Ontology-Based Method for Identifying Abnormal Ship Behavior: A Navigation Rule Perspective

Chunhui Zhou 1,2, Kunlong Wen 1,2, Junnan Zhao 1,2,*, Ziyuan Bian 1,2, Taotao Lu 1,2, Myo Ko Ko Latt 1,2 and Chengli Wang 3

1 School of Navigation, Wuhan University of Technology, Wuhan 430063, China; chunhui@whut.edu.cn (C.Z.); charliewkl@163.com (K.W.); bzy@whut.edu.cn (Z.B.); lutaotao@whut.edu.cn (T.L.); myoko2latt89@gmail.com (M.K.K.L.)
2 Hubei Key Laboratory of Inland Shipping Technology, Wuhan 430063, China
3 Zhejiang Scientific Research Institute of Transport, Hangzhou 310039, China; 15868873946@163.com
* Correspondence: junnan@whut.edu.cn

Abstract: Navigation rules are critical for regulating ship behavior, and effective water traffic management requires accurate identification of ships exhibiting abnormal behavior that violates these rules. To address this need, this paper presents an ontology-based method for identifying abnormal ship behavior. First, we analyzed navigation rules (local regulations) to extract key elements. Next, based on this extraction, we built a navigation rule ontology that categorized ship behavior into state behavior (ship behavior at a specific time point) and process behavior (ship behavior in a time interval). We then constructed an abnormal ship behavior ontology, defined using topological relationships and navigation rules. Finally, we constructed inference rules to detect abnormal ship behaviors by using SWRL (Semantic Web Rule Language) and validated the effectiveness of the method with ship instances. The experimental results demonstrate that this method can accurately infer ships’ behaviors that deviate from established navigation rules. This research has significant implications for reducing waterborne traffic accidents, improving navigational safety, and safeguarding maritime traffic.

Keywords: navigation rules; abnormal behavior; ontology modeling; SWRL; behavioral inference

1. Introduction

Maritime safety is crucial for the growth of the shipping economy. With the increasing number of vessels, traffic dynamics are becoming increasingly complex, and individual ship behavior is more variable, leading to frequent occurrences of abnormal behavior. Ship anomalies can cause severe consequences, including loss of life, environmental pollution, and property damage, posing significant challenges to maritime traffic regulation and navigational safety. Consequently, conducting research on ship behavior anomaly detection is both necessary and urgent.

With the advancement of maritime monitoring technology, spatial-temporal data on maritime traffic is growing rapidly. A behavior pattern matching model can be constructed to identify abnormal ship behavior by extracting statistical features from historical ship data [1] and analyzing ship behavior patterns [2]. To regulate ship behavior, some waterways have designated fairways and traffic channels, as well as establishing navigation rules such as Traffic Separation Schemes and routing systems. These local navigational rules are particularizations of the International Regulations for Preventing Collisions at Sea (COLREGs), with the goal of adapting to the navigational environments of the local water area while being generally bound by COLREG Rule 10. However, there is currently a lack of effective monitoring methods for detecting ship anomalies that violate...
navigation rules. Relying solely on manual monitoring (observation and evaluation of vessel behavior by human operators) is insufficient to meet the demands of modern regulatory requirements. Utilizing computational methods to semantically represent navigational rules facilitates the comprehension, interpretation, and effective identification of vessel anomalous behaviors in violation of regulations, thereby significantly enhancing the level of intelligent regulatory oversight.

Ontology, as a computationally recognizable tool [3], compensates for manual monitoring’s inadequacies. As a method of knowledge representation, ontology provides a unified semantic framework [4], facilitating systematic modeling and expression of complex navigational rules knowledge, thereby enhancing the understanding of navigational regulations. In maritime regulation, the use of ontology to construct semantic models of navigational rules and vessel behavior enables information sharing and reuse, thereby enhancing the intelligence level of regulatory systems. Ontology enables the effective monitoring and identification of vessel anomalous behaviors by integrating navigational rules and vessel behavior data.

This paper proposes an ontology-based inference method for identifying abnormal ship behavior. The goal is to gain a fundamental understanding and explanation of ship behavior patterns through the analysis and modeling of navigation rules and ship behavior. It allows us to identify abnormal ship behavior that deviates from the rules. This research contributes to a better understanding of abnormal ship behavior and better identification of risk factors, ultimately improving maritime traffic regulation and navigational safety.

The other chapters of this paper are organized as follows: Section 2 reviews some related works; Section 3 introduces the methods for parsing navigation rules and extracting key elements, ontology construction, and ship behavior inference; Section 4 presents the experiments and analysis; Section 5 discusses the method; and Section 6 concludes.

2. Literature Review

2.1. Related Research on the Application of Ontology Technology

Ontology technology, as a formal method of knowledge representation, has been widely applied across diverse domains, including transportation, agriculture, finance, and others.

In the domain of transportation, Yang et al. [5] utilized urban traffic ontology to achieve a unified representation of urban traffic information, as well as to define rules and algebraic operations for semantic fusion at the ontology level, aiming to achieve semantic integrity and consistency in city traffic information. David [6] proposed a transport disruption ontology for modeling events related to travel and transportation that have disruptive impacts on travelers’ journeys. It described how to capture traffic accidents and their impacts, as well as outlining the use of ontology rules in an interconnected travel information repository to support intelligent transportation systems. Agarwal et al. [7] utilized knowledge graph-assisted means to ontologize airworthiness rules. Once users created an original design ontology for aircrafts, they could compare it with the airworthiness rule ontology to identify any design vulnerabilities. Bagschik et al. [8] used ontology-based knowledge and modeling and production rule-based knowledge inference to understand the evolutionary dynamics of autonomous transportation systems, focusing on the transition from sparse to dense networks and the gradual increase in network efficiency. Additionally, they designed and implemented a flight safety information ontology that included key components of flight operation information. Mahdi et al. [9] employed the aviation network and methodology based on the Internet Protocol Suite (IPS) to construct a flight information ontology. They used Protege software to conduct the implementation process and reasoning, and they analyzed the system using actual data from Mashhad Airport in Iran.
In other domains, Malik [10] addressed the current lack of agricultural ontology development by proposing a generic method for representing entities and their relationships in an agricultural ontology, achieving the development of domain-specific ontologies in agriculture. Altinok [11] introduced an ontology-driven dialogue manager (OntoDM) to maintain dialogue state and coherence through domain ontologies. This method leverages domain knowledge to track entities of interest, such as products and services, thereby introducing dialogue memory and attention mechanisms, which are particularly applied in the banking and finance domain. Edison [12] constructed ontologies for renal tissue mapping and precision medicine research, facilitating comprehensive mapping of renal molecular, cellular, and anatomical profiles, improving renal data annotation, and redefining renal diseases, thus advancing precision medicine. Ayesha [13] developed an educational ontology detailing various university courses, serving as a guide for students to select future courses according to their needs.

2.2. Related Research on the Application of Ontology Technology in the Maritime Field

Ontology has also been extensively applied in the maritime domain. Song et al. [14], from the perspective of interpretable knowledge modeling, provided a computer-understandable method for behavior modeling. They provided a semantic model (Cognition Modeling and Semantic Reasoning of Ship) for defining ship behavior by combining multi-scale features in cognitive space. Zhong et al. [15] developed an ontological model of ship behavior based on COLREGs, with the goal of assisting machines in comprehending COLREG regulations using knowledge graph technology. The research considers ships as spatiotemporal objects, with behaviors described as variations in object elements at spatiotemporal scales, implemented using the resource description framework (RDF), function mapping, and set expression methods. Wen et al. [16] proposed a semantic model of ship behavior (SMSB), establishing a semantic network grounded in maritime traffic rules and good seamanship. They identified basic ship behavior in various aquatic scenes by constructing ontologies. A semantic model of in-harbor ship behavior based on ontology and the Dynamic Bayesian Network (DBN) was utilized to infer potential ship behavior. Georgios [17] proposed an Ontology-Based Data Access (OBDA) framework for effective maritime surveillance and event management through data access. This framework integrates real-time and historical vessel data to detect complex events and support decision-making. Roy [18] introduced an automatic reasoning concept verification model based on description logics to assist maritime personnel in detecting vessel anomalies and identifying maritime risks. Mirna [19] presented an Ontology-Based International Maritime Law Liability Decision Support System. The system analyzes carrier and shipper liability in cases of cargo loss or damage, utilizing a legal domain ontology called CargO-S to support the design and implementation of chained rules describing liability legal rules. Yu [20] addressed the semantic heterogeneity of heterogeneous data in maritime search and rescue operations through ontology, facilitating knowledge acquisition, sharing, and reuse.

2.3. Related Research on Abnormal Ship Behavior

A large number of scholars have conducted research on the detection of abnormal behavior in ships. According to the type of technology used, this study can be divided into traditional methods and deep learning-based methods. Most traditional methods are designed to detect or recognize specific scenes. Murray [21] utilized the DBSCAN clustering algorithm to cluster ships’ trajectories, established a historical trajectory atlas based on the clustering results, and employed the trajectories of normal ships as the standard for judging abnormal behavior. Li [22] proposed a ship behavior anomaly detection method based on trajectory analysis and Dynamic Time Warping (DTW). Abnormal trajectories that deviate from normal behavior are identified by calculating the similarity between trajectories and employing the DTW algorithm for trajectory matching and comparison. Gözde [23] introduced a maritime anomaly behavior detection method based on
trajectory pattern analysis. Abnormal trajectories that deviate from normal behavior are identified by extracting features from ship trajectories and applying pattern recognition techniques to predict ship trajectories.

In addition to the traditional methods mentioned above, deep learning-based methods are the mainstream abnormal ship behavior detection methods at present. Singh [24] proposed a framework for anomaly detection based on a multi-class artificial neural network (ANN) to classify intentional and unintentional AIS switch anomalies. Vespe [25] utilized historical AIS data and employed unsupervised learning algorithms, without the need for any specific prior-context descriptions, to identify vessel motion patterns. This facilitated vessel trajectory anomaly detection and enhanced maritime situational awareness by providing vessel traffic characteristics. Yang [26] proposed an abnormal ship behavior recognition method based on LSTM. By manually labeling abnormal ship behavior states and learning from a large amount of ship AIS data, they established an abnormal ship behavior recognition model and trained it on the TensorFlow platform. Liu [27] introduced the attention mechanism into GRU, obtained optimal GRU structural parameters through intelligent algorithms, and utilized the optimized GRU neural network for deeper feature extraction and training of abnormal ship behavior. Zhang [28] utilized trajectory clustering results as a reference model to train the Bidirectional Gated Recurrent Unit (BiGRU) recurrent neural network for real-time ship anomaly detection. The trajectory prediction results of the BiGRU model exhibited minimal error compared to the actual ship trajectories, indicating superior trajectory prediction performance.

Several studies on semantic analysis of abnormal ship behavior have been conducted, but research on detecting and inferring ship anomalies in relation to navigation rules remains relatively limited. This paper proposes an ontology-based inference method for detecting abnormal ship behavior in accordance with navigation rules. First, the key elements of navigation rules are extracted through rule analysis. Next, the navigation rules ontology is constructed, with ship behavior categorized and expressed accordingly. Then, based on the Semantic Web Rule Language (SWRL), inference rules for ship anomalies are developed to enable automated inference of abnormal ship behavior. Finally, experiments are conducted to validate the effectiveness of this anomaly detection approach.

3. Methodology

The framework for inferring abnormal ship behaviors predicated on the ontology of navigational rules is delineated in Figure 1. The methodology for this inference is structured in a four-step process that involves navigation rule analysis and element extraction, as well as the construction of both the navigational rule ontology and the abnormal ship behavior ontology, followed by the formulation of Semantic Web Rule Language (SWRL) inference rules to facilitate the reasoning of abnormal ship behaviors. The process commences with the dissection of textual content pertaining to navigational rules, employing a Latent Dirichlet Allocation (LDA) model to distill key elements from these rules. Subsequently, leveraging these extracted key elements, an ontology of navigational rules is established. Then, the ship behaviors are classified and expressed based on the navigation rules ontology. Ultimately, an ontology for abnormal ship behaviors is constructed, and the SWRL is utilized to devise conditional-action production rule reasoning, enabling the inference of abnormal behaviors in ships.
Figure 1. The framework of the abnormal ship behaviors detection.

3.1. Navigation Rule Analysis and Element Extraction

Navigation rules are important guidelines to regulate the behavior of ships, and by parsing the textual content of navigation rules, we can more comprehensively mine the information related to the behavior of ships, so as to extract the elements in the navigation rules.

3.1.1. Analysis of Navigation Rules

In this paper, the regulation of a routing system of the Yangtze River was taken as the research object, and the text content was analyzed to realize the extraction of navigation rules. The regulations consisted of 6 chapters, 33 articles, and 10 annexes covering traffic channel rules, maneuvering rules, berthing rules, and avoidance rules to ensure the safe navigation of ships.

1. Traffic channel rules

Traffic channel rules were categorized into traffic separation rules and recommended channel rules. Deepwater channels were constructed with upstream and downstream traffic lanes and a separation zone. The traffic separation rules are mainly applicable to large vessels to avoid grounding and other obstacles. The recommended channel rules are largely intended to ensure that smaller vessels can navigate effectively on the recommended routes while also limiting the types of vessels and the speed restrictions.

2. Maneuvering rules

The maneuvering rules were divided into speed rules, position rules, reporting rules, overtaking rules, large ship navigation rules, small ship navigation rules, high-speed ship navigation rules, special rules, and bridge water area navigation rules.

Speed rules limit the minimum and maximum speeds during maneuvering in the channel. The reporting rules stipulate ships to make position reports at specified positions. Position rules specify the navigational areas for different types of ships. The overtaking rules stipulate the behaviors of the overtaking vessel and the overtaken vessel during the overtaking process. Large ship rules, small ship rules, and high-speed ship rules limit the speed and position of large vessels, small vessels, and high-speed vessels, respectively. The special rules stipulate the navigation requirements for ships in special areas such as precaution areas. The bridge water area rules stipulate the mandatory behavioral norms of ships while passing through this area.

3. Berthing rules

Berthing rules are categorized into berthing rules for large ships, berthing rules for small ships, and berthing rules for special cases. The berthing rules for large ships require large ships to berth within the limited area declared by a competent authority. Berthing
rules for small ships stipulate that small ships should be moored in a specific area. The berthing rules for special cases stipulate for ships to be moored under special conditions.

(4) Avoidance rules

Avoidance rules are divided into general area avoidance rules and special area avoidance rules. The general area avoidance rules stipulate the avoidance requirements for ships navigating on the waterway and recommended channels. Special area avoidance rules provide for the avoidance of ships in special areas such as estuaries, tributaries, and specialized waterways.

According to the text of the navigation rules, a total of 22 rules \(\{\text{rule}_1, \text{rule}_2, \ldots, \text{rule}_{22}\}\) were extracted to establish the different types of rules, as in Table 1; the specific content of each rule is shown in Appendix A.

### Table 1. Extractions of navigation rules.

<table>
<thead>
<tr>
<th>Types of Navigation Rules</th>
<th>Categories</th>
<th>Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic channel rules</td>
<td>traffic separation rules</td>
<td>rule_1</td>
</tr>
<tr>
<td></td>
<td>recommended channel rules</td>
<td>rule_2</td>
</tr>
<tr>
<td>Maneuvering rules</td>
<td>speed rules</td>
<td>rule_3, rule_4</td>
</tr>
<tr>
<td></td>
<td>position rules</td>
<td>rule_5</td>
</tr>
<tr>
<td></td>
<td>reporting rules</td>
<td>rule_6</td>
</tr>
<tr>
<td></td>
<td>overtaking rules</td>
<td>rule_7</td>
</tr>
<tr>
<td></td>
<td>large ship rules</td>
<td>rule_8</td>
</tr>
<tr>
<td></td>
<td>small ship rules</td>
<td>rule_9</td>
</tr>
<tr>
<td></td>
<td>high-speed ship rules</td>
<td>rule_10</td>
</tr>
<tr>
<td></td>
<td>special rules</td>
<td>rule_11</td>
</tr>
<tr>
<td></td>
<td>bridge water area rules</td>
<td>rule_12, rule_13, rule_14, rule_15, rule_16, rule_17</td>
</tr>
<tr>
<td>Berthing rules</td>
<td>berthing rules for large ships</td>
<td>rule_18</td>
</tr>
<tr>
<td></td>
<td>berthing rules for small ships</td>
<td>rule_19</td>
</tr>
<tr>
<td></td>
<td>berthing rules for special cases</td>
<td>rule_20</td>
</tr>
<tr>
<td>Avoidance rules</td>
<td>general area avoidance rules</td>
<td>rule_21</td>
</tr>
<tr>
<td></td>
<td>special area avoidance rules</td>
<td>rule_22</td>
</tr>
</tbody>
</table>

#### 3.1.2. Element Extraction from Navigation Rules

In the study of navigation rules, revealing the underlying themes behind the text helps us to extract the key elements in the rules for a more comprehensive understanding. The LDA (Latent Dirichlet Allocation) model, which treats a document as a combination of multiple themes and describes each theme as a probability distribution of a particular vocabulary word, provides technical support for the extraction of the relevant elements of the navigation rules.

The LDA model treats documents as a combination of multiple topics, representing each topic as a probability distribution over a specific vocabulary. This approach facilitates the understanding and classification of complex navigation rule documents. By employing statistical methods, LDA identifies word patterns within documents and clusters these patterns into distinct topics, effectively revealing the main focus and structure of navigation rules. Additionally, LDA’s capability to handle unlabeled data makes it particularly suitable for processing large-scale navigation rule texts, which typically lack predefined labels. This enables the discovery of hidden themes and relationships, thereby supporting the element extraction of navigation rules.

The following are the basic steps of LDA modeling:

(a) Initialize the parameters. Determine the number of topics to be modeled \(K\); determine the number of words in the vocabulary \(V\). The hyperparameters \(\alpha\) and \(\beta\) are used to control the sparsity of the topic distribution and the word distribution.
(b) Random assignment of topics. For each vocabulary word in each document, a topic is randomly selected as the initial assignment.

(c) Iterative inference. For each vocabulary word \( w \) in each document \( d \), reassign topics; for each topic \( k \), calculate \( P(\text{topic } k | \text{document } d) \times P(\text{vocabulary word } w | \text{topic } k) \). Reassign topics based on the calculated probabilities.

(d) Statistics on topic and vocabulary distribution. Count the number of occurrences of each topic \( k \) in a document and compute the topic distribution \( P(\text{topic } k | \text{document } d) \). Count the number of occurrences of each vocabulary word \( w \) in topic \( k \) and calculate the vocabulary distribution \( P(\text{vocabulary word } w | \text{topic } k) \).

(e) Repeat steps (c) and (d) until the model converges or reaches a predetermined number of iterations.

(f) Theme analysis and element extraction. After the model has converged, extract the theme distribution of each document, analyze the vocabulary composition of each theme, and find the elements related to them in the navigation rules. At the same time, according to the needs of ontology construction, manually delete and change the elements in a targeted manner, so as to establish the actual elements.

Based on the elements in the navigation rules in the LDA model, the relevant elements in the navigation rules are mainly the navigation rules (Rules), the (Ships), the (Area), the (Time), the (Trajectory), and the (Behavior), as shown in Table 2.

Table 2. Element extraction.

<table>
<thead>
<tr>
<th>Types of Elements</th>
<th>Categories</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rules</td>
<td>Traffic channel rules</td>
<td>Regulations for traffic routes</td>
</tr>
<tr>
<td></td>
<td>Maneuvering rules</td>
<td>Regulations for navigation</td>
</tr>
<tr>
<td></td>
<td>Berthing rules</td>
<td>Regulations for berthing process of ship</td>
</tr>
<tr>
<td></td>
<td>Avoidance rules</td>
<td>Regulations for ship collision avoidance</td>
</tr>
<tr>
<td>Ships</td>
<td>Large ship</td>
<td>Length greater than 80 m</td>
</tr>
<tr>
<td></td>
<td>Small ship</td>
<td>Length less and equal than 80 m</td>
</tr>
<tr>
<td></td>
<td>High-speed ship</td>
<td>Speed more than 19 kn</td>
</tr>
<tr>
<td>Area</td>
<td>Recommended channel</td>
<td>A route for small ships to navigate</td>
</tr>
<tr>
<td></td>
<td>Deepwater channel</td>
<td>A route for large ships to navigate</td>
</tr>
<tr>
<td></td>
<td>Bridge water area</td>
<td>Water area near the bridge</td>
</tr>
<tr>
<td></td>
<td>Special area</td>
<td>Special precaution area</td>
</tr>
<tr>
<td></td>
<td>Anchorage</td>
<td>Designated position to anchor</td>
</tr>
<tr>
<td>Time</td>
<td>Timestamp</td>
<td>At a certain moment</td>
</tr>
<tr>
<td></td>
<td>Time period</td>
<td>A period of time</td>
</tr>
<tr>
<td>Trajectory</td>
<td>Trajectory point</td>
<td>Single trajectory point</td>
</tr>
<tr>
<td></td>
<td>Trajectory segment</td>
<td>A line segment connecting multiple trajectory points</td>
</tr>
<tr>
<td>Behavior</td>
<td>State behavior</td>
<td>The ship behavior at a certain moment</td>
</tr>
<tr>
<td></td>
<td>Process behavior</td>
<td>The ship behavior in a period of time</td>
</tr>
</tbody>
</table>

3.2. Ontology Construction

In this section, the navigation rule ontology is constructed to convert the navigation rule elements into a structured knowledge base, so as to realize the knowledge sharing of navigation rules. Based on the rule knowledge base, the classification and expression of ship behavior is realized, and then the ontology of abnormal ship behavior is constructed.

3.2.1. Navigation Rule Ontology Construction

This section establishes a navigation rule ontology from the perspective of navigation rule cognition, encompassing the construction of classes and property relationships. Based on the previous analysis of navigation rules and the extraction of relevant elements,
three elements—Ships, Rules, and Area—are identified as classes within the navigation rule ontology. Additionally, different navigational rules apply to vessels within various spatial domains. To determine the applicable navigational rules for each Area element, the rules are matched with the Area elements, and the results are stored in the Space_rules class. These four classes are the key to the cognition of navigation rules, as shown in Figure 2; the ontology model of navigation rule cognition, which contains the four elements of navigation rule cognition, can provide a framework to support the cognition of navigation rules.

Figure 2. The ontology model for navigation rules.

(1) Class

The Ships class represents ships. A ship is mainly for water transportation and is the basic concept in navigation rules, and the individual ship is represented by MMSI.

The Rules class represents the rules. Rules refer to the navigation regulations that ships navigating in the water should comply with, including traffic channel rules, maneuvering rules, berthing rules, and avoidance rules.

The Area class represents the spatial elements of the waterway. According to the extraction of spatial elements and different navigable waters delineated by the maritime authorities, the fairway is divided into the deepwater channel, recommended channel, anchorage, special area, bridge water area, and other Area elements, each of which contains different subclasses of elements.

The Space_rules class represents the matching of different Area elements with rules.

(2) Object property

According to the relationship between classes, the corresponding relationship properties are established to further improve the expression ability of the navigation rule ontology knowledge, as shown in Table 3.
Table 3. The object properties in navigation rules.

<table>
<thead>
<tr>
<th>Object Properties</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>hasintersection</td>
<td>The intersection relationship between Area and Rules</td>
</tr>
<tr>
<td>hasRules, isruleof</td>
<td>The relationship between Area and Rules (inverse of each other)</td>
</tr>
<tr>
<td>hasShips, inArea</td>
<td>The relationship between Area and Ships (inverse of each other)</td>
</tr>
<tr>
<td>shouldobey</td>
<td>The relationship between Rules and Ships</td>
</tr>
<tr>
<td>isbelongto</td>
<td>The relationship between Rules and Space_rules</td>
</tr>
</tbody>
</table>

(3) Data property

Based on the object property between classes alone, it is difficult to accurately express the knowledge of navigation rules, and it is also necessary to define the data property of the concepts. The specific data property settings are shown in Table 4.

Table 4. The data properties in navigation rules.

<table>
<thead>
<tr>
<th>Data Properties</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course</td>
<td>Ship’s heading</td>
</tr>
<tr>
<td>Lat</td>
<td>Latitude</td>
</tr>
<tr>
<td>Length</td>
<td>Ship’s length</td>
</tr>
<tr>
<td>Lon</td>
<td>Longitude</td>
</tr>
<tr>
<td>MMSI</td>
<td>Maritime Mobile Service Identify</td>
</tr>
<tr>
<td>Speed</td>
<td>Ship’s speed</td>
</tr>
<tr>
<td>Type</td>
<td>Ship’s type</td>
</tr>
<tr>
<td>Width</td>
<td>Ship’s width</td>
</tr>
<tr>
<td>hasPoint</td>
<td>Point Area element’s position</td>
</tr>
<tr>
<td>hasLine</td>
<td>Linear Area element’s range</td>
</tr>
<tr>
<td>hasPolygon</td>
<td>Planar Area element’s range</td>
</tr>
<tr>
<td>hasName</td>
<td>Area element’s name</td>
</tr>
<tr>
<td>hasString</td>
<td>Rules’ text</td>
</tr>
<tr>
<td>hasImportance</td>
<td>The importance of rules</td>
</tr>
</tbody>
</table>

Course, Lat, Length, Lon, MMSI, Speed, Type, and Width all represent the data properties of the Ships, which correspond to heading, latitude, longitude, longitude, mobile service identification, speed, ship type, ship width, and other information, respectively.

hasLine, hasPoint, hasPolygon, hasNumber, and hasName represent the data properties of the Area elements. hasPoint represents the Area element as a point, hasLine represents the Area element as a line, hasPolygon represents the Area element as a surface, and hasNumber is the number of the Area element. hasName is the name of the Area element.

hasString and hasImportance are the data properties of the Rules. hasString indicates that the rule is expressed as a string, and hasImportance indicates the importance level of the set rule.

3.2.2. Abnormal Ship Behavior Ontology Construction

The classification and expression of ship behavior is the basis for establishing an ontology of abnormal ship behavior. By classifying and expressing ship behaviors, the scope and characteristics of various ship behaviors can be more clearly understood, so as to effectively determine which behaviors may be abnormal. Accurate behavior classification and expression provide reliable training data and benchmarks for the abnormal ship behavior ontology, which improves its accuracy and efficiency. Therefore, standardized ship
behavior classification and expression are essential before the construction of abnormal behavior ontology.

(1) Ship behavior classification

Through the analysis of navigation rules, ship behavior is divided into 2 categories: state behavior and process behavior.

1) Ship state behavior

Ship state behavior is the state of the ship at any moment. Ship state behavior can be described by the ship’s position state, speed state, and heading state. According to whether the ship is moving, the ship state behavior is divided into navigation state behavior and stopping state behavior.

Ship navigation state behavior is the behavior of the ship while navigating in the waters. According to the properties of position, speed, and heading of the ship, the ship navigation state behavior can be divided into different types, as shown in Figure 3.

![Diagram of ship navigation behavior](image)

Figure 3. Diagram of ship navigation behavior.

Ship stopping state behavior is the behavior of a ship that remains stationary in the water. Based on the ship’s position and speed property, it can be determined whether the ship is anchoring or mooring.

2) Ship process behavior

Ship process behavior is a series of state behavior combinations of the ship in the process of sailing, maneuvering, and berthing. It is a complex behavioral process demonstrated by a trajectory segment connected with the ship’s trajectory points. According to the understanding of the navigation rules in the previous article, the process behavior is divided into four categories: channel area behavior (deepwater channel, recommended channel, special area, bridge water area), wharf area behavior, anchorage behavior, and other general area behavior. Different process behaviors exist in different waters, as shown in Table 5.

<table>
<thead>
<tr>
<th>Process Behaviors</th>
<th>Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>channel area behavior</td>
<td>navigation, crossing, entering, leaving</td>
</tr>
<tr>
<td>wharf area behavior</td>
<td>berthing, unberthing</td>
</tr>
<tr>
<td>anchorage behavior</td>
<td>entering, leaving, anchoring</td>
</tr>
<tr>
<td>other general area behavior</td>
<td>turnaround</td>
</tr>
</tbody>
</table>
(2) Ship topology relationships

Ship behavior is related to space and time, and in this study, the DE-9IM model was used to calculate the topological relationship between ship behavior and space. The DE-9IM model [29] was used to describe the topological relationship between entity a and entity b’s interior (Interior, I), boundary (Boundary, B), and exterior (Exterior, E), which constitutes an intersection of a 3 × 3 matrix, as in Equation (1):

\[
DE9IM(a, b) = \begin{bmatrix}
\text{dim}(I_a \cap I_b) & \text{dim}(I_a \cap B_b) & \text{dim}(I_a \cap E_b) \\
\text{dim}(B_a \cap I_b) & \text{dim}(B_a \cap B_b) & \text{dim}(B_a \cap E_b) \\
\text{dim}(E_a \cap I_b) & \text{dim}(E_a \cap B_b) & \text{dim}(E_a \cap E_b)
\end{bmatrix}
\]

(1)

*dim refers to the dimension, and DE-9IM computes the intersection between 3 regions of two geometric objects separately to derive the value of *dim*, which is 0 for points, 1 for lines, 2 for faces, and F for the multipoint null set (no intersection).

The topological relationship between ship trajectory elements and spatial elements is mainly manifested as the relationship between point and line, line and line, point and plane, and line and plane, and the set \( Tset = \{ Tset_1, Tset_2, \ldots, Tset_{12} \} \) of the topological relationship is obtained. The topological relationship of ships in the water space can be represented by one of \( Tset \), as shown in Figure 4. The blue point is the ship trajectory point, the blue line is the ship trajectory segment, the black lines are linear Area elements, and the closed planes are planar Area elements.

Figure 4. Topological relationship between ship trajectory and Area elements.

(3) Ship behavior expression

Based on the classification of ship behaviors and the calculation of topological relations in the previous section, ship state behaviors and process behaviors are expressed.
1) Ship state behavior expression

The ship state consists of different parameters which can be expressed by Equation (2):

\[ Q_i = \{ p_i, t_i, c_i, v_i, a, \varphi \} \]  

(2)

\( p_i \) is the ship’s position, \( t_i \) is the corresponding time point, \( c_i \) is the ship’s heading, \( v_i \) is the ship’s speed, \( a \) is the ship’s acceleration, and \( \varphi \) is the ship’s steering rate.

Combining the states of ship trajectory points and the spatial topological relations, the ship state behavior can be expressed as:

\[ \text{state}_i = \{ Q_i, T_{set}, Rule_k \} \]  

(3)

\( Q_i \) is the ship state, \( T_{set} \) is the topological relationship between ship trajectory points and spatial elements, and \( Rule_k \) is the rule for matching ship trajectory points.

2) Ship process behavior expression

On the basis of the expression of ship state behavior, the ship process behavior is expressed by combining the topological relationship between the ship trajectory segment and the spatial elements in the water. The ship process behavior can be expressed as:

\[ P = \{ (Q_{i...Q_{i+n}}), T_{set}, Rule_k \} \]  

(4)

\( P \) is a process behavior, \( (Q_{i...Q_{i+n}}) \) is a ship trajectory segment, \( T_{set} \) is a topological relationship between ship trajectory segments and spatial elements, and \( Rule_k \) is a rule for matching ship trajectory segments.

(4) Abnormal ship behavior ontology construction

Abnormal ship behavior usually refers to ship behavior that violates the navigation rules, is inconsistent with normal ship behavior, or has potential risks. Possible abnormalities in ship behavior are divided into 2 categories: state behavior abnormality and process behavior abnormality, as shown in Table 6.

Based on the 22 navigation rules extracted in the previous section, the existing abnormal ship behaviors were analyzed. Any abnormal ship behavior may violate multiple navigation rules. Additionally, some navigation rules corresponded to ship behaviors that were difficult to quantify, such as maintaining a safe speed. Consequently, after further analysis of each navigation rule, 13 types of abnormal ship behavior were identified, including 6 types of state abnormal behavior and 7 types of process abnormal behavior, as detailed in Table 6.

Table 6. Classification of abnormal behavior of ships.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>State abnormal</td>
<td>large ships with high speed in recommended channel</td>
</tr>
<tr>
<td></td>
<td>small ships in deepwater channel</td>
</tr>
<tr>
<td></td>
<td>the speed in the channel is too high</td>
</tr>
<tr>
<td></td>
<td>the speed in the channel is too low</td>
</tr>
<tr>
<td></td>
<td>the speed in the bridge water area is too high</td>
</tr>
<tr>
<td></td>
<td>the speed in the bridge water area is too low</td>
</tr>
<tr>
<td>Process abnormal</td>
<td>crossing the bridge water area</td>
</tr>
</tbody>
</table>
Among them, the process behavioral abnormality schematic is shown in Figure 5: trajectory 1 is the ship crossing in the bridge area waters, trajectory 2 is the ship deviating from the navigation channel, trajectory 3 is the ship turning around in the bridge area waters, trajectory 4 is the ship going against the flow, trajectory 5 is the ship occupying the separation zone for a long period of time, trajectory 6 is the ship sailing into the anchorage, which is an anchorage abnormality if it accelerates into the anchorage in the process, and trajectory 7 is crossing at a small angle.

Figure 5. Diagram of abnormal process behavior.

According to the previous classification and expression of abnormal ship behavior, the core classes and the property relationships between the classes in the abnormal ship behavior ontology are shown in Figure 6.
Figure 6. Core classes and interclass relationships in the ontology of abnormal ship behavior.

1) Classes in the abnormal ship behavior ontology

The Ships, Space_rules, and Area classes involved in the abnormal behavior ontology of ships in this section come from the navigation rules ontology. This section explains the Topology, Time, Trajectory and abnormal behavior (Ab_behavior) classes that are not involved in the navigation rules ontology.

Ab_behavior refers to abnormal ship behavior, which is the core class in the abnormal ship behavior ontology. Based on the classification and cognitive results of abnormal ship behavior in the previous section, abnormal ship behavior is divided into two subclasses, which embody the behaviors of the ship trajectory points and ship trajectory segments, respectively, including the class of state behavior abnormality (S_ab_behavior) and the class of process behavior abnormality (P_ab_behavior). State behavior abnormality can be divided into large ships with high speed in the recommended channel (ab1), non-high speed of ships with dangerous goods in the deepwater channel (ab2), the speed in the channel being too high (ab3), the speed in the channel being too low (ab4), the speed in the bridge water area being too high (ab5), and the speed in the bridge water area being too low (ab6). Process behavior abnormality is divided into crossing the bridge water area (ab7), deviation from the course (ab8), turnaround in the bridge water area (ab9), the ship going the opposite way from the right direction (ab10), spending a long time navigating within the separation zone (ab11), abnormal entering to the anchorage area (ab12), and crossing the channel with a small angle (ab13).

Topology refers to the class of topological relationships, which is a description of the relationship between ship trajectory classes and spatial elements, involving 12 different topological relationships such as Tset1, Tset2...Tset12. Ship trajectory points and ship trajectory segments have different topological relationships with spatial elements.

Time class refers to the time when abnormal ship behavior occurs and is a key element in the ontology of abnormal ship behavior. According to the characteristics of abnormal ship behavior, time is divided into time points and time intervals.

Trajectory class refers to the trajectory of a ship, which is divided into two subcategories: trajectory points (Traj_p) and trajectory segments (Traj_s).

2) Object properties

In order to describe the relationship between classes in the abnormal ship behavior ontology and further improve the expressive ability of the ontology knowledge, the object properties of the ontology were established as shown in Table 7.
Among them, `hasTimepoint` contains three sub-properties, `hasOccurTime`, `hasStartTime`, and `hasEndTime`, which represent the specific time when the state behavior occurs and the start time and end time of the process behavior, respectively.

3) Data properties

In order to describe the characteristics of each class of the abnormal ship behavior ontology, the data properties in the abnormal ship behavior ontology were established. The data properties of Ships class, Area class, and Space_rules class in this ontology are consistent with those in the navigation rule ontology. The data property of Time was established for the Time class on this basis, representing the UTC time of Timepoint in the time class, and was stored in the form of a timestamp.

4) Abnormal ship behavior ontology visualization

After completing the construction of classes and properties of the abnormal ship behavior ontology, it was implemented by using Protégé software. The concepts in the ontology of abnormal ship behavior exist in the form of classes. Based on the interclass relationships in the ontology of abnormal ship behavior, the hierarchical relationships of classes were added to the Protégé software, and visualization was achieved by using the OntoGraf plugin in the software. Figure 7 shows the visualized results of the abnormal ship behavior ontology and its relationships.

![Figure 7. Main classes, attributes, and their relationships in the ontology of abnormal ship behavior.](image-url)
3.3. Inference Methods for Abnormal Ship Behavior

Abnormal ship behavior inference involves deducing conclusions from established conditions, as illustrated in Figure 8. Once the ship trajectory data are integrated into the ontology, reasoning is applied to the abnormal ship behavior ontology. In this study, we leverage AIS data as a valuable asset for acquiring ship-related information. They furnish vital data, including Maritime Mobile Service Identity (MMSI), timestamp, longitude, latitude, sailing speed, and course of ground (COG), enabling us to utilize inference methods for detecting abnormal ship behavior using pre-processed AIS data.

The inference process comprises ontology reasoning and rule-based reasoning. Ontology reasoning checks the consistency of the abnormal ship behavior ontology to ensure its validity, while rule reasoning applies the formulated SWRL reasoning rules to derive conclusions regarding abnormal ship behavior.

(1) Ontological reasoning

Ontological reasoning refers to the process of acquiring new knowledge by using the definitions of concepts, entities, relationships, and attributes in an ontology, and specific reasoning is divided into satisfiability checking, classification reasoning, and instance reasoning.

Satisfiability checking is a crucial task in ontology reasoning, aimed at ensuring the consistency and validity of the ontology. It involves two aspects: ontology satisfiability checking and concept satisfiability checking. The former checks for contradictions or inconsistencies within the entire ontology, while the latter verifies whether concepts have valid interpretations. As shown in Figure 9a, the intersection of the concepts “Deepwater channel” and “Recommended channel” is an empty set, indicating that there is no spatial entity F that can simultaneously be both Deepwater channel and Recommended channel. If a concept Entity is an empty set, then the concept is unsatisfiable.

Classification reasoning refers to the process of assigning entities or concepts to their appropriate categories. As shown in Figure 9b, if Deepwater channel is a subset of channel, and channel is a subset of Area, then it can be inferred that “Deepwater channel is a subset of space”.

Instance reasoning involves deriving new instances based on known concepts and their relationships. As illustrated in Figure 9c, if it is known that F is a Deepwater channel and it is a subset of Space, then it can be inferred that F is a Space, and a new instance for the Space category is inferred. Additionally, if the relationship between F and Deepwater channel
channel is defined as ‘has_C’, and ‘has_C’ is a subclass of ‘has_B’, it can be deduced that there is a new binary relationship ‘has_B’ between F and Deepwater channel.

### Figure 9. Examples of ontological inference.

(2) Rule-based reasoning

Rule-based reasoning is primarily implemented through two methods: predicate logic and production rules. However, for many formulas, predicate logic may result in the loss of crucial information during the process of generating clauses, thereby reducing the expressiveness efficiency of those clauses. Hence, the adoption of condition-action production rules, which are easier to articulate, is preferred for reasoning. These rules are formally expressed as “If P Then Q” or “P → Q” [30], wherein if condition P is satisfied, conclusion Q can be inferred. Unlike implication formulas in predicate logic, where P and Q are strictly predicate formulas, in these rules, P and Q can also be symbols outside predicate formulas. In practical applications, P denotes phenomena or facts, while Q represents corresponding conclusions or actions, which facilitates the expression of causal relationships between any two concepts. Rule-based reasoning methods possess a clear logical structure, making them easy to understand and debug. The formalized representation of rules enables intuitive knowledge expression, enhancing system flexibility and adaptability to diverse application scenarios. The independence among rules ensures that adding, deleting, or modifying a specific rule does not directly impact other rules.

The inference rules established in this paper take the form “if condition_1 ^ condition_2 ^ ... ^ condition_n, then conclusion”. The formal representation is as shown in Equation (5), which indicates that there exist three classes, A, B, and C, with a non-empty intersection. If there is a property relationship P1 between an instance “?a” from class A and an instance “?b” from class B, as well as a property relationship P2 between an instance “?b” from class B and an instance “?c” from class C, then it can be inferred that there is a property relationship Q between the instances “?a” and “?c.”
\[ \exists \, A, B, C, A^* B^* C = \emptyset \]

\[ \text{if } A(?a) \wedge B(?b) \wedge P1(?a, ?b) \wedge C(?c) \wedge P2(?b, ?c) \]

\[ \text{then } Q(?a, ?c) \]

(5)

In this paper, SWRL is used to establish corresponding condition–action production rules for anomalous behaviors ab1 to ab13. As an example, the process of formalizing ship behavior rules is illustrated with the anomalous behavior ab1, as follows:

(1) \( \text{Ships(?s)} \text{^ Traj}_s(?seg) \text{^ Traj}_p(?p) \text{^ ab1(?Ab1)} \text{^ haspoint(?s, ?p)} \text{^ Recommended_fairway (?r)} \text{^ hasTopo(?p, ?r)} \text{^ swrlb:equal(?t, ”Tset5”)} \text{^ Speed(?p, ?a)} \text{^ Length(?p, ?l)} \text{^ swrlb:greaterThan(?a, ”19″^^xsd:float)} \text{^ swrlb:greaterThan(?l, ”80″^^xsd:float)} \rightarrow \text{hasS_ab(?s, ?Ab1)} \)

(2) \( \text{Ships(?s)} \text{^ Traj}_s(?seg) \text{^ Traj}_p(?p) \text{^ rule10(?r10)} \text{^ Space_rules(?R)} \text{^ ab1(?Ab1)} \text{^ hasS_ab(?s, ?Ab1)} \rightarrow \text{disobey(?s, ?r10)} \)

In the inference rule (1) described above, a vessel has a trajectory segment, and the segment contains trajectory points. Each trajectory point in the vessel’s segment has a topological relationship of type \( \text{Tset} \) with a recommended channel. If the vessel has a length greater than 80 m and a speed exceeding 19 knots, this indicates that a large high-speed vessel is navigating on the recommended channel, suggesting an abnormal state behavior. This leads to the inference that the anomalous behavior is categorized as ab1.

In inference rule (2), the inferred anomalous behavior ab1 is matched with the navigational rules, leading to the deduction that the violated navigational rule is \( \text{rule10} \).

Since SWRL rules do not inherently possess inference capabilities, a reasoning engine is required to infer anomalous vessel behaviors. The Pellet reasoning engine [31] is used to carry out the inference operations, and the resulting OWL ontology files can be further used for knowledge visualization, analysis, or extraction. The inference algorithm process is outlined in Algorithm 1.

---

**Algorithm 1. Pellet reasoning algorithm process.**

**Input:** Set of Concepts \( C \)

**Output:** Concept Tree \( T \)

**Step 1:** Initialize by creating a root node \( x \) with \( L(x) = \emptyset \)

**Step 2:** For each concept \( C_i \) in the set \( C \):
   
   If \( C_i \) has existential constraints, then
   
   \( L(x) = L(x) \cup \{C_i\} \).

   If \( D \in L(x) \) and \( \neg D \in L(x) \), then
   
   mark \( \{D, \neg D\} \) as a conflict.

**Step 3:** For each node \( x \) in the tree:
   
   For each concept \( C_j \) with existential constraints in \( L(x) \),
   
   create a new node \( y \),
   
   set \( L(y) = \{C_j\} \),
   
   add \( y \) as a successor to \( x \) with an edge \( (x, y) \).

**Step 4:** Check whether \( (x) \) at each node \( x \) contains any conflicts.

   If conflicts are found, prune the branch.
Step 5: The algorithm terminates when all nodes have been expanded without conflicts, or when no further existential constraints can be added.

End.

Suppose that the ontology model for anomalous ship behavior contains information indicating that ship A is navigating on recommended channel C, with its trajectory point B showing that the ship has a length of 90 m and a speed of 20 knots. When examining Ship A’s navigational status using the inference rules, an anomalous behavior (ab1) is detected, indicating a violation of rule 10. The transformation in the ontological inference is illustrated in Figure 10.

Figure 10. Diagram of anomalous behavior inference expression.

4. Case Study and Results

4.1. Study Area and Dataset

To explore the practicality of the proposed method in this paper, the study area selected was from Red Buoy No. 22 to the mouth of the Yangtze River in the Jiangsu section. Ship AIS trajectories within this area on 6 December 2023 were chosen for conducting experiments on inferring abnormal ship behavior. The original dataset contains seven types of information on ship dynamics and statics, with a total of 877,709 records.

The raw AIS data may present several types of errors, encompassing positional inaccuracies, velocity aberrations, and trajectory deviations. Positional inaccuracies denote instances where vessel data are erroneously marked at incorrect geographical coordinates, potentially including landmasses. Velocity aberrations signify situations where the vessel speed surpasses its maximum allowable navigational limit. Trajectory deviations manifest...
as discrepancies in ship trajectory points, leading to discernible deviations from neighboring trajectory points. To uphold experimental precision, this research employed a data cleansing strategy to address these irregular data occurrences. Following meticulous data preprocessing, the study retained a dataset comprising 846,675 ship records. AIS data quality dimensions were presented for processing errors of AIS tracks [32]. The ship AIS trajectories in the study area are depicted in Figure 11a.

**Figure 11.** Visualizes the study area and experimental data in the research waters.

As shown in Figure 11b, specific Area elements within the study area were delineated, including deepwater channels, recommended channels, separation zones, anchorages, and bridge water areas.

### 4.2. Results Analysis

Three experiments were designed in this study to validate three types of abnormal behaviors: speed anomalies, turnaround anomalies, and crossing anomalies. For speed anomalies, any speed inconsistent with the prescribed speed in navigation rules within the channel was identified as a speed anomaly. For turnaround anomalies, all turnaround behaviors were first identified, and then turnaround behaviors occurring in bridge areas were inferred as anomalies. For crossing anomalies, all crossing behaviors were initially identified, and then crossing behaviors occurring in bridge areas and those with small crossing angles were inferred as anomalies.

#### 4.2.1. Abnormal Speed Behavior

Navigation rules prescribe speed limits for vessels. Based on the inference results of abnormal ship speed behaviors, the quantities of vessels with excessive and insufficient speeds were counted, respectively. The distribution patterns of these behaviors in bridge areas and channels were analyzed. Furthermore, an analysis of abnormal speed behaviors was conducted for different types of vessels, including cargo ships, tankers, fishing boats, ferries, tugs, law enforcement vessels, and port operation vessels. The specific results are shown in Figure 12, which illustrates (a) the quantity of vessels with excessively low speeds in channels, (b) the quantity of vessels with excessively high speeds in channels, (c) the quantity of vessels with excessively low speeds in bridge water areas, and (d) the quantity of vessels with excessively high speeds in bridge water areas. From the inference results, it can be observed that the number of vessels navigating at excessive speeds in channels was significantly lower than those with low speeds. The majority of vessels with speed abnormalities were cargo ships, and the number of vessels with speed abnormalities in the upstream channel was significantly higher than in the downstream channel.
Additionally, the number of vessels traveling at excessive speeds in bridge water areas was higher than in other areas.

![Graphs showing vessel speed anomalies](image)

**Figure 12.** Analysis of inference results for ship speed anomalies. (a) Vessels with insufficient speeds in channels; (b) vessels with excessive speeds in channels; (c) vessels with insufficient speeds in bridge water; (d) vessels with excessive speeds in bridge water.

### 4.2.2. Abnormal Turnaround Behavior

A total of 128 turnaround behaviors were deduced from all the ship turnaround behaviors in the study waters, and the regional distribution of turnaround behaviors and time statistics are shown in Table 8.

**Table 8.** Statistical results for turnaround behavior.

<table>
<thead>
<tr>
<th>Area</th>
<th>Number</th>
<th>Average Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>bridge water area</td>
<td>1</td>
<td>5 min</td>
</tr>
<tr>
<td>channel</td>
<td>29</td>
<td>8 min</td>
</tr>
<tr>
<td>near the wharf</td>
<td>41</td>
<td>15 min</td>
</tr>
<tr>
<td>near the anchorage</td>
<td>51</td>
<td>10 min</td>
</tr>
</tbody>
</table>

Some of the typical turnaround behaviors are shown in Figure 13. (a) The turnaround trajectory shows that the ship turned around near the waterfront of the pier, with deceleration in the process of approaching the pier, and that the ship might have gone to berth at the pier, which is a normal turnaround behavior. (b) The turnaround trajectory shows...
that the ship turned around inside the channel near the pier, which is a normal turnaround behavior. (c) The turnaround trajectory shows that the ship navigated from the downward recommended channel and sailed into the upward recommended channel after the turnaround, which is a normal turnaround behavior. (d) The turnaround trajectory in (d) shows that the vessel sailed into the downward recommended channel from the waters outside the channel and sailed into the upward recommended channel after making a U-turn. The vessel was a harbor service vessel, and it may have been a normal turnaround, as it was going to other waters for operation after providing services at other terminals. (e) The turnaround track in (e) shows that the vessel sailed from the inner channel to the outer channel, made a U-turn outside the channel, and sailed into the downward recommended channel. The vessel was a law enforcement vessel, and it may have been an emergency turnaround for the role of law enforcement, which is a normal turnaround behavior. (f) The turnaround trajectory in (f) shows that the vessel was sailing in the bridge water area from the downward recommended channel and sailed into the upward recommended channel after making a turnaround, which is in violation of rule15. This was an abnormal turnaround behavior.
4.2.3. Abnormal Crossing Behavior

To infer abnormal ship crossing behaviors, all ship crossing behaviors were first reasoned, resulting in a total of 846 crossing behaviors identified. The spatial distribution and temporal statistics of these crossing behaviors are summarized in Table 9.

Table 9. Statistical results for crossing behavior.

<table>
<thead>
<tr>
<th>Area</th>
<th>Number</th>
<th>Average Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>crossing in bridge water area</td>
<td>1</td>
<td>7 min</td>
</tr>
<tr>
<td>crossing in channel</td>
<td>845</td>
<td>8 min</td>
</tr>
<tr>
<td>crossing channel with small angle</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

Some of the typical crossing behaviors are shown in Figure 14. Namely, (a) is a ferry sailing back and forth between terminals on both sides of the channel, which is a normal crossing behavior; (b) is a cargo ship crossing the channel from one side of the recommended downstream channel into the other side of the downstream channel near the channel bifurcation, which is a normal behavior; (c) is an oil tanker sailing out of the channel into the recommended upstream channel and then crossing the channel into the recommended downstream channel, which is a normal behavior; (d) is a cargo ship crossing the channel into the anchorage from the upstream deepwater channel, which is a normal crossing; (e) is a cargo ship anchoring in an anchorage and then crossing the channel to berth at a pier in a normal crossing; and (f) is a port service vessel entering the channel from outside the channel and crossing the bridge water area in violation of rules, which is an abnormal crossing.
Figure 14. Partial inference results for crossing behavior. (a) Crossing trajectory 1; (b) crossing trajectory 2; (c) crossing trajectory 3; (d) crossing trajectory 4; (e) crossing trajectory 5; (f) crossing trajectory 6.

The experimental results indicate that an abnormal ship behavior reasoning method based on the ontology of abnormal ship behaviors can accurately infer the existence of abnormal behaviors in ships. This method can accurately identify abnormal ship state behaviors and process behaviors in different scenarios, providing effective technical support for water traffic supervision.

5. Discussion

Accurately identifying abnormal vessel behavior is crucial for enhancing maritime traffic supervision and navigation safety. There are two primary approaches to identifying...
abnormal ship behaviors: data-driven and knowledge-driven methods [15]. Data-driven abnormal ship behavior identification methods learn the characteristics of traffic data and predict ship trajectories based on predominant features, thereby identifying “abnormal behaviors” that deviate from these mainstream characteristics. However, these methods lack knowledge about rule-compliant behaviors, making it difficult to determine whether a vessel’s behavior adheres to established rules.

Knowledge-driven methods for identifying abnormal ship behaviors leverage behavior reasoning modeling techniques, including rule-based systems, case-based reasoning, and ontological reasoning, to generate identification models. This paper proposes an ontology-based approach for identifying abnormal ship behaviors, achieving accurate identification of vessel behaviors that contravene navigation rules by delving into their intricacies. The advantages of ontology-based reasoning methods lie primarily in their ability to represent semantic concepts and their relationships in a structured manner, organize and structure knowledge in a clear manner, provide machine-readable representations, and support expressive capabilities for the reasoning process.

Employing the methodology delineated in this study, experiments were carried out within the Jiangsu segment of the Yangtze River, where the abnormal behaviors of ships were systematically identified and analyzed. The results of this study can be applied in the maritime supervision system to achieve accurate identification of abnormal behavior of ships and can automatically match the navigation rules violated by ships. This will effectively reduce the time consumption of manual detection and enhance the intelligence level of maritime supervision.

The semantic expressions of some navigation rules are relatively complex and cover a wide range of abnormal behaviors, which brings challenges to quantitative analysis and inference identification. For example, the safe speed in rules is not a fixed value but depends on the specific situation. Such uncertainty makes it difficult for a reasoning machine to perform automatic reasoning and judgement on such rules. Future research endeavors may pivot upon the intricate semantic formulations of navigational rules, employing methodologies such as rule decomposition and knowledge modeling to delve deeper into the analysis of abnormal ship behaviors within complex navigational rules. This pursuit holds promise for extending the applicability of the proposed methodology to maritime domains worldwide, characterized by diverse sets of navigational regulations.

6. Conclusions

We aimed to address the lack of effective monitoring means for the existing abnormal behaviors of ships violating navigation rules, as it is difficult to meet modern regulatory needs through manual monitoring alone. This paper researched an ontology-based identification method for abnormal behaviors of ships to improve detection efficiency and accuracy. By analyzing the navigation rules, the elements of navigation rules were extracted; according to these, an ontology of navigation rules was established, and the classification and expression of ship behaviors were realized. Then, an ontology of abnormal ship behaviors was established to realize the reasoning of abnormal ship behaviors. The experimental results show that the method can accurately identify the abnormal behavior of ships. The research results of this paper provide a basis for maritime traffic supervision and enhance the level of navigation safety.

Author Contributions: Conceptualization, C.Z.; methodology, K.W., J.Z. and Z.B.; software, Z.B.; validation, C.Z. and K.W.; formal analysis, Z.B., T.L. and M.K.K.L.; investigation, J.Z.; data curation, J.Z.; writing—original draft preparation, K.W. and Z.B.; writing—review and editing, C.Z., K.W., J.Z. and M.K.K.L.; visualization, K.W., J.Z. and T.L.; supervision, C.Z.; project administration, C.Z. and C.W.; funding acquisition, C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science Foundation of China (grant number 52171349), the Laboratory of Transport Pollution Control and Monitoring Technology (2022JH-F038),
and the Key Research Plan of Zhejiang Provincial Department of Science and Technology, China (2021C01010).

**Institutional Review Board Statement:** No applicable.

**Informed Consent Statement:** No applicable.

**Data Availability Statement:** Data is available upon request from the authors.

**Acknowledgments:** We sincerely thank the editor and reviewers for their kind and helpful comments on this manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

### Appendix A. Navigation Rules

1. **Traffic channel rules**

   - **rules:** The deepwater channel is mainly for large ships.
   - **rules:** The recommended channel is mainly for small ships.

2. **Maneuvering rules**

   - **rules:** Ships should navigate at a safe speed at all times.
   - **rules:** Ships should navigate at speeds between 4kn and 15kn.
   - **rules:** Ships should navigate in specified channel.
   - **rules:** Ships should navigate to the right according to the fairway direction.
   - **rules:** Ships should have a dynamic report when passing a position verification point.
   - **rules:** Ships should report their position when passing a position reporting line.
   - **rules:** Ships should overtake from the port side of the overtaken ship; the overtaken ship should take actions to assist in avoidance.
   - **rules:** A large ship with a low speed should navigate along the right edge of the channel and can enter the recommended channel under the condition of ensuring safety.
   - **rules:** Small ships carrying dangerous goods at high speed can navigate to the right edge of the deepwater channel.

3. **Berthing rules**

   - **rules:** Ships should obey the special rules in special areas.
   - **rules:** Ships should navigate at safe speeds in the bridge water area.
   - **rules:** Speed should not exceed 11kn in the bridge water area.
   - **rules:** Ships should not stop their engines when bound for navigating, turning, crossing, or passing non-navigable bridge openings in the bridge water area.
   - **rules:** Ships should not overtake or navigate side by side when passing through the restricted bridge water area.
   - **rules:** When ships approach the docks or berth within the bridge water area, they should avoid normally navigating ships.

4. **Berthing rules**

   - **rules:** Large ships should be anchored within the anchorage or stopping area.
   - **rules:** Small ships should choose anchorage and berthing areas for stopping, excluding sea vessel anchorage and berthing areas. Stopping out of the channel is allowed when it is safe.
   - **rules:** In special circumstances, stopping can be performed nearby.

5. **Avoidance rules**

   - **rules:** Ships entering or exiting estuaries, tributaries, or special areas should give way to vessels that are navigating within designated traffic lanes or recommended channels.

### References


**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.