An Ontology-based Algorithm of Behavior Analysis and Intention Prediction for Space Object

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Abstract

Behavior analysis and intention prediction for space objects especially none-cooperative space objects is an important link of space situation awareness. This paper developed an application ontology called OntoStarBehavior to analysis the behavior of space objects. This ontology classified space object behavior systematic and built model of relationship between behavior, behavior sequence, and intention. Not only the domain knowledge but also some methods of data mining were used to mine the rules of space object behavior during the model process of OntoStarBehavior. This paper proposed one Ontology-based Behavior Analyzing and Intention Predicting Algorithm(OBAIPA). This algorithm combined the analysis of behavior sequence and semantic reasoning to recognize behavior sequence and predict intention of space object from multisource time series data. Both the ontology and the algorithm had been validated through experiments.

Keywords: Space Object, Behavior Analysis, Behavior Sequence, Ontology.

1. Introduction

Along with the development of space technology, the number of artificial is growing. The space safety as an important problem has received attention from many countries. Nowaday, the space threat is mainly shown in two aspects. One aspect is the safety threaten which is caused by deficiency of space traffic management and some objective factor such as space debris and celestial bodys. Another threat occurred because of some artificial space objects with intelligence and flexible maneuverability. These space mobile platform have the ability to attack and conceal true intention while facing countespace. Accordingly, the comprehensive utilization of Resident Space Object’s (RSO) perception information and environmental information, accurate recognition of space object, behavior analysis and intention prediction are basic requirements of space safety early warning in the future and have great significance for achieving Space Domain Awareness (SDA) and assistant decision making.

Although RSO monitoring has decades of technical accumulation, the continuous tracking of space object is hard to be guaranteed. The categories of observable space object behavior are also limited. Therefore, it is difficult to identify the behavior and intention of space object directly. For RSO’s behavior especially the behavior of various new mobile platform and intelligent spacecraft, academia and industry lack in-depth research and analysis. However, those behaviors always have high value or threat. How to analyse the behavior or behavior pattern and predict intention based on the RSO’s sensing information is an urgent problem to solve.

Some early studies on space object behavior are mainly used for the design of spacecraft and modeling system. The main application includes three aspects. The first one is validating the system function of spacecraft(1). The second is analysing behaviors of subassembly in satellites(2). The last is studying the method of mathematical representation for system behavior of spacecraft (3).

Besides, some investigators analyse cooperative space objects’ behaviors in order to avoid failures(4). They use knowledge and rules base to percept and judge the active state of controled space object, and make decision to change action command. Another study focus on the maneuver analysis for spinning thrusting spacecraft and
spinning tethered spacecraft in order to solve some problem like reducing the velocity pointing error \(^{(5)}\).

With the further development of aerospace technology and sensing technology, the space safety has gradually attracted serious concern of academe. As the requirement of Space Situation Awareness (SSA), the recognition and analysis of space object behavior from observation data has been a new research focus\(^{(6,7)}\).

A Space Object Behavior Ontology (SOBO)\(^{(6)}\) has been built to assess whether or not a spacecraft or operator is in compliance with Inter-Agency Space Debris Coordination Committee (IADC) guidelines. And an extended ontology SOBO-BN has been built for satellite collision threat evaluation\(^{(7)}\).

In general, the theoretical research and technology analysis for RSO’s behavior combine the analysis of space observation big data, ontology and machine learning. Combining the knowledge model and analysis technology driven by data can make the process of behavior analysis and intention prediction more objective and understandable.

The existing research on space object behavior focuses on Anomaly Recognition, which can identify space object behavior, but lacks analysis of complex behavior patterns. This paper proposes a method to analyse behavior and predict intention. A space object behavior analysis ontology called OntoStarBehavior has been built at first. Concepts of behavior, behavior sequence, intention and purpose are modeled in this ontology. The OntoStarBehavior uses languages of OWL-DL and SWRL. Based on it, an algorithm of behavior analysis and intention prediction is proposed. This algorithm uses little observation data to calculate features of low level behavior through known atomic behavior. A process of calculating and reasoning layer by layer helps obtaining high level behavior sequences and then predict intention of behavior sequences.

The body of this thesis mainly contains three parts as follows.

1) The ontology modeling of OntoStarBehavior.
2) The Ontology-based Behavior Analyzing and Intention Predicting Algorithm (OBAIPA).
3) The data from three sources (attitude\(^{(8)}\), maneuver history\(^{(9)}\), and TLE\(^{(9)}\) has been collected to generate a data set of behavior and intention. One simulation experiment using this data set has been performed to validate the feasibility of OntoStarBehavior and OBAIPA.

2. Behavior analysis and intention prediction

based on ontology for space object

This chapter includes two parts. Part 1 is about the OntoStarBehavior modeling. This thesis used two languages to build ontology. One language is OWL-DL which is used to model concepts of space object behavior ontology, another is SWRL which is used to model the knowledge of behavior analysis. The knowledge of the process of modeling is mainly from professional literature, existing ontology, data mining, expert knowledge and the space object information posted on some websites. Part 2 is about the ontology-based algorithm for behavior analysis and intention prediction.

2.1 OntoStarBehavior Modeling

This section introduces the modeling of space object, behavior and intention in OntoStarBehavior.

2.1.1. Top Concepts of OntoStarBehavior

SpaceObject, Intention and Feature constitute the top concept of OntoStar-Behavior. The SpaceObject can be divided into Debris, Satellite and Spacecraft. The Intention includes Atomic_Behaviour and Behavior_Sequence. The concept of Feature primarily describes the features of space object behavior, such as Orbit and Position. These features have used one application ontology called OntoStar\(^{(10)}\) for reference.

Fig. 1. Top concepts of OntoStarBehavior

One space object can execute many atomic behaviors. Some atomic behaviors constitute a low-level behavior sequence. A high-level behavior sequence is composed of some low-level sequences. The category of behavior sequence responds the intention of space object.

2.1.2. Space Object Modeling

Space object is the subject of behavior. The space objects operating in low-Earth orbit are studied in this paper. The behavior analysis and intention prediction are mainly performed for multiple behaviors of the same space object at different time periods, without considering the situation of tasks executed by multi-objects. So a behavior sequence contains behaviors which have the same subject.
In the data attributes, some intrinsic attributes that do not change over time are defined, including country, launch time, design life, quality, size, etc. For individuals, the attribute value of unknown space objects can be obtained by observing such as quality and size. For known space objects, the attribute value of the country, launch time, and design life can be obtained through the official information, documentation, and other channels.

From the sensor data, the states and parameters of space object at different times can be obtained. These states and parameters are described in the OntoStarBehavior by the data attributes of the atomic behavior and behavior sequences. SpaceObject is related to Atomic_Behavior by the object attribute execute; SpaceObject is related to Behavior_Sequence by the object attribute has_intention.

2.1.3. Behavior and Intention Modeling

In the knowledge modeling of artificial intelligence, the intention refers to the control mechanism of the agent behavior\(^{11}\), that is, the activity or activity sequence selected by the agent in order to achieve a certain goal. This paper models the intention as an Atomic Behavior or Behavior Sequence that is performed by a space object to accomplish a purpose. In OntoStarBehavior, all intentions can be represented by atomic behavior and behavioral sequence. Atomic_Behavior is a basic behavior that cannot be separated. And Behavior_Sequence is a complex behavior that consists of multiple atomic behaviors in accordance with a certain logical relationship. In the OntoStar Behavior, a behavior sequence is defined as a sequence of multiple actions with intrinsic connections arranged in chronological order within a certain period of time.

Atomic_Behavior is the basis of the complex behavior, including the Payload_Atomic_Behavior, Orbit_Control_Atomic_Behavior, and Attitude_Control_Atomic_Behavior. For example, the atomic behavior of the payload includes imaging, swinging, etc. The atomic behavior of the orbit control is mainly maneuverburn. The atomic behavior of the attitude control includes Yaw_Ramp and Yaw_Flip.

Figure 2 shows the architecture of atomic behavior concepts.

From the sensor data, the changes of states and parameters of the space object at different times can be obtained. These states and parameters are described by the data attributes of the atomic behavior. The atomic behavior data attributes include the orbital elements, the change of parameters, the start time, the end time, and the duration, etc.

In addition to the subclass axioms inherited from Intention, Atomic_Behavior also has proprietary constraints. For example, “has_position exactly 1 Position” indicates that one atomic behavior has one and only one position.

The behavioral sequence includes Normal_Behavior_Sequences and Abnormal_Behavior_Sequences\(^{12}\). The sequence of normal behavior mainly refers to a series of behaviors which are executed by space objects for some purpose, including Orbit_Transfer_Sequence, Orbital_Maneuvers_Sequence\(^{13}\), Attitude_Control_Sequence, Close_Approach_Sequence\(^{14}\), etc. Abnormal_Behavior_Sequence includes Orbital_Anomaly, Attitude_Anomaly, and Payload_Anomaly. Figure 3 shows the architecture of the intention and behavior sequence in the OntoStarBehavior.

![Fig. 2. The architecture of atomic behavior concepts](image-url)

![Fig. 3. The architecture of the intention and behavior sequence in the OntoStarBehavior](image-url)

The data attributes of the behavior sequence include the start_time, end_time, duration, average_interval_time, standard_deviation_interval, and space object state parameters passed from the included sub-behaviors. The before and after are reciprocal object attributes which represent the order relationship between behaviors. The relationship between behavior sequence and behavior is
representing class boundaries are used to strictly define concepts (i.e., defining necessary and sufficient conditions of concepts). OntoStarBehavior's equivalence class axioms about behaviors or behavior sequences are mainly derived from the knowledge of mathematical models in the professional literature and the knowledge gained from data mining.

In addition, OntoStarBehavior also has various SWRL rules such as rules for identifying the behavior of each layer, rules for judging relationship between behaviors and behavior sequence, and rules for indicating the order between sub-behaviors in a sequence. These rules are built based on the description of satellites mission\(^{[13]}\) and result of data mining.

2.2 **Ontology-based behavior analysis and intention prediction algorithm**

The space object observation data is discrete time series data. To analyze behavior, the key step is to perform sequence segmentation and extract the sequence corresponding to the actual intention. Therefore, this paper proposes Ontology-based Behavior Analysis and Intention Predicting Algorithm (OBAIPA).

When observing a set of atomic behaviors of a space object over a period of time, the features can be extracted from the observation data. These features include inclination\(_{\text{change}}\), eccentricity\(_{\text{change}}\), semi-major\(_{\text{change}}\), attitude\(_{\text{angle}\_\text{change}}\), start\(_{\text{time}}\), end\(_{\text{time}}\), acceleration, etc. As all of the features have been processed, the algorithm OBAIPA can be used to segment and predict possible intentions from the input sequence of the atomic behaviors.

When the intention can be judged in advance within the actual time span of the intention, there will be a higher value of assisting decision. The principle adopted in this paper is to predict intentions with the shortest possible sequence. The OBAIPA is of process of finding out a meaningful behavior sequence from the input linked list of atomic behaviors. The goal of reasoning at each level is to divide the input linked list of behaviors into a series of behavior sequences with high-level semantics. And the length of each sequence do not exceed the threshold.

The reasoning is started from a temporary sequence that contains only one behavior from the input behaviors at each layer, and then the subsequent behaviors are added to the temporary sequence one by one to perform sequence feature calculation and reasoning to determine whether the current sequence satisfies the conditions of sequence pattern in OntoStarBehavior. When the sequence has been identified as a specific sequence pattern, the sequence is added into a temporary list, and a new sequence that contains the next behavior from input behaviors is to be identified. After traversing all the input behaviors, the temporary list is used as input of next layer. When new sequence can not be generate at the highest layer, the algorithm is terminated. In essence, the algorithm is to perform layered segmentation and recognition of an observed long sequence of atomic behaviors. Only the segments that can be identified are considered as effective segmentation at each layer.

The results of the lowest layer are short behavior sequences consist of atomic behavior and the results of high layer are long behavior sequences consist of short sequences. Intentions of both short sequences and long sequences can be obtained from the knowledge base of OntoStarBehavior.

The algorithm of OBAIPA is shown as follows.

**Algorithm:** OBAIPA (A,L,ontology)

**Input:**
- A //atomic behavior list arranged in chronological order
- L//constant, the max length of a behavior sequence which is composed of some atomic behaviors or sub-sequences
- ontology //ontology built as knowledge base

**Output:**
- List <Behaviour> B//All behavior sequences are saved to a linked list. The list initially is empty.

1. \(B \leftarrow \text{higherSeqs}(A,L,\text{ontology})\)//generate the first layer of behavior sequences from linked list of atomic behavior
2. \(\text{tempList} \leftarrow \text{B}\)//save this layer of behavior sequences to a temporary linked list
3. \(\text{do}\)
4. \(\text{if}(B.\text{contains}\_\text{tempList})=\text{false})\)
5. \(B.\text{addall}\_\text{tempList};)/\text{add the behavior sequences of temporary linked list to list B}\)
6. \(\text{end if}\)
7. \(\text{tempList} \leftarrow \text{higherSeqs}(B,L,\text{ontology});/\text{generate the higher layer of behavior sequences from list B}\)
8. \(\text{While} (\text{tempList} \neq \text{List} \&\& B.\text{contains}\_\text{tempList})=\text{false})\)
   \(//\text{when the temporary list is empty or the sequences of Bcontains all sequences of the temporary list, end the loop proces.}\)
9. \(\text{Return} B//\text{obtain all layers of behavior sequences} \)

//higherSeqs() is a function to identify upper layer behavior sequence combined from low layer behavior
10. Function higherSeqs(A, L,ontology)//use knowledge of ontology to generate a linked list of behavior sequences from A
11. i ← 1; i is the subscript of behavior in A.
12. List< Behavior> seqs ← {}; //initialize the linked list of result
13. Sj = {}; // Sj is a temporary sequence used to combine behaviors from A. Its initial value is empty.
14. While(A.index(i) ≠ null)
15. Ai ← A.index(i); //take the i-th element from A
16. Sj.add(Ai); //add the behavior Ai to sequence Sj
17. Sj.setFeatures(); //calculate the sequence features based on the sub-behavior of Sj
18. insertInd(ontology, Sj, "Behavior_Sequence"); //insert the Sj into ontology as individual which is class of Behavior_Sequence
19. insertInd(ontology, Ai, Ai.getType()); //insert the Ai into ontology as individual
20. insertRel(ontology, Sj, Ai, "contains"); //insert the object property of contains between Sj and Ai into ontology
21. bool isConsist = pellet.isConsistent(ontology); //use pellet reasoner to check consistency
22. if isConsist = false
23. Sj.remove(Ai); //if result is inconsistent, remove the Ai from Sj
24. deleteInd(ontology, Ai); //delete individual of Ai from ontology
25. i++;
26. continue; //take Ai from A, enter next loop if Ai is not null, repeat the above steps
27. end if
28. s_type ← pellet.getMostSpecificType(ontology, Sj); //obtain the type of behavior sequence Sj after reasoning
29. bool is_sub ← isSubClassOf(s_type, "BehaviorSequence"); //judge whether s_type is subclass of Sj
30. if is_sub = true
31. seqs.add(Sj); //Sj is a meaningful behavior sequence. Add it to seqs of result list.
32. i++;// take Ai from A, enter next loop if Ai is not null, repeat the above steps
33. else if (Sj.length() < L)
34. i++;// take Ai from A, enter next loop if Ai is not null, repeat the above steps
35. else
36. i++;
The final simulation data is tabled as Table 1.

Table 1. Behavior and intention of satellite Jason 1.

<table>
<thead>
<tr>
<th>Space Object</th>
<th>Atomic Behavior</th>
<th>Intention type</th>
<th>Intention number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jason1</td>
<td>Burn</td>
<td>Altitude keeping</td>
<td>30</td>
</tr>
<tr>
<td>Jason1</td>
<td>Attitude control</td>
<td>Attitude stabilization</td>
<td>50</td>
</tr>
<tr>
<td>Jason1</td>
<td>Burn</td>
<td>Inclination keeping</td>
<td>13</td>
</tr>
<tr>
<td>Jason1</td>
<td>Burn</td>
<td>Orbit transfer</td>
<td>3</td>
</tr>
</tbody>
</table>

The experimental simulated the observation process and continuously inputted the atomic behaviors and observation data. The input of atomic behaviors and observation data were saved in the database of the corresponding space object. When new behavior was observed and corresponding observation data was obtained, the stored atomic behavior record that was closest to the current observation time and had not been identified, together with the currently tracked atomic behavior data constituted a linked list as input. When the intentions were identified from the trace data of a period of time, the new atomic behavior obtained by the next trace was used as the starting node of the linked list. The results of the experiment were used to validate the correctness and contrast the time span of actual intention to those of inferred intention.

Table 2. The result of intention prediction for Jason 1.

<table>
<thead>
<tr>
<th>Intention</th>
<th>Correct number</th>
<th>Recall rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude keeping</td>
<td>24</td>
<td>80%</td>
</tr>
<tr>
<td>Inclination keeping</td>
<td>10</td>
<td>76.9%</td>
</tr>
<tr>
<td>Attitude stabilization</td>
<td>49</td>
<td>98%</td>
</tr>
<tr>
<td>Ocean detection</td>
<td>24</td>
<td>/</td>
</tr>
<tr>
<td>Orbit transfer</td>
<td>3</td>
<td>100%</td>
</tr>
</tbody>
</table>

The category of satellite was unknown in this experiment while reasoning. Table 2 illustrated the results of intention prediction. The recall-rate was calculated according to the inferred intention and actual intention. When the result of multi-level intentions contained the actual intention at a period of time, it was considered to be a correct identification. The correct identification included two parts. One was whether the predicted categories includes the actual intention category, and the other was whether the time span of intentions were basically the same.

The intention of ocean detection identified at the fourth row in Table 2 was the additional result obtained through reasoning that the original data had not been marked. This level of intention prediction was equivalent to identifying the specific type of space object. According to the definition in the ontology, the ocean detection sequence is the attitude adjustment mode of the ocean observation satellite, and the purpose is to maintain the normal attitude to observe the sea level height and wave height. Its attitude adjustment shows periodic changes and has a long time interval.

After analyzing the data, the time sampling difference between the behavior data and TLE data is mainly reason that some intention are unrecognized. When the physical properties are calculated from the TLE data according to the time of the maneuver behavior, the calculated physical characteristics may be inaccurate due to time inconsistency. In addition, as a result of the influence of the space environment such as the geomagnetic explosion, the speed of the satellite's altitude will change. If the altitude drops too fast, the error caused by the inconsistent of observation time will be increased. One solution is to mining separately from these data to obtain targeted SWRL rules.

4. Conclusions

Based on the problem of how to analyze behavior and predict intention using sensor data of space object, this thesis has built an ontology of OntoStarBehavior and proposes OBAIPA which is one ontology-based algorithm of behavior analysis and intention prediction.

The feasibility of this method has been validated through experiment. The contrast of time span indicates that this method has practical value. The result indicates that the method proposed can obtain the meaningful behavior sequences from sensor data and atomic behavior and predict intention correctly. The hierarchical identification can greatly reduce the complexity of combinatorial calculation from observation data.

In addition, this method has good scalability. As long as the corresponding knowledge is added into the OntoStarBehavior, the OBAIPA algorithm can be used to analyze the new behavior or intention.

More research should be done in the future. The knowledge base need more knowledge to identify all kinds
of behavior sequence correctly. And more categories of satellites should be simulated to perform experiments.

Acknowledgment

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References

(8) The maneuver history and attitude history for each of the satellites was retrieved from the NASA web site found at http://ilrs.gsfc.nasa.gov
(9) The TLEs were downloaded from the Space-Track web site found at http://www.spacetrack.org
(15)The domain knowledge about satellites was downloaded from the aviso web site found at http://www.aviso.com