An Ontology-Based Framework for Climate Sensor Data*

Meriem Djezzar[1,*], Mounir Hemam[1], Ridha Mehalaine[1], Zahia Benamour[1] and Zianou Ahmed Seghir[1]

[1]ICOSI Laboratory, University of Abbes Laghrour, Khenchela, Algeria

Abstract

The effective management of climate data requires seamless integration, sharing, and analysis of diverse environmental information collected via sensor technologies and Wireless Sensor Networks (WSN). These networks generate vast amounts of heterogeneous data, and ensuring their interoperability and reusability is essential for building robust domain-specific or cross-domain applications. This paper proposes an ontology-based framework leveraging semantic web technologies to address the challenges of semantic interoperability in climate sensor data. Our approach extends the SSN ontology to define a domain-specific vocabulary, enabling the semantic annotation of sensors, observations, and measurements with spatial, temporal, and thematic metadata. Climate sensor datasets are published as linked data to facilitate efficient querying, integration, and analysis of sensor descriptions and real-time streams. Additionally, a reasoning mechanism is applied to these semantically enriched datasets to infer implicit knowledge, identify significant patterns, and respond to complex queries.

Keywords

Semantic Modeling, Ontology, Sensor Web, Interoperability, Climate Data

1. Introduction

The climate sensor data encompasses the information and measurements gathered by the sensors used to monitor environmental parameters associated with climate. These sensors collect data on variables such as temperature, humidity, atmospheric pressure, wind speed and direction, solar radiation, precipitation, and other climate-related factors [1]. This information is essential to understand the current and historical climatic conditions within a particular area or region. Climate Sensor Data find numerous applications across various domains. In meteorology and climatology, it is used to study and monitor weather patterns, climate trends, and extreme events. Climate Sensor Data is also employed in agricultural and environmental sciences to optimize irrigation practices, assess soil moisture levels, and monitor the health of ecosystems.

4th International Workshop on Multilingual Semantic Web, December 10, 2024

*Corresponding author.

meriem.djezzar@univ-khenchela.dz (M. Djezzar); hemam.mounir@univ-khenchela.dz (M. Hemam); r_mahalaine@univ-khenchela.dz (R. Mehalaine); benamor.zahia@gmail.com (Z. Benamour); zianou.ahmed.saghir@univ-khenchela.dz (Z. A. Seghir)

0000-0003-0004-1227 (M. Djezzar); 0000-0002-4410-4528 (M. Hemam); 0000-0002-2999-7604 (R. Mehalaine); 0000-0001-9590-8625 (Z. Benamour); 0000-0003-3310-1062 (Z. A. Seghir)

CEUR Workshop Proceedings ceur-ws.org ISSN 1613-0073

Climate sensor data are collected from multiple sources, such as weather stations, climate monitoring networks, research institutions, satellites, and environmental monitoring equipment. Weather stations are strategically placed to collect localized climate data, whereas climate monitoring networks consist of interconnected stations or sensors spread over a larger area to capture more comprehensive data. Research institutions often use specialized sensors to monitor specific climate variables for research purposes.

Wireless Sensor Networks (WSN) have become increasingly important in climate monitoring due to their ability to collect real-time environmental data from diverse sources. These networks, consisting of distributed sensors, allow for the real-time collection of environmental data on climate-related phenomena [2]. However, managing these data, which often originate from heterogeneous sources and lack semantic context, poses a significant challenge for their practical use. The absence of semantic metadata complicates the integration, interoperability, and effective utilization of data from various sensor networks.

In this context, the use of Semantic Web technologies, coupled with tailored ontologies, offers a solution to enrich climate sensor data [3]. An ontology-based framework provides a common semantic structure for describing sensors, observations, and measurements, integrating metadata on spatial, temporal, and thematic properties. This framework facilitates semantic annotation of sensor data, improving interoperability, and enabling better analysis and decision making for climate risk management. This paper presents an ontology-based framework for climate sensor data, aiming to enhance the retrieval, interpretation, and integration of data from heterogeneous sensor networks. By enriching sensor descriptions and data streams with semantic metadata, our approach facilitates data access and supports inferences that help in complex decision-making processes related to climate change and risk management. To address the challenges of managing and utilizing climate sensor data, we exploit semantic web technologies for the following reasons:

- Semantic descriptions provide explicit and structured meanings for climate sensor data, making it understandable and manageable by machines.
- Semantics enhances interoperability by harmonizing heterogeneous climate sensor data under a shared vocabulary.
- Climate sensor data streams can be linked to existing web resources, facilitating seamless access and reuse by external applications.
- Semantic reasoning engines allow the inference of high-level abstractions, leveraging domain-specific expertise.

To address the challenges of managing and utilizing climatic sensor data, the main contributions of this paper are as follows:

- Definition of a Climate Sensor Data Ontological Model: Firstly, we define an ontological model for climate sensor data, extended from the modular SSN ontology [4]. The developed model consists of various concepts that describe both climatic sensor characteristics and the data they generate, such as measurements and observations from the meteorological and climatology domain. This model provides a unified framework for organizing and standardizing sensor data specific to climatic conditions.

- Semantic Annotation and Enrichment of Climate Sensor Data: Building upon the developed ontological model, we propose the semantic annotation and enrichment of climate sensor descriptions and climatic data streams with metadata. This semantic layer enhances interoperability and provides essential contextual information for better understanding of the climatic conditions. Specifically, we focus on annotating climate data with spatial, temporal, and thematic metadata, making it more accessible for both human interpretation and machine processing.
- Publication of Linked Climate Sensor Data: In order to support seamless integration and sharing, we propose to publish climatic sensor datasets following linked data principles [5]. This approach allows for smooth navigation across climatic sensor data and other related datasets, enabling the efficient reuse of information across various applications related to climate monitoring.
- Semantic Rule-Based Reasoning: Finally, we apply a semantic rule-based reasoning approach to derive high-level abstractions from climate sensor data. The reasoning engine is based on the Semantic Web Rule Language (SWRL) [6], which allows us to infer climatic patterns and detect significant insights from the semantically enriched sensor data. This reasoning layer enhances decision-making and provides the foundation for more complex queries regarding climate change and risk management.

The remainder of this paper is organized as follows. After some preliminary concepts discussed in Section 2, we present, in Section 3, our approach proposed for semantic enrichment of climate sensor data. Finally, conclusion about the current phase of the work and our future work will be given in Section 4.

2. Preliminary Definitions

2.1. Semantic Web Framework

The Semantic Web, as envisioned by Tim Berners-Lee and developed under the guidance of the W3C Semantic Web Activity [7], aims to enhance the current web by encoding the meaning (semantics) of resources into a format that is machine-readable. This transformation allows computers to efficiently search, process, integrate, and present web content in a more meaningful and intelligent way.

At the core of the Semantic Web are key technologies, including the Resource Description Framework (RDF) [8], RDF Schema (RDF-S) [9], and the Web Ontology Language (OWL) [10]. These technologies enable the representation, organization, and reasoning over data in a semantic manner.

Resource Description Framework (RDF). RDF provides a graph-based model for linking data within a specific domain using named relationships. In RDF, data is expressed as triples: subject-predicate-object, which resemble a sentence's structure with a subject, verb, and object. These triples form a directed graph where the subject and object are nodes, and the predicate represents the relationship between them. Each element in the triple is uniquely identified by a Universal Resource Identifier (URI), similar to how web pages are addressed [11]. This structure not only facilitates data linking but also supports the extensibility of the web by allowing new concepts and relationships to be defined with unique URIs.

Web Ontology Language (OWL). OWL is an advanced language designed on top of RDF and incorporates Description Logic, a subset of First Order Logic, to provide formal semantics. OWL enables the creation of detailed ontologies that include complex relationships, constraints, and logical inferences. Its use is crucial for developing machine-interpretable models that support reasoning and interoperability across domains.

Querying and Reasoning with Semantic Web Data. To query RDF data, the W3C has standardized SPARQL [12], a robust query language that allows for the retrieval and manipulation of Semantic Web data. SPARQL's graph-matching capabilities make it an essential tool for interacting with RDF datasets. Additionally, rule-based reasoning plays a significant role in extracting implicit knowledge from semantic data. Rule languages such as SWRL (Semantic Web Rule Language) and RIF (Rule Interchange Format) enable advanced reasoning, while frameworks like the Jena Semantic Web Framework provide general-purpose rule engines for working with ontological data. These tools allow systems to derive high-level abstractions, uncover hidden patterns, and address complex queries, making the Semantic Web an indispensable technology for modern data integration and analysis.

By leveraging these technologies and frameworks, the Semantic Web transforms traditional data into a richly interconnected knowledge graph, enabling intelligent systems to deliver more relevant and actionable insights across diverse domains.

2.2. Semantics in Sensor Networks

The concept of the Semantic Sensor Web [13] combines semantic web technologies with sensor networks to provide declarative descriptions of sensors, networks, and domain concepts. This integration allows for enhanced querying, searching, and management of both the network and the data it generates. Among various contributions to this field, the work of the W3C Semantic Sensor Network Incubator Group remains a cornerstone for bridging semantic web technologies with sensor networks. **Semantic Sensor Network Frameworks.** These frameworks rely on reference ontologies to annotate sensor data, devices, and associated services. Numerous ontology proposals have emerged, each varying in purpose and scope. Notable examples include OntoSensor [14], CSIRO [15], and the widely adopted Semantic Sensor Network (SSN) Ontology [16]. The SSN ontology, in particular, provides a unified standard for describing sensor network data and has become the foundation for many subsequent ontologies.

Evolution of Sensor Ontologies. Before the SSN ontology, several domain-specific sensor ontologies were developed to address specific needs. While they were effective in their respective fields, their scope and reasoning capabilities were often limited. Compton et al. [17] conducted a detailed review of these early sensor ontologies, analyzing their conceptual scope, expressive power, and reasoning abilities. Many later ontologies built upon the SSN ontology, extending it in three main directions:

1. General Extensions: General ontologies have been developed by building upon the SSN ontology, aiming to create broader, more universally applicable standards [18, 19]. These extensions improve the ability to adapt sensor ontologies for diverse domains and applications.

2. Application-Specific Extensions:: To meet the unique requirements of various fields, the SSN ontology has been modified or extended with additional concepts [20, 21]. These changes tailor the ontology to specific domains, enhancing its ability to describe particular applications clearly and effectively.
3. Ontology Integration: Combining the SSN ontology with other domain-specific ontologies has proven to be a powerful approach for addressing practical challenges [22]. Since sensor data often involves linked data, merging ontologies enables a more comprehensive application range and improves the utility of sensor networks in real-world scenarios.

2.3. Climate Ontology

A climate ontology is a formal representation of knowledge about the climate domain, using a structured and standardized approach to describe and categorize climate-related data, concepts, and relationships. It aims to capture key climatic variables, phenomena, and interactions in a machine-readable format, enabling efficient data integration, analysis, and decision-making across various systems and applications.

The primary objective of a climate ontology is to create a common framework for understanding climate data, facilitating interoperability between different data sources, platforms, and domains. It provides a shared vocabulary for representing climatic variables, such as temperature, precipitation, wind speed, humidity, and atmospheric pressure, and their relationships to other factors, such as time, location, and environmental conditions. Climate ontologies also enable the annotation of climate sensor data with metadata that enhances data quality, context, and meaning.

2.3.1. Key Components of a Climate Ontology

- Climatic Variables: Climate ontologies define concepts for key climatic variables such as air temperature, wind speed, precipitation, solar radiation, and others. These variables are often characterized by units of measurement, range, and temporal and spatial attributes.
- Relationships and Interactions: Relationships are defined between different climate parameters and phenomena. For example, the relationship between temperature and humidity, or the influence of solar radiation on wind patterns. These relationships are essential for modeling climate processes and understanding the dynamics between various factors in the climate system.
- Spatial and Temporal Context: Climate ontologies typically include metadata related to the spatial (geographical) and temporal (time-based) dimensions of climate data. This enables the accurate representation of climate measurements across different locations and time intervals, which is crucial for global climate models and localized climate studies.
- Sensor and Measurement Information: An essential aspect of climate ontologies is the representation of climate sensors and their observations. By associating sensors with the climate variables they measure, the ontology ensures accurate data collection and facilitates the integration of climatic sensor data from diverse sources, such as weather stations, satellite data, and wireless sensor networks.

Here we list some main open ontologies and vocabularies in the climate domain.

- SOSA Ontology[1]. This ontology is applied in CA to representation of sensor related vocabularies such as sensors, observations, samples, etc.
- Climate and Forecast ontology [2]. All of the geophysical features (e.g. air temperature).

3. PROPOSED APPROACH

To address the challenges associated with managing and utilizing climate sensor data, our proposed approach is based on a structured and ontology-driven framework leveraging Semantic Web technologies. This framework aims to enhance the semantic representation, integration, and usability of climate sensor data by providing a unified model for describing sensors, their observations, and the associated metadata. By combining ontological modeling, semantic annotation, and rule-based reasoning, our approach ensures interoperability.

3.1. Building an Ontology for Climate Sensor Data

The first activity of this work focuses on designing an ontology tailored to climate sensor data, based on the W3C SSN ontology. This ontology serves as the foundation for describing sensors, their characteristics, observations, and measurements specific to the climatic domain. To systematically build the climate sensor ontology, we followed three main steps:

3.1.1. Requirements Specification Step

The development of a climate sensor ontology involves addressing several critical aspects to ensure its relevance, usability, and effectiveness in the domain of climate sensor data. These aspects include:

Domain Knowledge: This aspect consists of delimiting as precisely as possible the domain that the ontology going to cover.

Intended Users: It is essential to identify the target users of the ontology, which may include researchers, climate scientists, application developers, and decision-makers. Understanding the needs of these users ensures that the ontology is designed to support their specific requirements, such as data analysis, integration, or decision support.

Operational Goal: This aspect defines the primary purpose of the ontology within the climate sensor data domain. For this work, the goal is to facilitate semantic interoperability, improve data annotation, and enhance decision-making processes by providing a shared semantic framework for describing and analyzing climate sensor data.

Ontology Scope: Determining the most critical global terms that represent the key entities in climate sensor data is a vital step. For the climate domain, these global terms include:

- Sensor: Devices that measure specific climate parameters (e.g., temperature, humidity).
- Observation: The act of collecting climate-related data through sensors.
- Result: The data or value produced by an observation.

[1]https://www.w3.org/TR/2017/REC-vocab-ssn-20171019/
[2]https://www.w3.org/2005/Incubator/ssn/ssnx/cf/cf-property

- Phenomenon: The environmental or climatic variable being observed (e.g., precipitation, wind speed).
- Time: The temporal context of observations.
- Feature of Interest: The specific aspect of the environment or climate that is being measured or monitored.
- Location: The spatial context or geographical area where observations are made.
- Climate Zone: The regional classification of the observation site based on climate characteristics (e.g., tropical, temperate, arid).
- Climate threshold: Predefined limits for specific phenomena.

The result of this step is a requirements specification document represented in RDF format. This document connects three types of entities (see Table I): a resource (representing the climate sensor ontology being developed), properties (corresponding to the four identified aspects), and the association of a resource with a property through a property value (representing the outcome of each aspect).

Subject (resource)	Predicate (property)	Object (value)
Ontology to be created identified by a URI	Aspect	Result of an aspect

Table 1
Requirements Specification Document as an RDF Declaration

3.1.2. Conceptualization Step

The conceptualization phase is a critical part of constructing the climate sensor ontology, as it lays the foundation for the rest of the development process. The primary objective of this step is to organize and structure domain knowledge in a way that is independent of the specific paradigms of knowledge representation that will be used for formalization. During this phase, we create a set of semi-formal representations, referred to as the ”conceptual ontology,” which captures the core concepts and relationships within the domain of climate sensor data.

Our conceptualization approach combines top-down and bottom-up methodologies. Initially, the most important concepts are identified and defined to address the primary requirements of the domain. These concepts are then generalized and extended to create a comprehensive and scalable model. This hybrid approach ensures a balance between specificity and adaptability, making the ontology suitable for diverse applications.

In the climate domain, the conceptualization requires ontological knowledge for several key aspects:

- **Sensor Observations:** Representing the data collected by sensors, such as temperature, humidity, or precipitation measurements.
- **Dataset Observations:** Modeling datasets that aggregate sensor observations over time and space.
- **Situations:** Capturing contextual information, such as weather events or climate anomalies.

- **Temporal and Spatial Locations:** Providing precise modeling of the time and geographic locations associated with sensor data.

Figure 1, Figure 2 and Figure 3, represent a subset of important concepts and relations, represented in our ontology.

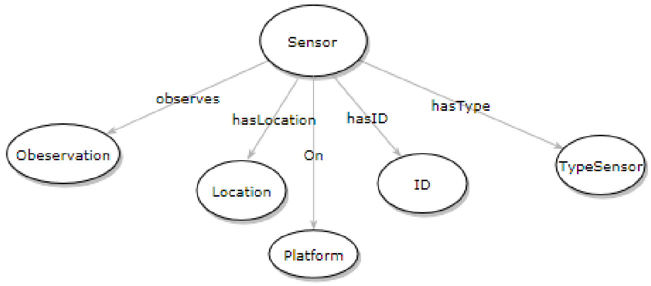

Figure 1: THE SENSOR CLASSES

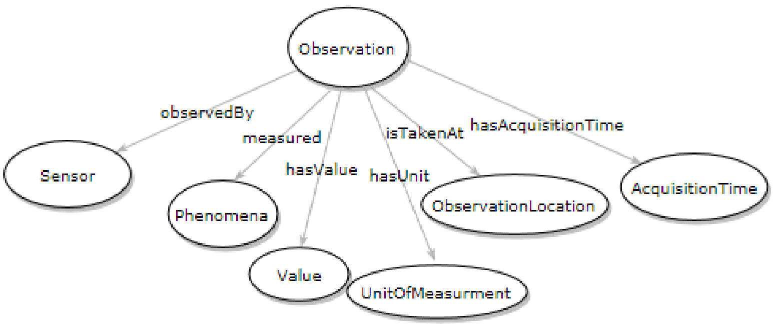

Figure 2: THE OBSERVATION CLASSES

The resulting ontological model for climate sensor data is built around two core concepts: the Sensor Concept and the Observation Concept. The Sensor Concept captures the characteristics of climate sensors, while the Observation Concept focuses on the data collected by these sensors.

As shown in Figure 1, the Sensor Concept models essential sensor attributes such as Location, Identification (ID), Measurement, Platform, and SensorType. The Location entity represents geographic information related to the sensor's placement, whereas the SensorType entity defines the typology of the sensor (e.g., temperature sensor, humidity sensor, etc.).

The Observation Concept, depicted in Figure 2, encompasses details about the physical characteristics of the measurements. Each observation is associated with an AcquisitionTime entity, which records the time period during which the environmental phenomenon was observed. Additionally, the ObservationLocation entity specifies the exact geographic location where the observation took place.

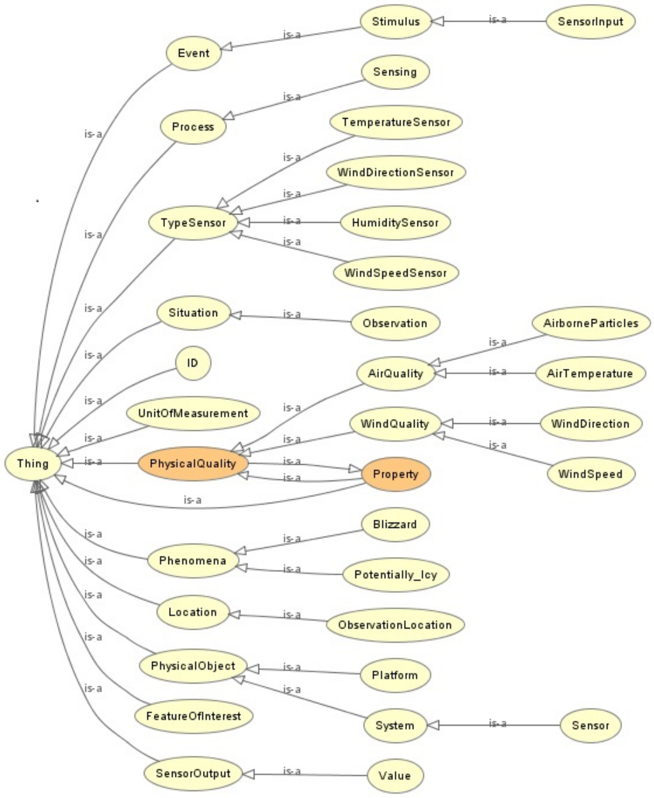

Figure 3: ONTOLOGY CLASS HIERARCHY

The development of the ontological model for climate sensor data was carried out using Protégé, an open-source ontology editor and knowledge acquisition tool developed by Stanford University. Protégé facilitated the [23] design of the class hierarchy and property structure of the proposed semantic data model, specifically tailored for managing climate sensor data. Furthermore, it was utilized to define constraint rules governing the relationships and attributes within the model to ensure logical consistency.

The ontology was serialized in OWL (Web Ontology Language) format, making it compatible with widely used ontology management tools, such as the Jena API. Figure 4 provides a visualization of the main classes, object properties, and data properties of the ontological model for climate sensor data, as developed in Protégé.

3.1.3. Semantic Annotation of Sensors and Climate Sensor Data

To make raw climate sensor data meaningful, it is essential to tag them with semantic metadata. This step involves attaching semantics to both sensors (including their properties such as climate zone and observed phenomena) and sensor streams (the measurements and observations collected by these sensors). The semantically enriched climate sensor data are formatted in RDF according to our proposed ontological model. These annotated sensors and sensor streams are then stored in a triple store, which allows for efficient storage, retrieval, and querying of triples using semantic queries. This process enables the data to be easily shared and reused across systems and applications.

Climate sensor streams represent observations and measurements from the physical world. These streams must include descriptive attributes such as time, location, and observed phenomena to provide meaningful context. For example, consider an air temperature measurement of 8°C taken at Khenchela city center on January 21, 2024, at 8:15 AM GMT. This observation can be semantically annotated in RDF format as follows:

```
<ex:Obs1 rdf:type ex:AirTemperature>
<ex:Obs1 ex:isTakenAt "Khenchela city centre">
<ex:Obs1 ex:hasValue "8">
<ex:Obs1 ex:hasAcquisitionTime "2024-01-21T08:15:00">
<ex:Obs1 ex:hasUnitOfMeasurement "Celsius">
```

We provide an RDF representation of two sensors using our ontological model, tailored for climate data. Both sensors are instances of the Sensor concept, but each observes a distinct climatic property: precipitation or solar radiation. Additionally, these sensors are located on different weather stations, highlighting their spatial context within the climate monitoring system:

```
<ex:Sensor_1 rdf:type ex:Sensor>
<ex:Sensor_1 ex:observedProperty ex:Precipitation>
<ex:Sensor_1 ex:onPlatform ex:WeatherStation_1>

<ex:Sensor_2 rdf:type ex:Sensor>
<ex:Sensor_2 ex:observedProperty ex:SolarRadiation>
<ex:Sensor_2 ex:onPlatform ex:WeatherStation_2>
```

3.1.4. Linked Climate Sensor Data

Publishing climate sensor data on the Semantic Web using machine-interpretable representations enhances the structure and accessibility of these resources. However, semantic descriptions that are not linked to existing data on the Web are often limited to local processing and confined to specific domain ontologies. By linking climate sensor data to other resources on the Web, it becomes possible to obtain enriched information across multiple domains, thereby expanding its utility and applicability.

The construction of climate sensor data as linked data provides a powerful mechanism for sensor network providers and data consumers to connect sensor descriptions with diverse datasets available on the Web. Attributes such as location, sensor type, observed phenomena, and measurements can be associated with other web resources. This integration bridges the gap between physical-world data and logical-world data, enabling applications such as:

- The creation of smart environments that utilize real-time climate data for automation and optimization.
- Business intelligence systems that leverage climate information for strategic planning.
- Automated decision-making systems that rely on interconnected data for enhanced accuracy and responsiveness.

Furthermore, linked climate sensor data supports advanced querying, reasoning, and data sharing on the same principles as traditional linked data. By adhering to linked data principles, climate datasets are published in an interoperable format, fostering their seamless consumption and integration into diverse systems and applications. This creates an open and scalable platform for researchers, policymakers, and industries to access climate information, uncover insights, and develop innovative solutions for climate monitoring, adaptation, and mitigation.

3.1.5. Knowledge Reasoning

Rule-based reasoning plays a crucial role in processing climate sensor data, as it is one of the most effective methods for deriving new and implicit knowledge from existing datasets. It enables advanced data processing, particularly in scenarios where data is incomplete, uncertain, or inconsistent. Rule-based reasoning is instrumental in providing approximate or indirect answers to user queries when precise responses cannot be generated due to missing information or the unavailability of specific data points. This capability is particularly valuable in climate monitoring, where sensor data may be sporadic or affected by environmental conditions.

The W3C Semantic Web Rule Language (SWRL) has been established as a standard for rule representation in the Semantic Web. SWRL is built upon OWL and follows an antecedent $\longrightarrow$ consequent structure to define rules. Its main advantage lies in its seamless integration with OWL ontology schemas, enabling enhanced expressivity while maintaining compatibility with semantic web technologies. This makes SWRL particularly well-suited for domain-specific applications, such as climate monitoring and analysis, where reasoning over complex relationships is required.

Examples of Rule-Based Reasoning in Climate Monitoring

1. Inferring Weather Alerts:

Using SWRL, rules can be defined to automatically generate alerts for extreme weather events. For instance:

```
If (Observation hasValue "Temperature > 40°C") AND (Observation hasLocation "Urban Are
THEN (GenerateAlert "Heatwave Alert").
```

This rule identifies high-temperature observations in urban areas and triggers a heatwave alert, assisting in climate risk management and public safety measures.

2. Estimating Missing Data:

```
If (Observation_1 hasLocation "Region A") AND (Observation_2 hasLocation "Adjacent Reg
AND (Observation_1 hasValue "Precipitation")
THEN (Estimate Observation_2 hasValue "Similar Precipitation as Region A").
```

In cases where sensor data is incomplete, rule-based reasoning can estimate missing values. For example:

This rule infers precipitation data for a region by referencing adjacent areas with similar climatic conditions, ensuring more comprehensive data coverage

4. Conclusion and Perspective

This paper introduced an ontology-based framework for managing climate sensor data, leveraging Semantic Web technologies to address the challenges of semantic interoperability, integration, and efficient utilization of heterogeneous data sources. By extending the SSN ontology, the proposed framework provides a structured semantic representation of sensors, observations, and measurements, enriched with spatial, temporal, and thematic metadata.

Publishing climate sensor datasets as linked data enables seamless querying, integration, and analysis while fostering interoperability across diverse domains. The application of semantic reasoning further enhances the framework's capability to infer high-level abstractions, identify significant patterns, and support complex decision-making processes.

The framework demonstrates its potential to improve the accessibility, reusability, and contextual understanding of climate sensor data, which are critical for addressing challenges in climate change monitoring, risk management, and environmental decision-making. Future work will focus on extending the ontology to cover additional environmental variables, integrating real-time reasoning capabilities, and applying the framework to broader cross-domain applications.

References

[1] P. K. Sahu, Leveraging wireless sensor networks for environmental monitoring and sustainable development: A review of current trends and future directions, Environment and Sustainable Development Perspectives and Issues (2024) 18.

[2] S. Duobiene, K. Ratautas, R. Trusovas, P. Ragulis, G. Šlekas, R. Simniškis, G. Račiukaitis, Development of wireless sensor network for environment monitoring and its implementation using ssail technology, Sensors 22 (2022) 5343.

[3] A. Rhayem, M. B. A. Mhiri, F. Gargouri, Semantic web technologies for the internet of things: Systematic literature review, Internet of Things 11 (2020) 100206.

[4] A. Haller, K. Janowicz, S. J. Cox, M. Lefrançois, K. Taylor, D. Le Phuoc, J. Lieberman, R. García-Castro, R. Atkinson, C. Stadler, The modular ssn ontology: A joint w3c and ogc standard specifying the semantics of sensors, observations, sampling, and actuation, Semantic Web 10 (2019) 9–32.

[5] C. Bizer, T. Heath, T. Berners-Lee, Linked data-the story so far, in: Linking the World's

Information: Essays on Tim Berners-Lee's Invention of the World Wide Web, 2023, pp. 115–143.
[6] S. Mehla, S. Jain, Rule languages for the semantic web, in: Emerging Technologies in Data Mining and Information Security: Proceedings of IEMIS 2018, Volume 1, Springer, 2019, pp. 825–834.
[7] P. Hitzler, A review of the semantic web field, Communications of the ACM 64 (2021) 76–83.
[8] C. Vandana, A. A. Chikkamannur, Semantic ontology based iot-resource description, International Journal of Advanced Networking and Applications 11 (2019) 4184–4189.
[9] G. E. Trouli, A. Pappas, G. Troullinou, L. Koumakis, N. Papadakis, H. Kondylakis, Summer: Structural summarization for rdf/s kgs, Algorithms 16 (2022) 18.
[10] A. Patel, N. C. Debnath, A comprehensive overview of ontology: Fundamental and research directions, Current Materials Science: Formerly: Recent Patents on Materials Science 17 (2024) 2–20.
[11] M. Djezzar, M. Hemam, D. Ouhiba, Z. A. Seghir, Generation of heterogeneous semantic annotations of xml pages: A multi-viewpoints approach, Informatica 45 (2021).
[12] A. Perevalov, A. Gashkov, M. Eltsova, A. Both, Understanding sparql queries: Are we already there? multilingual natural language generation based on sparql queries and large language models, in: International Semantic Web Conference, Springer, 2024, pp. 173–191.
[13] B. Sejdiu, F. Ismaili, L. Ahmedi, Integration of semantics into sensor data for the iot: A systematic literature review, International Journal on Semantic Web and Information Systems (IJSWIS) 16 (2020) 1–25.
[14] D. J. Russomanno, C. R. Kothari, O. A. Thomas, Building a sensor ontology: A practical approach leveraging iso and ogc models., in: IC-AI, 2005, pp. 637–643.
[15] W. Lian, L. Fu, X. Niu, J. Feng, J.-H. Wang, Solving sensor ontology metamatching problem with compact flower pollination algorithm, Wireless Communications and Mobile Computing 2022 (2022) 9662517.
[16] M. Compton, P. Barnaghi, L. Bermudez, R. Garcia-Castro, O. Corcho, S. Cox, J. Graybeal, M. Hauswirth, C. Henson, A. Herzog, et al., The ssn ontology of the w3c semantic sensor network incubator group, Journal of Web Semantics 17 (2012) 25–32.
[17] M. Compton, C. A. Henson, L. Lefort, H. Neuhaus, A. P. Sheth, A survey of the semantic specification of sensors (2009).
[18] C. Wang, N. Chen, C. Hu, S. Yan, W. Wang, A general sensor web resource ontology for atmospheric observation, in: 2011 IEEE International Geoscience and Remote Sensing Symposium, IEEE, 2011, pp. 3436–3439.
[19] G. Atemezing, O. Corcho, D. Garijo, J. Mora, M. Poveda-Villalón, P. Rozas, D. Vila-Suero, B. Villazón-Terrazas, Transforming meteorological data into linked data, Semantic Web 4 (2013) 285–290.
[20] R. Bendadouche, C. Roussey, G. De Sousa, J.-P. Chanet, K. M. Hou, Extension of the semantic sensor network ontology for wireless sensor networks: The stimulus-wsnnode-communication pattern, in: 5th international workshop on semantic sensor networks in conjunction with the 11th international semantic web conference (ISWC), 2012, pp. 16–p.
[21] M. Djezzar, M. Hemam, M. Maimour, F. Z. Amara, K. Falek, Z. A. Seghir, An approach for semantic enrichment of sensor data, in: 2018 3rd International Conference on Pattern

Analysis and Intelligent Systems (PAIS), IEEE, 2018, pp. 1–7.
[22] A. J. Gray, R. García-Castro, K. Kyzirakos, M. Karpathiotakis, J.-P. Calbimonte, K. Page, J. Sadler, A. Frazer, I. Galpin, A. A. Fernandes, et al., A semantically enabled service architecture for mashups over streaming and stored data, in: The Semanic Web: Research and Applications: 8th Extended Semantic Web Conference, ESWC 2011, Heraklion, Crete, Greece, May 29–June 2, 2011, Proceedings, Part II 8, Springer, 2011, pp. 300–314.
[23] H. Knublauch, M. Horridge, M. A. Musen, A. L. Rector, R. Stevens, N. Drummond, P. W. Lord, N. F. Noy, J. Seidenberg, H. Wang, The protege owl experience., in: OWLED, 2005.