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Construction of Space Object Situation Information Service Based on Knowledge Graph

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ABSTRACT To effectively guarantee the safety and efficiency of space activities, and to meet the needs of different levels of users for space object situation (SOS) knowledge, formalized and standardized SOS knowledge is needed to assist cognition. A knowledge graph (KG), as a suitable technology that can formally express knowledge and construct a standardized knowledge base, can provide knowledge generation, representation and intelligent service of SOS. In this paper, an SOS information service based on the KG (SOSKG) was constructed. Aimed at different scales of components in SOS, a multi-granularity knowledge structure was constructed, and a formalized expression of SOSKG was realized. To incorporate the complex relations into the SOSKG, a multi-level semantic relation parsing model and formalized representation were proposed from the three aspects of basic relations, spatial relations, and temporal relations. Additionally, a multi-element knowledge construction model was constructed to address the dynamic characteristics of various relations in SOSKG under a complex spatio-temporal environment. This study constructed different cases and scenarios to test the service, and the results show that the proposed service can effectively organize and express SOS knowledge in a complex spatio-temporal environment, provide an intermediate bridge between users and SOS knowledge, and promote users' cognition of SOS knowledge.

INDEX TERMS Space object situation, information service, knowledge graph, semantic relation parsing, knowledge representation, dynamic spatial-temporal environment.

I. INTRODUCTION

The exploration and usage of space by countries around the world has led to the launch of various space objects, including artificial earth satellites, manned spacecraft, and deep-space exploration equipment. Advances in technology have also increased the potential for space objects in outer space to play greater roles in serving the different needs of various industries and people on earth. To maintain space interests, ensure space safety, and maximize the effectiveness of space objects, it is necessary to obtain the operating situation and trends of space objects; that is, the space object situation (SOS). Simultaneously, because various space objects mainly serve humans on earth, relations and effectiveness between space objects and ground objects must be obtained, while acquiring SOS information. Space objects constitute the main component of space activities; the recognition of SOS is the basis of various space activities [1], and is the premise and basis for effective and correct space decisions and actions [2]. Ground objects are also indispensable components of space objects' activities that must be studied extensively. Therefore, in this paper, SOS is mainly focused on space objects and related ground objects. Accordingly, obtaining the operational status and future trends of space objects and their various connections with ground objects is necessary.

However, because space objects are usually outside the earth's atmosphere with complex environmental factors and operate at a high speed in a predetermined orbit, their states and trends have complex spatio-temporal characteristics and various uncertainties, and their relations with ground objects are constantly changing. Therefore, simply obtaining original information about space objects is inconvenient for data management, storage and retrieval. This simplistic approach also makes it difficult for non-professional field personnel

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to obtain, understand, and recognize SOS, which hinders the popularization and dissemination of related disciplines and SOS knowledge to the public.

To facilitate the cognitive needs of users at different levels on SOS, it is necessary to complete the ''data-information-knowledge'' transformation process to reduce the understanding threshold of knowledge. To this end, data and information must be transformed into structured and formalized knowledge. A knowledge graph (KG) is a suitable technology that can formally express knowledge and build the standardized knowledge base [3]. In the field of artificial intelligence, KGs have been widely used and have yielded useful results. KGs can help humans interact with machines by constructing different semantic networks and providing functions such as intelligent search, machine translation, and machine understanding; these functions have greatly improved human life [4]. In professional fields, KGs can be used to provide knowledge generation, representation, and intelligent service.

To (i) transform the data and information of SOS into structured and formalized knowledge, (ii) construct a dynamic SOS knowledge service in a complex spatio-temporal background, (iii) provide a unified interface for users at different levels to acquire SOS knowledge, and (iv) improve users' cognitive level of SOS, this paper proposes an SOS information service based on the KG (SOSKG). The main contributions and work of this paper are as follows:

(a) A multi-granularity SOS knowledge structure is designed, and a formalized knowledge representation is constructed based on the analysis of related concepts of SOS;
(b) Starting from basic relations, spatial relations and temporal relations, a multi-level semantic relation parsing model is constructed, and a standardized description of space objects' relations is formed;
(c) A multi-element knowledge construction model is constructed for SOSKG;
(d) The proposed service is studied and tested by taking the information query of space objects, earth observations from remote sensing satellites, a signal acquisition of navigation satellites, and conjunction analysis as cases.

Based on this work, the ultimate goal of this study is to construct a KG-based SOS information service to promote the study of SOS and the distribution of SOS knowledge.

II. RELATED WORK

A. SPACE SITUATIONAL AWARENESS ONTOLOGY

Space situational awareness (SSA) is vital to maintaining space security and ensuring countries around the world can reap the benefits of space. SSA is defined as the current and predictive necessary knowledge of space events, threats, activities, situations, and the status and capabilities of various space systems. It can help commanders, decision makers and other participants in space activities to obtain space information and maintain its benefits [5]. With the continuing increase in number of space objects with different functions and purposes, the space environment will become increasingly complex, which will also lead to additional threats to space objects. Therefore, increasingly accurate and complete SSA information is urgently needed. To this end, different countries and organizations have raised the need for sharing SSA data and capabilities, as well as access to deeper information to ensure the security of space objects [6]. To meet these requirements, researchers have performed various studies on SSA based on ontology.

Rovetto [6] analyzed three different ontology architectures for space data and domain models and applied them to SSA to facilitate the management and sharing of various space object data and apply an applicable ontology, thereby providing a variety of possibilities for SSA data fusion. To promote the sharing of SSA data and reduce the threat posed by space debris to other space objects, Rovetto proposed a debris-oriented ontology architecture [7] and an SSA-oriented ontology [8]. The research results in the field of orbital environment ontology and SSA [9] were summarized to promote the development of global SSA in a more secure direction. Based on [7] and [8], Rovetto constructed a generalized ontology oriented to space objects, and provided taxonomies and definitions for them. Based on ongoing research, the Union of Concerned Scientists' (UCS) satellite ontology [10] was constructed based on the UCS satellite database, and the application of ontology to the European Space Agency (ESA) SSA project was taken as an example [11]. Rovetto researched the knowledge management of space data based on ontology, and analyzed the application of ontology in different fields of space science in detail [12]. In addition, Cox *et al.* [13] discussed the advantages of ontology over other methods of space object classification and multivariate data fusion and explained the advantages of ontology in improving and maintaining long-term SSA. Walls *et al.* [14] constructed an ontology-based space object behavior data management case and briefly explained the construction process.

SSA based on ontology can achieve more reliable results in data fusion, and provide suitable results for query statements constructed by professional users; these include structured query language (SQL) statements, or simple queries by non-professionals. However, these applications only complete the transformation of SOS data to SOS information, which cannot meet more complex query conditions, such as ''how many signals transmitted from Beidou navigation satellites can be received at the current position?''.

B. KNOWLEDGE GRAPH

1) OVERVIEW OF KNOWLEDGE GRAPH

The concept of KG, which is one of the basic technologies of intelligent services, was first proposed by Google in 2012. Since its introduction, KGs have played an important role in semantic search, intelligent question answering, intelligence analysis, decision support, etc. [15]. A KG describes the entities in an objective world, such as concepts, people, and objects and their relations through graphs, thereby composing a kind of knowledge base [16].

A KG usually consists of a data layer and a schema layer. The schema layer acts as the concept model and logical basis, which is usually implemented by ontology, and is used to constrain the data layer by rules and axioms. The data layer stores described facts in multiple tuples such as ''entity-relation-entity'' or ''entity-attribute-value'' to form a graph-like knowledge base. Each node in the graph represents an entity, and the relations between nodes or attributes of nodes are represented by edges.

Based on the various advantages and wide applications of KG technology, open KGs suitable for different fields have been constructed. Examples include English KGs such as DBpedia [17], Freebase [18], YAGO [19], Wikidata [20] and BabelNet [21]; and Chinese KGs such as Zhishi.me [22] and CN-DBpedia [23]. Simultaneously, the Chinese Open Knowledge Graph Alliance (OpenKG) was formed and established the OpenKG.CN platform [24] to promote the popularization and applications of KGs and semantic technologies by achieving the openness and interconnection of KG data. Based on these open KGs, various industry KGs that are applicable to different industries (such as finance, agriculture, geography, meteorology, medicine and education) have also been constructed. These include the Gene Ontology [25] and Traditional Chinese Medicine KG [26] for biomedicine, Crop Diseases and Insect Pests [27] for agriculture, FOAF for social relations [28] and KGs for social networks [29], GeoNames Ontology and GeoKG for geospatial big data [30], [31], OSM Semantic Network [32]–[34], transportation KG [35], [36], KGs for multimedia conferencing process management [37], etc.

2) APPLICATIONS OF KNOWLEDGE GRAPH

As an important part of artificial intelligence and an area of significant research interest in the field of information, KGs provide a superior ability to organize, manage, and understand semantic information. In general, the applications of KGs mainly fall within the following categories [15], [36], [38]:

(a) Semantic search. KGs have become the core of semantic search. Unlike traditional keyword-based search engines, search engines based on KGs, such as Google and Baidu, can analyze entities or concepts corresponding to keywords and provide users with structured and rich search results and related information, including keywords. For example, when a user searches for ''Beidou Navigation Satellite'', in addition to introducing the Beidou satellite navigation system, it can also obtain information on other global navigation systems, such as the United States' GPS, Russia's GLONASS navigation system, and the Galileo satellite positioning system of the European Union.

(b) Intelligent question answering. KG-based intelligent question answering can analyze questions in the form of natural language and find the required results from various related systems. As an advanced information retrieval method, the questioner does not need to have the professional knowledge or terminology. This improves problem-solving efficiency, lowers the threshold for acquiring knowledge, and reduces labor costs. KG-based intelligent question answering technology has been widely used in intelligent customer services and government affairs.

(c) Personalized recommendation. Different users have different requirements, and a KG can be used to analyze user preferences based on the user portrait and deliver relevant information that best meets their expectations. The most typical application scenario is product recommendation in e-commerce.

In general, KGs are large-scale, semantic-rich, high-quality, and structure-friendly. Simultaneously, based on its application in the organization, expression, and service of knowledge, it is well suited to the knowledge service construction of SOS. However, all kinds of objects and corresponding relations in SOS are in high-speed dynamic changes under the complex spatial-temporal environment, the existing general and domain KGs are mainly focusing on static objects and their relations, and cannot be easily applied to SOS. Therefore, it is necessary to perform information extraction, relation calculation, and knowledge organization on various structured, semi-structured, and unstructured data, before using a KG to realize the integration and semantic interaction of SOS information. An SOS information service constructed based on the KG assists users of various levels in acquiring SOS data, information, and knowledge.

III. FRAMEWORK OF SOSKG

The SOSKG proposed in this paper is shown in FIGURE 1. First, through the collection of SOS data and information, various data are stored in different types of databases. The related concepts in SOS are then obtained, and mapping between concepts and the data is established. The multi-level semantic relation parsing model is used to obtain the semantic relations between entities, concepts, attributes and other factors in SOS. Finally, a multi-element knowledge construction model is used to construct the formalization, categorization, or representation knowledge in SOS to realize the service based on the KG. The knowledge based on the KG can be understood more effectively and easily by users than unorganized or quantitative results.

Concepts, entities, and attributes can be acquired and organized in SOS after acquiring relevant data and information using expert knowledge and through combining related content proposed or constructed by different scholars in the process of constructing SOS-related ontology.

As an essential part of the KG, the relations between concepts, entities, and attributes are crucial. The various quantitative relations obtained through analysis and calculation are not easy for users to comprehend. Therefore, this paper constructs a multi-level semantic relation parsing model to obtain the relations and corresponding semantic representations

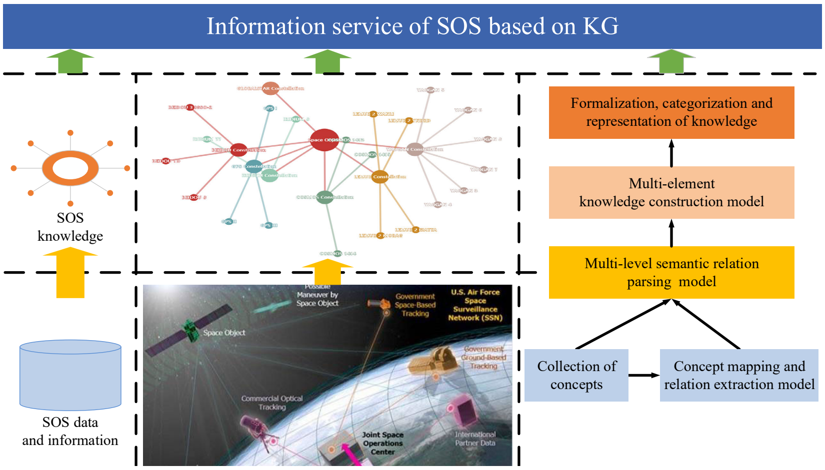


FIGURE 1. **Framework of SOSKG.**

in SOS. Simultaneously, because space objects constantly perform various activities in a complex spatial-temporal environment, various relations in SOS are extremely complicated and constantly changing. To obtain relevant knowledge and scenarios, this study builds a multi-element knowledge construction model to obtain various static and dynamic relations in SOS, and describes them quantitatively or qualitatively through mappings with semantics.

The main purpose of constructing SOSKG is to provide users with an SOS knowledge service that meets diverse needs, and with various static and dynamic data and information related to the query demands to the greatest possible extent. The service provides users with an intuitively three-dimensional (3D) scene and an easy-to-understand KG.

A. MULTI-GRANULARITY KNOWLEDGE STRUCTURE OF SOSKG

Space objects operate in outer space and connect with various ground objects on the earth (e.g., ground stations, people, moving vehicles). These interactions result in complex and variable changes of concepts, entities, and relations in SOS. Among the research targets of SOS, there are both indivisible fine-grained objects and comprehensive coarse-grained knowledge. The fine-grained objects include the North American Aerospace Defense Command catalog number (NORAD ID), dry mass, sensor type, and ground station position. The coarse-grained knowledge includes the space environment, satellite constellations, ground objects, and so on. These objects render it impossible to describe and understand SOS with a single granularity when constructing the SOSKG. Understanding the world from different levels is a cognitive mechanism inherent in humans [39]. Therefore, as shown in FIGURE 2, by studying the multi-granularity related content [35], [40], [41], this study proposes a multi-granularity knowledge structure to realize a description of data, information, and knowledge at different scales in SOSKG. The multi-granularity knowledge structure of SOSKG includes

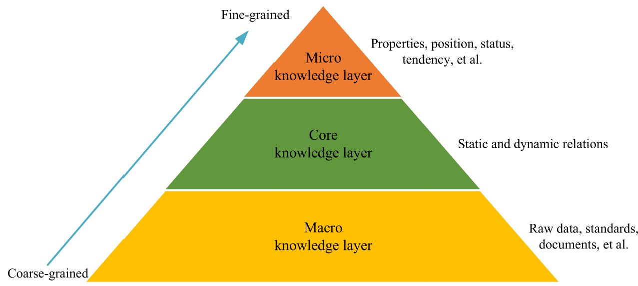


FIGURE 2. **Multi-granularity knowledge structure of SOSKG.**

a macro knowledge layer, core knowledge layer and micro knowledge layer, each being interconnected. The granularity gradually decreases from the macro layer to the micro layer, and the coarse knowledge layer provides support for the fine knowledge layer. The descriptions and interrelations of various layers are as follows:

1) MACRO KNOWLEDGE LAYER

The information on SOS in the macro knowledge layer is coarse-grained and can be represented by (1). This layer represents the raw data obtained from various data sources and contains the description, specification, and constraints of SOS from various countries, organizations, or individuals. It mainly includes raw data, related technical reports, and standards of SOS. The information in these files is linked by NORAD ID, international number, or the space object's name.

$$G_{macro} = \{G_{macro}^1, G_{macro}^2, \ldots, G_{macro}^i, \ldots, G_{macro}^n\}, \quad (1)$$

where G_{macro} represents the macro knowledge, G_{macro}^i represents a component of macro knowledge, and $1 \leq i \leq n$.

2) CORE KNOWLEDGE LAYER

The granularity of information in the core knowledge layer is between coarse-grained and fine-grained information and can be represented by (2). The information in the core knowledge layer is obtained through the process of extraction and calculation from the macro knowledge layer. This knowledge includes various relations between physical objects and attributes in SOS, such as basic relations, spatial relations, and temporal relations.

$$G_{core} = \{G_{core}^1, G_{core}^2, \ldots, G_{core}^i, \ldots, G_{core}^n\}, \quad (2)$$

where G_{core} represents the core knowledge, G_{core}^i represents a component of core knowledge, and $1 \leq i \leq n$.

3) MICRO KNOWLEDGE LAYER

The information in the micro knowledge layer is fine-grained and can be represented by (3). These data include the attribute information, ephemeris data, and operating status, which can be directly obtained. Through this information, the fixed detailed description information, such as the life period, design specification, and function, can be obtained, as well as the position and status of space objects.

$$G_{micro} = \{G_{micro}^1, G_{micro}^2, \ldots, G_{micro}^i, \ldots, G_{micro}^n\}, \quad (3)$$

where G_{micro} represents the micro knowledge, G_{micro}^i represents a component of micro knowledge, and $1 \leq i \leq n$.

B. RELATED CONCEPTS AND FORMALIZED REPRESENTATIONS OF SOSKG

To construct SOSKG, in addition to the necessary data, the concepts, entities, and relations that exist in SOS must be clarified. On this basis, a multi-level semantic relation parsing model and multi-element knowledge construction model are proposed. The concepts, entities, and relations in SOS must meet the needs of different levels of users for SOS knowledge, and the description of SOS constructed in this paper can be expressed as:

$$D_{SOS} = \{D_O, D_A, D_R, D_S, D_T\}, \quad (4)$$

where D_{SOS} represents a five-tuple representing SOS; D_O represents a collection of all entities in SOS, which include space object entities, ground object entities, etc.; D_A is the attributes of D_O; and D_R represents the description of relations between entities and attributes. The changes in entities, attributes, and relations of space objects are not convincing if the spatial and temporal factors are not considered. D_S and D_T represent the spatial and temporal factors, respectively, of various entities, attributes, and relations in SOS. The entity corresponding to each tuple in D_{SOS} can be expressed in (5), and some cases of concepts and entities are shown in TABLE 1.

$$I_{SOS} = \{I_O, I_A, I_R, I_S, I_T\}. \quad (5)$$

IV. MULTI-LEVEL SEMANTIC RELATION PARSING MODEL FOR SOSKG

After obtaining the related concepts and standardized representations in SOSKG, the relations between concepts and entities must be established, which is an important part of the KG. In focusing on different types of objects, different structures of data, and different granularity of knowledge in SOS, this study builds a multi-level semantic relation parsing model for SOSKG to achieve the semantic parsing of data and information on different scales in SOS, achieve the "data-information-knowledge" transformation of SOS, and complete the transformation to semantic knowledge.

TABLE 1. Cases of concepts and entities in SOS (part).

Concept	Sub-concept	Instance
Object (*O*)	Satellite	BEIDOU 16
Attribute (*A*)	Physical attribute	800 kg
Relation (*R*)	Orientation relation	Right forward
Space (*S*)	Satellite position	(4375, 3499, 3983) km
Time (*T*)	Time instant	2019-11-01 00:00:00

A. BASIC SEMANTIC RELATIONS OF SOSKG

Basic semantic relations, which can be directly obtained from the original data, are mainly used to describe the relations between concepts, attributes and instances in SOS. These relations are also the basis for the subsequent establishment and acquisition of various space object relations. With the assistance of various databases and experts, the main basic semantic relations in SOS include:

(a) *kind_of*: Used to describe the hierarchical relation between concepts and between attributes. For example, a geosynchronous-orbit (GEO) satellite is a sub-concept of satellite concepts, and a physical attribute is a sub-concept of attributes;

(b) *attribute_of*: Used to describe the relation between attributes and concepts, such as a physical attribute being an attribute of satellites;

(c) *instance_of*: Used to describe the relation between concepts and instances, and betweenattributes and instances. For example, BEIDOU 16 is an instance of satellites, and 2300 kg is an instance of the weight attribute;

(d) *has_a_x*: Used to describe the relation between concepts, attributes, or instances. x represents different concepts, attributes, or instances. For example, the weight attribute of BEIDOU 16 is 2300 kg, which can be expressed as:

$$\text{(BEIDOU 16) } has\_a\_weight \text{ (2300 kg)} \quad (6)$$

(e) *y_by*: Used to describe different affiliation relations between concepts. Terms such as *owned*, *operated*, and *launched* can be used. For example, BEIDOU 16 is owned by China and can be expressed as:

$$\text{(BEIDOU 16) } owned\_by \text{ (China)} \quad (7)$$

B. SPATIAL SEMANTIC RELATIONS OF SOSKG

Basic semantic relations cannot meet the complex needs of users, and there are more complex spatial relations between

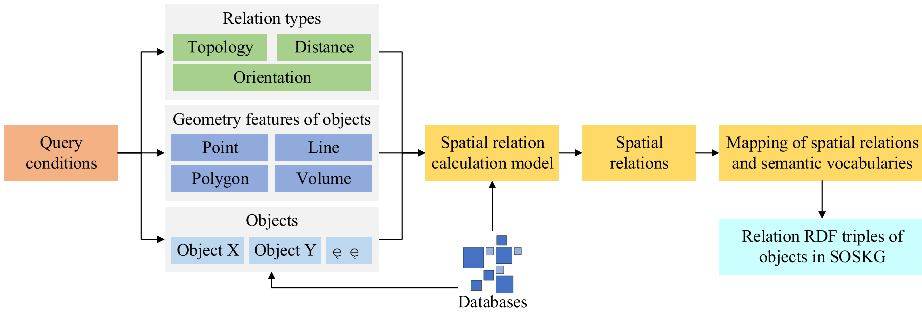


FIGURE 3. Process flow of spatial semantic relations in SOSKG.

space objects and ground objects. In outer space, a space object not only needs to cooperate with other space objects to complete complex tasks, but must also avoid threats such as collisions, this process should be controlled by ground objects. Simultaneously, an important task of space objects is to serve various objects on earth, so establishing effective and perfect links with ground objects is vital to space objects. The relations between space objects and ground objects is the focus in SOS; thus, to satisfy the cognition of various spatial relations, the relations need to be converted into content that users can easily understand. Therefore, it is necessary to construct semantic spatial relations.

The process flow of space semantic relations in SOSKG is shown in FIGURE 3. The judgment of spatial relations can be made only after the geometric features of the objects are determined. Therefore, through the query conditions, in addition to obtaining the entities from the database that are used to calculate the spatial relations, it is also necessary to specify the geometric features of different entities. After clarifying the objects and the geometric features, through combining the data in the database, the calculation model is used to obtain different types of spatial relations. By establishing the mapping between quantitative spatial relation expressions and qualitative semantic descriptions, the construction of spatial relation RDF tuples of space objects is achieved, and the basic form is shown in (8).

$$D_R^{Type} = \{ObjectX, ObjectY, Type, SemanticVocabulary\}, \quad (8)$$

where D_R^{Type} indicates that the spatial relation type between *ObjectX* and *ObjectY* is *SemanticVocabulary*. *SemanticVocabulary* includes the spatial topology, spatial orientation, and spatial distance relations. Through (8), the spatial relation between objects in SOSKG can be described using "The *Type* between *ObjectX* and *ObjectY* is *SemanticVocabulary*".

The spatial relations between space objects, or between space objects and ground objects, undergo dynamic changes, and calculations must be performed according to different conditions. The spatial relations studied in this paper mainly include topology, orientation, and distance relations. These spatial relations are dynamic and exist between space objects (such as remote sensing satellites and data relay satellites), between ground objects (such as the ground coverage area of remote sensing satellites and cities) and between space objects and ground objects (such as navigation satellites and signal receiving stations).

1) SPATIAL TOPOLOGY RELATIONS

When the distance between the space objects is lower than a certain threshold, a significant collision risk is involved. Therefore, within a certain distance, an ellipsoidal sphere (ES) must be constructed as a safety space for space objects.

When the ESs of two space objects are tangential, intersecting, or overlapping, the collision probability is high; otherwise, the collision probability is low. When the distance is large, the topology relation between spatial objects is essentially the topology relation between points; when the distance is small, it is essentially the topology relation between the ES of space objects.

In addition to the topology relation between space objects, the topology relations between ground objects (ground stations, mobile devices, and so on) and space objects are usually disjoint. However, the most important connection between ground objects and space objects, which is also the aspect of highest concern for users, is the relation between ground objects and the coverage area of space objects on the ground. Examples include the topology relation between the ground coverage area of a remote sensing satellite and Zhengzhou, a city of China, or the topology relation between signals transmitted from Beidou navigation satellites and users.

In SOS, the geometric features of objects at different scales include points, lines, planes, and volumes. For example, a space object can be considered as a point when calculating distance, the moving trajectory of a space object as a line, the ground coverage area of a remote sensing satellite as a plane, and the ES as a volume. The topology relation in SOS is in 3D space, and to facilitate the calculation, this paper uses the widely used nine-intersection model (9IM) [42] to express the topology relations between different objects in SOS, as shown in (9):

$$T(A,B) = \begin{bmatrix} A^\circ \cap B^\circ & A^\circ \cap \partial B & A^\circ \cap B^- \\ \partial A \cap B^\circ & \partial A \cap \partial B & \partial A \cap B^- \\ A^- \cap B^\circ & A^- \cap \partial B & A^- \cap B^- \end{bmatrix}, \quad (9)$$

where A and B represent two objects with geometric features including point, line, plane, and volume; A° and B° represent the insides of the objects; ∂A and ∂B represent the edges of the objects; A^{-} and B^{-} represent the outsides of the objects. The results of the elements in (9) can be 0 or 1 according to different combinations. The correspondence between spatial topology relations and semantic descriptions [43], [44] from (9) is shown in TABLE 2.

TABLE 2. **Descriptions and representations of topology relations in SOSKG.**

Semantic description	9IM matrix	Semantic description	9IM matrix
(a) Disjoint	$\begin{bmatrix}0&0&1\\0&0&1\\1&1&1\end{bmatrix}$	(b) Meet	$\begin{bmatrix}0&0&1\\0&1&1\\1&1&1\end{bmatrix}$
(c) Overlap	$\begin{bmatrix}1&1&1\\1&1&1\\1&1&1\end{bmatrix}$	(d) Cover	$\begin{bmatrix}1&1&1\\0&1&1\\0&0&1\end{bmatrix}$
(e) Contain	$\begin{bmatrix}1&1&1\\0&0&1\\0&0&1\end{bmatrix}$	(f) Equal	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$
(g) CoveredBy	$\begin{bmatrix}1&0&0\\1&1&0\\1&1&1\end{bmatrix}$	(h) Inside	$\begin{bmatrix}1&0&0\\1&0&0\\1&1&1\end{bmatrix}$

The topology relations in SOSKG can be obtained using the correspondences between the 9IM matrix and the semantic descriptions in TABLE 2. However, due to different applications and requirements, the same topology relation can usually be described using different vocabularies. For example, *meet* can be described using *intersect*, *cross*, etc. To describe spatial topology relations in different scenarios more accurately, it is necessary to build mappings between topology relations and corresponding semantic vocabularies, as shown in TABLE 3. TABLE 4 shows the partial correspondences between factual scenarios, topology relations, and semantic representations in SOSKG.

TABLE 3. **Mapping examples of spatial topology and semantics in SOSKG (part).**

Object A	Object B	Geometry features	Topological type	Relations vocabulary
Satellite	Satellite	Volume-Volume	Overlap	Overlap, intersect, cross, join, include, …
Satellite	Station	Point-Volume	Inside	Inside, observe, in sight, into view, …
Ground coverage	Person	Plane-Point	Disjoint	Disjoint, no signal, far away from, apart from, divide, …

2) SPATIAL ORIENTATION RELATIONS

The various space objects in SOS have high motion in outer space, so it is impossible to describe the orientation relations between objects according to geographical orientations such as east, south, west, and north. To establish the relative orientation relations between different types of objects in SOS, this article uses various methods to describe relations according to reference objects. These relations can be divided into spatial orientation relative to space objects and relative to ground objects.

a: SPATIAL ORIENTATION RELATIVE TO SPACE OBJECTS

As shown in FIGURE 4, point S represents the space object, and point D represents the space object or ground object. O-XYZ uses the centroid of S as the origin of the coordinate system, the X-axis is the motion direction of S, and the Z-axis is located in the orbital plane, which is perpendicular to the X-axis and is positive away from the earth. The Y-axis is obtained by cross-multiplying the X-axis and Z-axis. $\boldsymbol{SD}$ is the vector from S to D, and $\boldsymbol{SW}$ is the projection of $\boldsymbol{SD}$ on the XOY plane. The azimuth A is defined as the angle from the positive direction of X-axis to $\boldsymbol{SW}$ clockwise, ranging from 0° to 360°; the pitch P is defined as the angle between $\boldsymbol{SD}$ and the XOY plane, ranging from −90° to 90°, and pointing along the Z-axis is positive and in the other direction is negative. We use (x_S, y_S, z_S) and (vx_S, vy_S, vz_S) to represent the position and velocity of S, and (x_D, y_D, z_D) and (vx_D, vy_D, vz_D) to represent the position and velocity of D; then, A and P of D relative to S can be expressed by (10) and (11), respectively.

$$A = \begin{cases} \arccos(\dfrac{\boldsymbol{SW}\cdot\boldsymbol{X}}{|\boldsymbol{SW}|\,|\boldsymbol{X}|}), & 0 \le \omega \le \pi/2 \\ 2\pi - \arccos(\dfrac{\boldsymbol{SW}\cdot\boldsymbol{X}}{|\boldsymbol{SW}|\,|\boldsymbol{X}|}), & \pi/2 < \omega \le \pi, \end{cases} \tag{10}$$

$$P = \frac{\pi}{2} - \arccos(\frac{\boldsymbol{Z}\cdot\boldsymbol{SD}}{|\boldsymbol{Z}|\,|\boldsymbol{SD}|}), \tag{11}$$

where $\boldsymbol{X}$, $\boldsymbol{Y}$ and $\boldsymbol{Z}$ are the positive direction of the X-axis, Y-axis and Z-axis respectively, $\boldsymbol{SW} = \boldsymbol{SD} - \cos(P)\,|\boldsymbol{SD}|\cdot\boldsymbol{Z}$, and $\omega = \arccos(\frac{\boldsymbol{SW}\cdot\boldsymbol{Y}}{|\boldsymbol{SW}||\boldsymbol{Y}|})$.

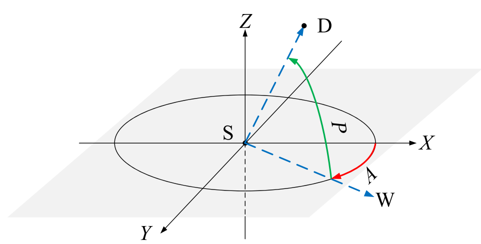


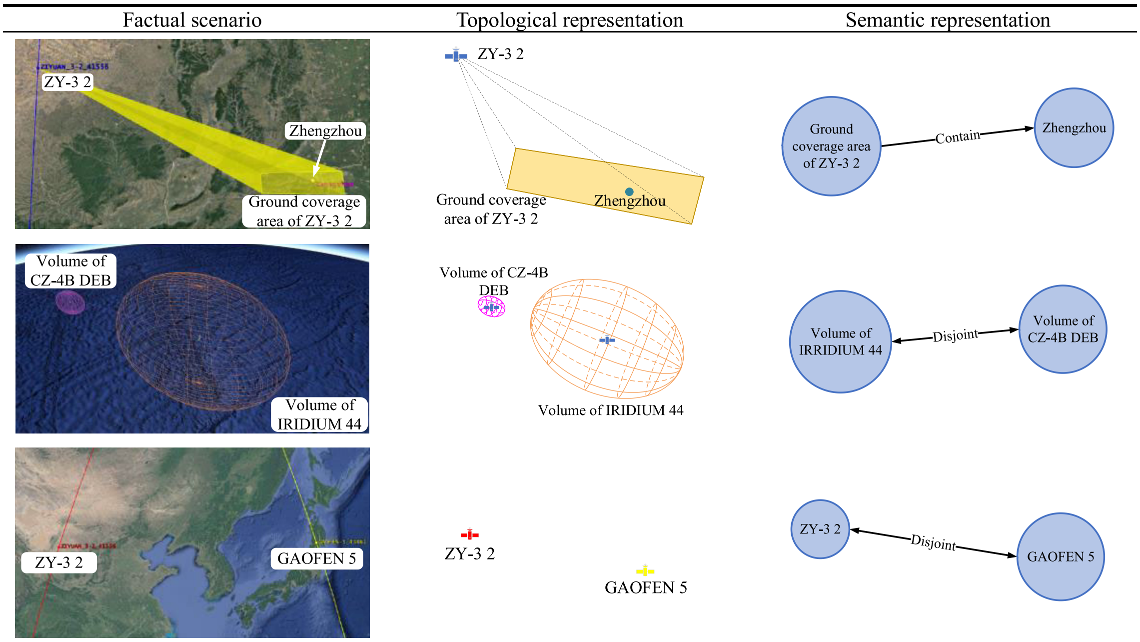
FIGURE 4. **Definition of the azimuth and pitch relative to space objects in SOS.**

b: SPATIAL ORIENTATION RELATIVE TO GROUND OBJECTS

In addition to the orientation relations between space objects and ground objects, the relations between ground coverage of space objects and ground objects must be considered. Therefore, the spatial orientation relations relative to ground objects include (i) the relations with space objects and (ii) the relations with the ground coverage of space objects.

The orientation relations of space objects relative to ground objects are shown in FIGURE 5. Point S represents the

TABLE 4. Correspondences between actual scenes, topology relations, and semantic representations in SOSKG (part).



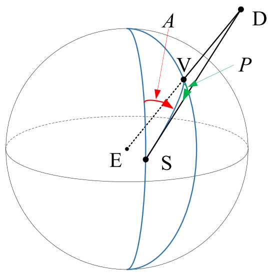


FIGURE 5. Definition of the azimuth and pitch of the space object relative to the ground object in SOS.

ground object, point D represents the space object, and point V represents the sub-satellite point of S. The latitude and longitude coordinates of S are (S_{lon}, S_{lat}), the position of D is (x_D, y_D, z_D), and the latitude and longitude coordinates of V are (V_{lon}, V_{lat}). SD is the distance between S and D. The angles A and P are the azimuth and pitch, respectively, of space object D relative to ground object S. A is defined as the angle of V relative to the north-east of S, with range 0°-360°. P is defined as the intersection angle between SD and the horizontal plane at S, with range 0°-90°. A and P can be calculated by the following equation [45]:

$$\begin{cases} A = \arcsin\left\{\dfrac{\cos(V_{lat})\sin(V_{lon}-S_{lon})}{\sin(SV)}\right\} \\ P = \dfrac{\pi}{2} - \arcsin(\dfrac{ED}{SD}\sin(SV)), \end{cases} \tag{12}$$

where SV can be obtained by (13):

$$\cos(SV) = \sin(S_{lat})\sin(V_{lat}) + \cos(S_{lat})\cos(V_{lat})\cos(V_{lon}-S_{lon}) \tag{13}$$

For the orientation relations of the ground coverage of the space object (relative to the ground object), as the relations are all on the ground, they can be described by using the angle and the four orientation words of east, south, west and north. The orientation relation between points on the ground can be easily described, such as the orientation relations between the ground station and the sub-satellite point. However, for a planar object, such as the ground coverage of the remote sensing satellite, its orientation is not convenient to calculate or describe.

To judge the orientation relations between planar objects, this study obtains the centroids of them to convert planar objects into point objects, and judges the orientation relations between these point objects to represent the relations between different types of planar objects. The orientation relation between points is shown in FIGURE 6.

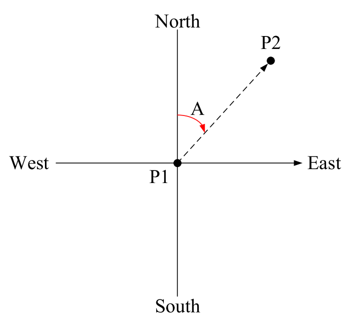


FIGURE 6. Orientation relation between points.

c: SEMANTIC REPRESENTATION AND SCENARIO MAPPINGS OF SPATIAL ORIENTATION RELATIONS

After obtaining the quantified representation of the orientation relations relative to space objects and ground objects, mappings must be established between the quantitative and semantic representations of spatial orientation relations. Of these, the mappings between the orientation relations

TABLE 5. Mappings between orientation relations relative to space objects and semantics in SOSKG.

Quantification	Semantic representation	Quantification	Semantic representation
$0° < A < 180°$	A degrees to the right of the motion direction	$0° < P < 90°$	P degrees up
$180° < A < 360°$	(360–A) degrees to the left of the motion direction	$-90° < P < 0°$	P degrees down
$A = 0°$	Directly in front	$P=90°$	Directly above
$A = 180°$	Directly behind	$P=-90°$	Directly below

TABLE 6. Mappings between orientation relations relative to ground objects and semantics in SOSKG.

Quantification	Semantic representation	Quantification	Semantic representation
$A = 0°$	Directly north	$0° < A < 90°$	A degrees north by east
$A = 90°$	Directly east	$90° < A < 180°$	(180–A) degrees south by east
$A = 180°$	Directly south	$180° < A < 270°$	(A–180) degrees south by west
$A = 270°$	Directly west	$270° < A < 360°$	(360–A) degrees north by west
$P=0°$	On the horizon	$0° < P < 90°$	P degrees above the horizon
$P=90°$	Directly above	$P < 0°$	Out of sight

relative to space objects and semantics are shown in TABLE 5, and those between the orientation relations relative to ground objects and semantics are shown in TABLE 6. Notably, in TABLE 5, when $P = 90°$ or $P = -90°$, the relative orientation relation between space objects is directly above or below, and A is invalid at this time. Based on the orientation relations and semantic representations, the partial correspondences of SOS scenarios, orientation and semantic relations are shown in TABLE 7.

3) SPATIAL DISTANCE RELATIONS

As an important part of spatial relations, the distance relation describes the distance between objects in SOS. The relation plays an important role in spatial analyses such as collision warnings. In general, the distance between objects in SOS is mainly described by its Euclidean distance. The spatial positions of objects S and D are (x_S, y_S, z_S) and (x_D, y_D, z_D) respectively, and the Euclidean distance is as follows:

$$Dist = \sqrt{(x_S - x_D)^2 + (y_S - y_D)^2 + (z_S - z_D)^2}, \tag{14}$$

After obtaining the Euclidean distance, the mapping between the Euclidean distance and semantics of space objects can be established, such as far, far away, remote, near, close, etc. Based on this principle, the partial correspondences of SOS scenarios, Euclidean distances and semantic relations are shown in TABLE 8.

C. TEMPORAL SEMANTIC RELATIONS OF SOSKG

The objects in SOS are in a complex spatial-temporal environment, and various relations change with the variation of spatial and temporal factors. Therefore, it is impossible to properly discuss the relations in SOS and to achieve effective reasoning without considering the spatial-temporal factors [44]. For example, the distances of space objects at different times may be 1000 km and 10 km. It is impossible to determine whether these objects are close to or far from each other from these two distances without the temporal factor. By considering the temporal factor, the change of the distance between space objects can be obtained.

In SOS, the temporal factor includes a time instant, such as a user acquiring the signal of a satellite at time instant t, and a time interval, such as a user acquiring the signal of a satellite B within the time interval T. Temporal factors have different scales, such as hours, days, months, or years. Temporal relations include the relation between time instants, the relation between time intervals, and the relation between a time instant and a time interval [44]. By using t_1 and t_2 to represent time instants, where t_1 is earlier than t_2, and using T_1 and T_2 to represent time intervals, partial examples of temporal relation mappings in SOSKG can be shown in TABLE 9.

D. FORMALIZED SEMANTIC RELATION REPRESENTATION OF SOSKG

By integrating the basic, spatial, and temporal relations and their semantic representations, the main relations between objects can be established. This paper constructs a formalized and unified representation of relations between different objects in SOS, as shown in (15).

$$D_S = \{O_m, O_s, R_b, \{R_t, R_o, R_d\}, T\}, \tag{15}$$

where D_S represents the unified description of relations in SOS, O_m represents the master object and the reference object, O_s represents the slave object that must obtain relations relative to O_m, R_b represents the basic relations between O_m and O_s, and R_t, R_o, and R_d represent the spatial topology, orientation, and distance relations of O_s relative to O_m, respectively; the dynamic changes of basic and spatial relations between O_m and O_s are described using the time relation T. The formalized and unified representation in (15) can be transformed into natural language expressions. For example, if R_b represents "the slave object receives data sent from the master", R_t represents "disjoint", R_o represents "southeast direction", R_d represents "far away from", and T represents "time instant t", D_S can be easily converted into the natural language description as shown below:

At time instant t, the object O_s can receive the signal from object O_m. At this time, the topology relation between O_m and O_s is disjoint, and O_s is located in the southeast direction of O_m and is far away from O_m.

TABLE 7. Correspondences of scenarios, orientation, and semantic relations in SOSKG (part).

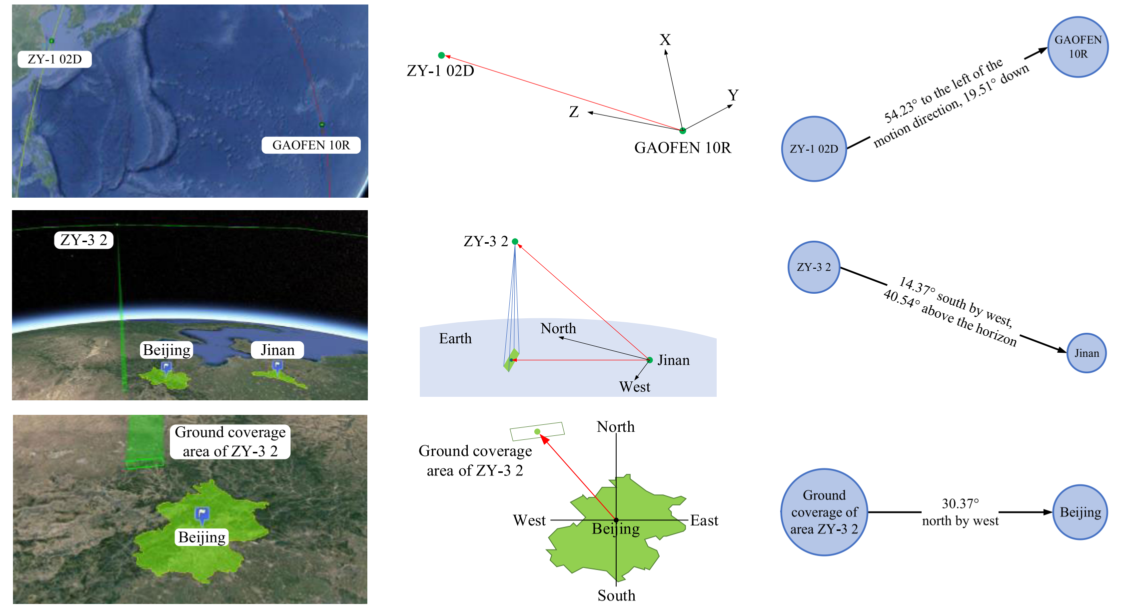


TABLE 8. Correspondences of scenarios, distance, and semantic relations in SOSKG (part).

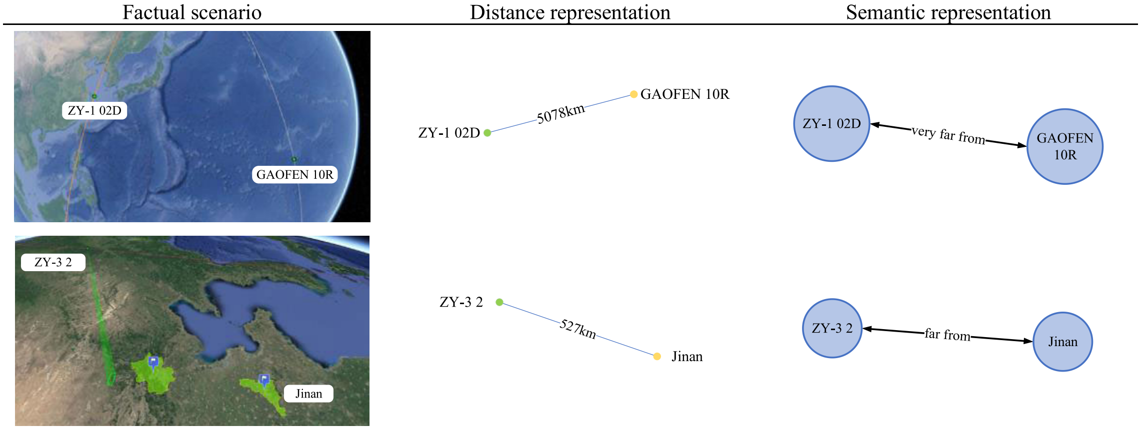
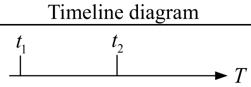
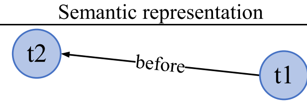
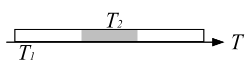
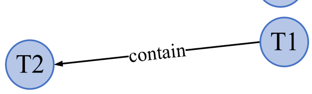
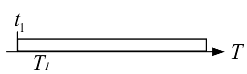
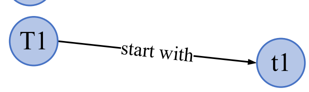


TABLE 9. Examples of the temporal relation mappings in SOSKG (part).

Relation type	Expression	Timeline diagram	Semantic representation
Relation between time instants	before (t_1 , t_2)		
Relation between time intervals	contain (T_1 , T_2)		
Relation between time instant and interval	startWith (T_1 , t_1)		

V. MULTI-ELEMENT KNOWLEDGE CONSTRUCTION MODEL IN SOSKG

The basic attributes and static relations are usually static knowledge that can be obtained through an analysis of databases and online knowledge. However, due to the high-speed and dynamic movement, the status and trends of space objects are constantly changing. The relations between space objects, and between space objects and ground objects,

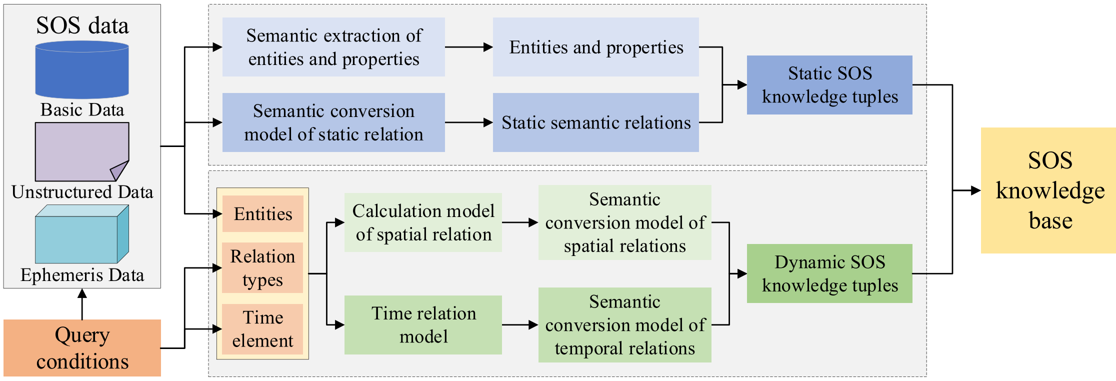


FIGURE 7. Process of multi-element knowledge construction.

are constantly changing with spatial-temporal factors, which lead to dynamic changes in the corresponding knowledge. Therefore, SOS knowledge can be divided into static knowledge and dynamic knowledge. Dynamic spatial-temporal factors must therefore be considered when extracting the relations of objects in SOS.

In addition to various space objects outside the Earth's atmosphere, to conduct space activities and make full use of space objects, various ground objects are indispensable. These objects include the launch sites for satellites, ground stations for satellite operation and control, and tens of millions of mobile devices and the humans relying upon them. There are various inextricable relations between space objects and ground objects, so when cognizing SOS, all the constituent factors of space activities should be considered in dynamic changes.

To realize the formalized expression and description of knowledge in space activities, this paper proposes a multi-element knowledge construction model oriented to SOSKG for extracting SOS knowledge. As shown in FIGURE 7, the construction process includes three principal parts:

(a) From the multi-source heterogeneous data of SOS, obtaining the entity attributes and static relations related to SOS through the entity and attribute semantic extraction, using the static relations semantic transformation in the multi-level semantic relation parsing model to generate static knowledge tuples, and storing them in the databases in advance to facilitate subsequent queries;

(b) According to the query conditions, obtaining the entities from databases and parsing the relation types and temporal elements of interest. Based on the multi-level spatial and temporal semantic relations parsing model, and the attribute information and historical ephemeris data, constructing the spatial relations of objects in SOS dynamically, and generating dynamic knowledge tuples through mapping with semantics;

(c) Based on the static and dynamic knowledge tuples, SOS knowledge bases are constructed for different types of objects, and results that are easy for users to understand are generated and returned.

When building static SOS knowledge tuples using the basic data, the D2RQ tool is used. D2RQ [46] is a tool that completes the process of virtualizing the data that is already stored in relational databases into read-only RDF tuples. The data in RDF tuples can be queried through SPARQL or be directly obtained through the network. Unstructured data is obtained from websites such as N2YO [47] and Gunter's Space Page [48] by web crawlers and is stored in Neo4j, a popular graph database. When obtaining interested objects, a static tuple related to the object is obtained from the static SOS knowledge tuples and used as part of the SOS knowledge base provided to the user.

The basis and premise for dynamic knowledge in SOS is to obtain the position and velocity of the object based on the temporal factor. The two-line element (TLE) [49] is the most commonly used element for orbit calculation. To obtain a higher prediction accuracy, the SGP4/SDP4 model issued by NORAD is usually used [50] and the position and velocity of the space object at any time can be easily obtained. The TLE data includes the epoch time, and as the time from the epoch time becomes longer, the accuracy of the orbit forecast gradually decreases; thus, NORAD usually releases the revised TLE data at regular intervals. The ephemeris data that is earlier than and closest to the time in the epoch is needed. when calculating the position and velocity of space objects according to the time provided. To complicate this further, if the user requires the position and velocity over a time interval, then a series of TLE data must be used. Therefore, the time series database InfluxDB is used to store the historical TLE data of all space objects obtained from SpaceTrack, and the TLE data set to be used is obtained based on the time interval. Taking conjunction analysis as an example, the construction process of dynamic SOS knowledge tuples is shown in FIGURE 8.

VI. CASE STUDIES

Base on the multi-level semantic relation parsing model and multi-element knowledge construction model, this study

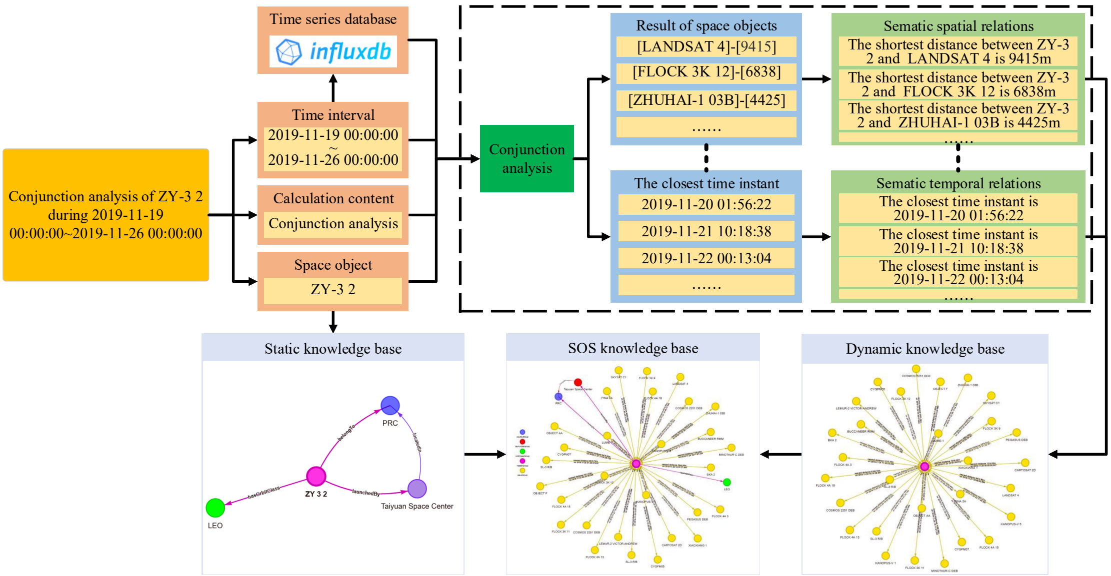


FIGURE 8. Construction process of dynamic SOS knowledge tuples.

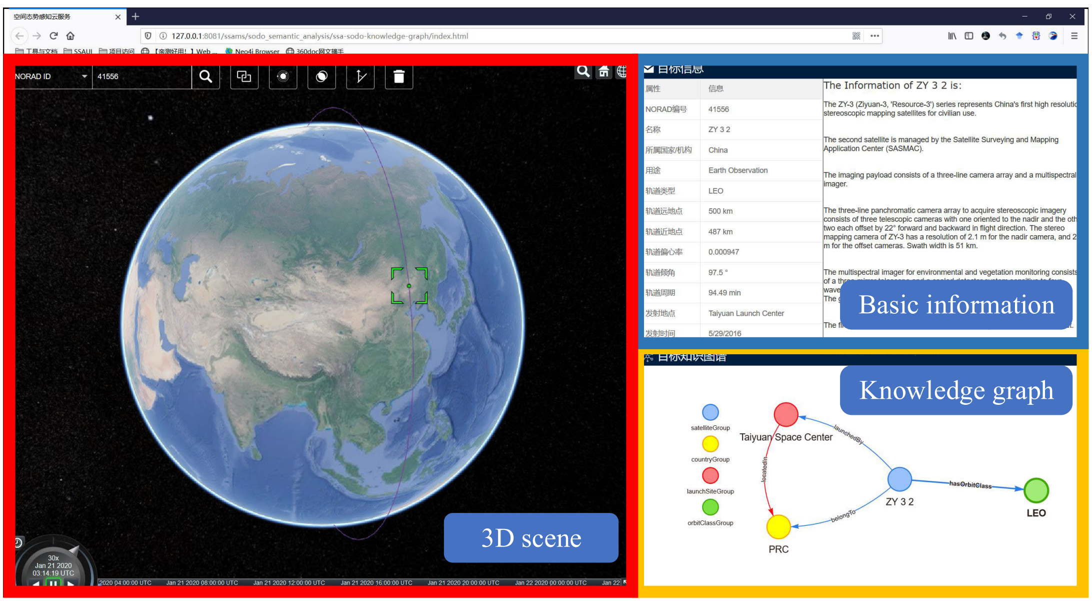


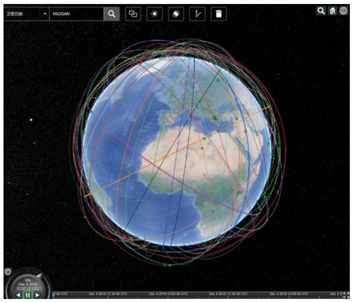
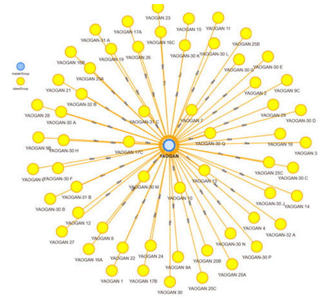
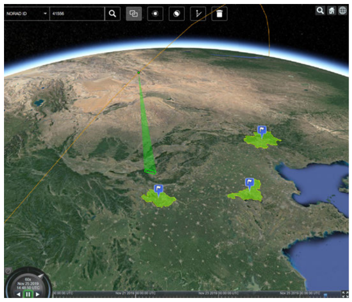
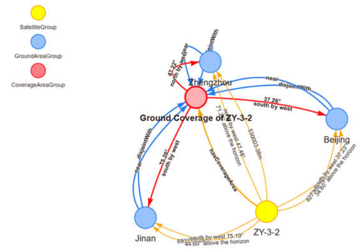
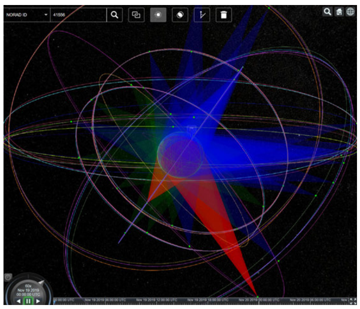
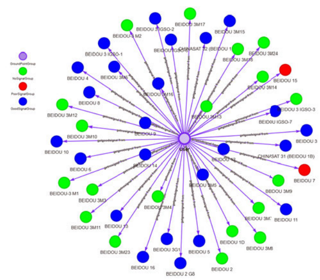
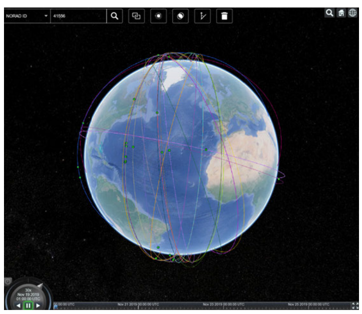
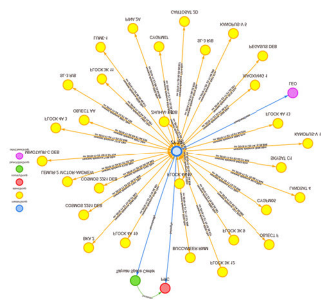
FIGURE 9. SOS information service based on the KG.

builds SOSKG, and displays the 3D scenarios and KGs of related applications.

The experimental data in this paper mainly includes: (1) basic data of space objects, mainly from CelesTrak, the UCS Satellite Database, and the STK database; (2) historical ephemeris data of space objects, mainly from SpaceTrack; (3) vector data of different administrative levels, including continents, countries, provinces/states, cities and geographical names; and (4) webpage or online data from N2YO, Gunter's Space Page, Baidu Encyclopedia and Wikipedia. These data include launch site information, launch vehicle data, and satellite launch data. The experimental platform is a Windows 10 system. The databases include MySQL, Neo4J, and InfluxDB. MySQL is used to store structured relational data, Neo4J is used to store graph data, and InfluxDB is used to store historical ephemeris data.

The SOS information service based on the KG is shown in FIGURE 9, which mainly includes three parts: a 3D scene, basic information, and the KG. The 3D scene is based on Cesium [51], which is used to display the operating scenario of space objects and other objects, and help users establish an intuitive understanding of the current SOS. The basic information includes the basic information of the selected space object, such as name, home country, purpose,

TABLE 10. Display of scenarios and construction of KGs in SOS (part).

Construction content	Visualization scenario	Knowledge graph
(a) Querying space objects with a keyword		
(b) Spatial relations between space objects and ground objects		
(c) Signal coverage of navigation satellites		
(d) Conjunction analysis and basic information display		

orbital period, etc., and descriptions obtained from various websites using the web crawler. The KG in this service shows the entities that are associated with the current space object, such as the home country, orbit class, and launch site.

In addition to the basic display in FIGURE 9, the service can display specific scenarios and corresponding knowledge graphs supported by the proposed service, as shown in TABLE 10. TABLE 10 (a) shows all related on-orbit space objects in the current database that are queried with "YAOGAN" as the key word. The visual scenario shows the operation of space objects and displays all related space objects using the knowledge graph. TABLE 10 (b) shows the spatial relations of satellite ZY-3 2 and its ground coverage area with Beijing, Jinan and Zhengzhou at 2019-11-25 14:48:50; these relations include the orientation relation, topology relation and distance relation. TABLE 10 (c) is the display of Beidou navigation satellite signals that can be searched at specific locations, where blue indicates a better signal received, red indicates a poor signal, and green indicates no signal. TABLE 10 (d) shows the conjunction analysis, and the knowledge graph shows space objects with a distance of less than 10 km from ZY-3 2 at a time point between 2019-11-19 00:00:00 and 2019-11-26 00:00:00.

VII. DISCUSSION AND CONCLUSION

The activities of countries, governments, businesses, or individuals are often inseparable from various spacecraft operating in outer space. Acquiring SOS is necessary to maintain space security and safeguard space interests. Simultaneously, it is necessary to provide the public with easy-to-understand SOS information and thereby promote education and knowledge related to aerospace. To meet these needs, in this study SOSKG was constructed, which is an SOS information service based on KG.

Through evaluating different scales of SOS, a multi-granularity SOS knowledge structure was proposed, and its relevant concepts, entities and interrelations were briefly explained. Based on this framework, the basic relations, spatial relations, and temporal relations of space objects were analyzed and mapped with corresponding semantics. A multi-level semantic relation parsing model was constructed to realize the standardized description and formalized representation. Based on the semantic relations, a multi-element knowledge construction model was established for the spatio-temporal characteristics in SOSKG. The operation scenarios and knowledge graphs of SOS were displayed using open SOS-related data and visualization tools Taking the fuzzy query, spatial relations of space-to-ground observation, navigation satellite signal coverage, and conjunction analysis as examples, the service was verified and displayed. The results show that the service can meet the cognitive requirements of different users for SOS.

However, there are still some deficiencies and necessary improvements in our study that will be addressed in future research. These areas primarily include:

(a) The current study mainly created a data graph, information graph, and knowledge graph [52], but it was impossible to reason out the unknown information. Therefore, we need to perform further research on a wisdom graph.

(b) There are many contents and fields in SOS, but this study only implemented and tested a portion of them. Therefore, future studies should be expanded to other areas (collision warning, reentry analysis, orbit prediction, etc.) to achieve a richer KG that can meet diverse requirements.

(c) The first condition for constructing a KG is to obtain the necessary data. In addition to the attribute data and historical ephemeris data of space objects, there are also behavior data (e.g., maneuver data, behavior data) and characteristic data (e.g., radar cross section data, optical property data.) that were not used in this study. Future research should integrate more data to perform SOS knowledge calculations.

(d) To better assist decision-making processes, it is also necessary to actively provide users with interesting and important information in accordance with their interests while filtering unimportant or uninteresting information. This will improve the quality and efficiency of users' knowledge acquisition.

In general, the service proposed in this paper provides a new reference method for SOS knowledge acquisition. Through assisting users in obtaining data, information, and knowledge of SOS, a certain degree of guarantee for space activities can be achieved through our model. Further improvements and expansions of the service are expected to provide more effective services for users and important contributions to space activities.

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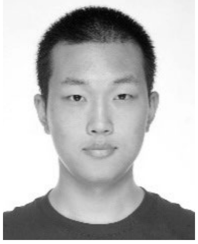

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