Shirui P, Linhao L, Yufei W, Chen C, Jiapu W, Xindong W. Unifying Large Language Models and Knowledge Graphs: A Roadmap. IEEE Transactions on Knowledge and Data Engineering (TKDE), 2024. arXiv:2306.08302v3. https://doi.org/10.48550/arXiv.2306.08302.

 