The KnowWhereGraph Ontology: A Showcase

Cogan Shimizu[1,*], Shirly Stephen[2], Rui Zhu[3], Kitty Currier[2], Mark Schildhauer[4], Dean Rehberger[5], Pascal Hitzler[6], Krzysztof Janowicz[2,7], Colby K. Fisher[8], Mohammad Saeid Mahdavinejad[6], Antrea Christou[1], Adrita Barua[6], Abhilekha Dalal[6], Sanaz Saki Norouzi[6], Zilong Liu[2,7], Meilin Shi[2,7], Ling Cai[9], Gengchen Mai[10], Zhangyu Wang[2] and Yuanyuan Tian[11]

[1]*Wright State University, OH, USA*

[2]*University of California, Santa Barbara, CA, USA*

[3]*University of Bristol, United Kingdom*

[4]*National Center for Ecological Analysis & Synthesis, CA, USA*

[5]*Michigan State University, MI, USA*

[6]*Kansas State University, KS, USA*

[7]*University of Vienna, Austria*

[8]*Hydronos Labs, Princeton, NJ, USA*

[9]*IBM Research, CA, USA*

[10]*University of Georgia, GA, USA*

[11]*Arizona State University, AZ, USA*

Abstract

KnowWhereGraph is one of the largest fully publicly available spatially enabled knowledge graphs. It includes data on natural hazards (e.g., hurricanes, wildfires), climate variables (e.g., air temperature, precipitation), soil properties, crop and land-cover types, demographics, and human health, among other themes. These have been leveraged through the graph by a variety of applications to address challenges in food security and agricultural supply chains; sustainability related to soil conservation practices and farm labor; and delivery of emergency humanitarian aid following a disaster. This paper showcases the KnowWhereGraph ontology, which acts as the schema for the KnowWhereGraph. We discuss how it enables the powerful spatial and semantic integration across these datasets, our validation paradigm, and the applications it supports.

Keywords

Geospatial Knowledge Graphs, Ontology Engineering, Modular Ontology Modeling, Geo-Enrichment

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

1. Introduction

KnowWhereGraph[1] (KWG) is one of the largest, publicly available geospatial knowledge graphs in the world. The KWG supports applications in the food, agriculture, humanitarian relief, and energy sectors and their attendant supply chains, generally; environmental policy issues relative to interactions among agricultural sustainability, soil conservation practice, and farm labor; and delivery of emergency humanitarian aid, within the US and internationally. It brings together over 30 datasets related to observations of natural hazards (e.g., hurricanes, wildfires, and smoke plumes), spatial characteristics related to climate (e.g., temperature, precipitation, and air quality), soil properties, crop and land-cover types, demographics, and human health, among others, resulting in a knowledge graph with over 16 billion triples.

We present the KnowWhereGraph ontology, resulting from significant knowledge and ontology engineering and reuse, which integrates these datasets, to address meaningful use cases, and provides answers to questions such as "what is here", "what happened here before", "how does this region compare to..." at a high spatial resolution across the entire globe [1].

2. Related Work

There are a few ontologies that deal with geospatial information, but not to the extent or breadth that the KWG ontology provides. In some cases, we re-use related ontologies (e.g., SOSA/SSN [2]) and describe them in Section 3.4.

Some standardized and structured vocabularies for describing environmental concepts exist but have limitations that impacted their usability and effectiveness within the context of the KWG. Moreover, these vocabularies are either large and complex, with many concepts and relationships, or too simple, which makes them challenging to use effectively.

The Environmental Ontology (ENVO) ENVO covers a wide range of environmental concepts [3], but unfortunately has limited coverage of human-related environmental concepts, such as environmental pollution. Some definitions in ENVO are ambiguous or imprecise, which led to confusion and misinterpretation. For example, "flood" as a continuant versus "flooding" as an occurrent made it ambiguous for us to realistically categorize a flood, as reported by NOAA.

Semantic Web for Earth and Environmental Terminology (SWEET) SWEET has expansive coverage of geospatial and environmental terms and properties [4]. Unfortunately, as a whole, SWEET tends to be imprecise, having overlapping definitions and inconsistent use of relations. For example, both "phenomenon" and "observable property" refer to measurable or observable

Ontology Showcase and Demonstrations Track, 9th Joint Ontology Workshops (JOWO 2023), co-located with FOIS 2023, 19-20 July, 2023, Sherbrooke, Québec, Canada.
*Corresponding author.
cogan.shimizu@wright.edu (C. Shimizu); shirlystephen@ucsb.edu (S. Stephen); rui.zhu@bristol.ac.uk (R. Zhu); kcurrier@ucsb.edu (K. Currier); schild@nceas.ucsb.edu (M. Schildhauer); rehberg@msu.edu (D. Rehberger); hitzler@ksu.edu (P. Hitzler); krzysztof.janowicz@univie.ac.at (K. Janowicz); colby@hydronoslabs.com (C. K. Fisher); saeid@ksu.edu (M. S. Mahdavinejad); christou.2@wright.edu (A. Christou); adrita@ksu.edu (A. Barua); adalal@ksu.edu (A. Dalal); sanazsn@ksu.edu (S. Saki Norouzi); zilong.liu@univie.ac.at (Z. Liu); meilin.shi@univie.ac.at (M. Shi); lingcai@ucsb.edu (L. Cai); gengchen.mai25@uga.edu (G. Mai); zhangyuwang@ucsb.edu (Z. Wang); yuanyuantian@asu.edu (Y. Tian)
https://coganshimizu.com/ (C. Shimizu); https://people.cs.ksu.edu/~hitzler/ (P. Hitzler)
0000-0003-4283-8701 (C. Shimizu)

[1]https://knowwheregraph.org/

characteristics of the natural world. Another example is where 'part of' and 'has part' are used interchangeably to describe hierarchical relationships between concepts.

Google Data Commons & Schema.org The Google Data Commons,[2] powered by annotations from Schema.org[3] provides a mechanism via its "Map Explorer" tool to visualize data that has a geospatial component. However, by its nature, Schema.org is a semantically shallow representation, which generally indicates the type of data something is. This was insufficient for the heavy semantic harmonization needs of the KWG ontology.

3. The KnowWhereGraph Ontology

The KWG ontology satisfies several requirements: enabling geospatial integration, facilitating data integration, providing rich inferencing, and expediting maintainability. We describe these below.

Enable Geospatial Integration The primary purpose of KWG is to provide a convenient method for integrating data along a geospatial dimension. This is integral to the mission of the project and, subsequently, a core requirement for the graph and its schema.

Facilitate Data Integration KnowWhereGraph must be capable of providing an overarching framework for the semantic harmonization of key terms and concepts.

Provide Rich Inferencing Beyond a 1:1 representation of the (integrated) datasets, KWG's schema must be expressive enough to infer latent relationships between datasets, such as causality of events or the inheritance of spatial characteristics.

Highly Maintainable To be maximally useful, KWG must be easily maintained by the community. This includes both the degree of facilitation of data integration, but how amenable the schema – and thus the graph – are to modification: either through the incorporation of new or evolving use cases, rectifying conceptual errors in the graph, or adapting to changes.

To facilitate satisfying these requirements we utilize the Modular Ontology Methodology (MOMo; [5]), which leverages ontology design patterns [6] as first-class citizens to enable quick, iterative, plug-and-play schema development. Through a process called template-based instantiation [7] a single pattern can be used to represent similar datasets with minimal effort; this process is documented in additional detail [8].

3.1. Represented Domains

KWG represents a myriad of domains – and is capable of integrating more. Any domain that is capable of being represented along a geospatial axis can be incorporated. As of now, the graph generally supports the hazard (and related) domains. That is, it supports given physical phenomena that can negatively impact places, people, or the economy, including the specifics of who is impacted, what is impacted, and how the impacts can be mitigated. In addition to the four general requirements above, the KWG ontology supports several pilot use cases across different domains.

Humanitarian Relief Disasters are complex and dynamic situations requiring humanitarian organizations to evaluate and respond rapidly to many different issues simultaneously. Often what

[2] https://www.datacommons.org/
[3] https://schema.org

Thematic Dataset	Source Agency	Example Attributes
Soil Properties	USDA	soil type, farmland class
Wildfires	USGS, USDA, USFS, NIFC	wildfire type, num acres burned
Earthquakes	USGS	magnitude
Climate Hazards	NOAA	casulaties, property damage
Experts (Covid-19 Mobility)	Direct Relief	name, affiliation, expertise
Expert (General)	KWG, UC System, Direct Relief, Semantic Scholar	name, affiliation, expertise
Cropland Types	USDA	crop types (raster data)
Air Quality	EPA	air quality index
Smoke Plumes Forecasts	NOAA	daily smoke plume forecast
Climate	NOAA	temperature, precipitation
Disaster Declarations	FEMA	area, amount approved
Smoke Plume Extents	NOAA	smoke plume extent
BlueSky Forecasts	BlueSky	PM10, PM5
Highway Networks	DoT	road type, road length, signage
Public Health Observations	CDC, USCB, University of Wisconsin	poverty, diabetes, obesity
Public Health Infrastructure	HIFLD	pharmacies, hospitals
Social Vulnerability	CDC, ATSDR	social vulnerability index
Hurricane Tracks	NOAA	max wind speed, min pressure

Table 1
This table shows the thematic datasets (i.e., those which describe physical phenomena and their relation to time and places) that are integrated via the KWG ontology.

is most needed to improve effective response is quick access to the right experts at the right time. To assist in identifying people with expertise in humanitarian aid and relief, with a particular focus on health and the health care impacts of disasters, we are working with Direct Relief to showcase how our knowledge graph can give them rapid access to area briefings, including previous events and physical properties of, for example, climate and transportation infrastructure in the affected regions.

Food Supply Chain Resilience Moreover, understanding and improving the robustness and adaptability of the food supply chain is of critical importance to make it more resilient to disturbances in food supply and demand networks. Network fracturing and delayed recovery during extreme weather events is always an inherent risk when it comes to wildfires, floods, and other natural hazards. In the face of uncertain natural hazards, which are increasing in frequency and severity, it is vital that the implications of these disruptions are evaluated for the source nodes of our supply chains, such that resiliency in the whole supply chain can be promoted. To solve this challenge, we are partnering with the Food Industry Association (FMI), which has identified food safety and food quality issues rising from environmental disasters or disturbances as high-priority industry concerns.

3.2. Integrated Datasets

Tables 1 and 2 show condensed views of the datasets that the KWG Ontology integrates. These datasets are widely sourced, originating from non-governmental organizations (NGOs), US governmental agencies, open source data, and the commercial sector (with attribution).

Place-Centric Dataset	Defining Authority	Spatial Coverage
S2 Cells	Google	Lvl 9 (Global), Lvl 13 (US)
Global Administrative Regions	GADM.org	Global
US Federal Judicial Districts	DoJ, ESRI	US
National Weather Zones	NOAA	US
FIPS Codes	USCB	US
Designated Market Areas	Nielsen	US
ZIP Codes	USPS	US
Climate Divisions	NOAA	US
Census Metropolitan Area	USCB	US
Drought Zone	NDMC	US
GNIS	USGS	US

Table 2
This table shows the place-centric datasets (i.e., those which describe human-meaningful regions) which are integrated via the KWG ontology.

3.3. Using the KWG Ontology

KWG, and thus the KWG Ontology, are used in the pilots described above, as well as in several tools (e.g., Knowledge Explorer [9], which supports “follow-your-nose” exploration) for information retrieval and visualization and geo-enrichment services. These tools are online and can be found, with additional documentation and tutorials at https://knowwheregraph.org/tools/.

3.4. Ontologies Reused in the KWG Ontology

We have developed several standalone ontologies and resources, and reuse a number of well-known, standardized, or W3C-recommended vocabularies, taxonomies, and ontologies. This helps to support greater interoperability with other knowledge graphs, to maintain consistency in our data model, and to leverage existing tools that support these vocabularies.

Ontology Design Patterns During the development of the KWG ontology, we both create new and adapt ontology design patterns (ODP; [6]). So far, four new patterns have been developed: the hierarchical features ODP [10], the causal relations ODP [11], the taxonomy alignment ODP [12], and the computational observation ODP [13]. We adapted existing patterns from MODL [14]: EntityWithProvenance ODP and the AgentRole ODP.

GeoSPARQL We used GeoSPARQL [15, 16], an Open Geospatial Consortium (OGC) standard, to represent our geospatial data in RDF. It, in turn, reuses the OGC Simple Features (SF) standard, which defines a set of geometric primitives (e.g., points or polygons) and their spatial relationships. Within the KWG ontology, we represent any discrete geographic feature type (Hazard, Region, and their subclasses) that has a spatial extent as a subclass of GeoSPARQL’s geo:SpatialObject class. We also use the spatial relationships from GeoSPARQL (based on DE-9IM spatial relations) to establish pre-computed spatial relationships between any two spatial features. While several graph databases support GeoSPARQL, we found a number of features of GraphDB including its support of GeoSPARQL [17] made it the best candidate for KWG.

SOSA/SSN The Sensors, Observations, Sampling, and Actuator Ontology [18], coupled with the Semantic Sensor Network ontology (SOSA/SSN; [19]) are used to model observations made by sensors that detect, measure, or observe properties of features [2]. They can be made to work together by refining the interpretation of two concepts: sosa:FeatureOfInterest, and sosa:Observation. In the KWG ontology, a sosa:FeatureOfInterest represents both the thing whose property can be observed and anything that can have a spatial representation and an associated geometry.

Observations (and their collections) in SOSA are defined as the act of measuring, estimating, or calculating the value of a property using a sensor (device, agent, or software), while a feature of interest is an element whose property is being observed to arrive at a result.

OWL-Time The Time ontology is (re)used for all representations of time within the KWG ontology. The super-property for most time-related conceptualizations is kwg-ont:hasTemporalScope, which effectively has a range of any temporal entity from OWL-Time. For serializations, we reuse the XML schema datatypes.

Metadata and Provenance To easily maintain metadata and provenance, we reuse several vocabularies to describe the KWG ontology. For example, we use annotation properties from Dublin Core Metadata Initiative (DCMI) Metadata Terms [20] to describe the title, description, rights, license, date created, and creator. We use Friend of a Friend (FOAF [21]) to describe the development team and their roles. The Simple Knowledge Organization System (SKOS) is used to annotate definitions, examples, and the taxonomic structure between domain concepts. Finally, we use PROV-O [22] to describe the provenance of resources, e.g., to track the provenance and lineage of a dataset.

QUDT The QUDT (Quantities, Units, Dimensions and Data Types) ontology [23] is used for representing climate measurement data (such as temperature, Palmer drought severity index, cooling degree days) and their corresponding units of measure. Specific climate quantity types (such as mean or value) are denoted using the kwg-ont:Quantity class, a subclass of kwg-ont:Quantity-Value. Measured values and corresponding data properties are then captured using data properties qudt-unit:unit and qudt-unit:numericValue.

The Expertise Ontology KWG contains information on agents who are experts on topics related to specific disaster types, disaster management activities, named disasters, and public health. The Expertise Ontology[4] (EO) was developed to represent all varied expertise-related information consistently. At a high level, EO consists of a core set of classes and properties to 1) model experts (individuals or groups), topics, and their relations, 2) represent hierarchical relations between topics of different levels of granularity, and 3) connect topics with relevant content in a knowledge graph. EO facilitates representing not only research- and theory-based expertise, but also experience-based expertise by modeling the activities that an expert may have engaged in or their role and affiliation within an organization, and scopes these spatially and temporally.

The Disaster Management Domain Ontology KWG contains at least 11 hazard datasets and at least one hazard (Fire) from four different sources (see Table 1). To model their semantics and enable integration using any existing ontologies, we are developing the Disaster Management Domain Ontology (DMDO), which will provide a framework to align diverse hazard types, formats of data, and domain vocabularies consistently within KWG, but also for better situational awareness through clarification of the spatiotemporal interactions of similar events. The ontology disambiguates hazards from disasters and their impacts, but also distinguishes spatiotemporal events from their observations. DMDO also formalizes the UNDRR hazard classification [24] using the taxonomy alignment ODP [12].

3.5. Evaluation

The KnowWhereGraph Ontology has been evaluated through its ability to meet use-case requirements, as outlined in Section 3. We do this through interviewing domain experts and analyzing

[4]https://github.com/KnowWhereGraph/expertise-ontology

competency questions and their corresponding SPARQL queries with results.

In formulating aspects of the ontology, and especially in understanding specific thematic datasets, it is necessary to draw in the expertise of knowledgeable practitioners and subject matter experts. By iterating through multiple versions of the ontology with multiple different experts, we are able to converge on a common conceptualization. To evaluate the materialization, as well as the effectiveness of querying against the graph, we develop suites of competency questions. These allow for the connection between natural language, expected usage of the graph, and the KWG ontology (via the formulation of a SPARQL query). The analysis of the actual results, as opposed to expected results, allows us to evaluate if our conceptualization mirrors domain expertise and meets our use-case needs.

In a secondary manner, the KWG ontology is evaluated through its usability. That is, how well it meets the needs of developers creating applications against the entire knowledge graph. To this end, we realized that the materialization (aka shortcuts) would be necessary to link more effectively places and their identifiers (and subsequently simplify queries). For example, regions from different place-centric datasets could previously only be obtained through a complex query that drilled down to a cell-based representation, and then abstracted back upwards to the region in question. An entirely new version of the ontology was rolled out to accommodate this identified need. Finally, we provide a set of shapes (defined in the SHApes Constraint Language; SHACL; [25]) to validate the materialization of the ontology, which can be found online[5] and in [26].

4. Conclusion

The KnowWhereGraph is a complex project with multiple evolving use cases, a large team, and an ambitious goal. We have presented the KnowWhereGraph Ontology, which integrates over 30 datasets to power several motivating use cases. It was developed using a pattern-based method (i.e., modular ontology modeling [5]) that reused a significant number of existing environmental and geospatial ontologies, vocabularies, and resources.

Availability We provide multiple types of documentation for the KnowWhereGraph Ontology: living documentation (generated using [27]) coupled with schema diagrams (generated manually) can be found at [28], alongside a static, technical report (generated using [29]). Finally, the ontology itself can be found in [30] and is released under the CC BY 4.0 license. The KnowWhereGraph is maintained by the KnowWhereGraph team; more details can be found in [31].

Acknowledgments

This work was funded by the National Science Foundation under Grant 2033521 A1: KnowWhere-Graph: Enriching and Linking Cross-Domain Knowledge Graphs using Spatially-Explicit AI Technologies. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

[5]https://github.com/KnowWhereGraph/KWG-SHACL

References

[1] K. Janowicz, P. Hitzler, W. Li, D. Rehberger, M. Schildhauer, R. Zhu, C. Shimizu, C. K. Fisher, L. Cai, G. Mai, J. Zalewski, L. Zhou, S. Stephen, S. G. Estrecha, B. D. Mecum, A. Lopez-Carr, A. Schroeder, D. Smith, D. J. Wright, S. Wang, Y. Tian, Z. Liu, M. Shi, A. D'Onofrio, Z. Gu, K. Currier, Know, know where, knowwheregraph: A densely connected, cross-domain knowledge graph and geo-enrichment service stack for applications in environmental intelligence, AI Mag. 43 (2022) 30–39. URL: https://doi.org/10.1609/aimag.v43i1.19120. doi:10.1609/aimag.v43i1.19120.

[2] K. Janowicz, A. Haller, S. Cox, M. Lefrançois, D. L. Phuoc, K. Taylor, Semantic Sensor Network Ontology, W3C Recommendation, W3C, 2017. Https://www.w3.org/TR/2017/REC-vocab-ssn-20171019/.

[3] P. L. Buttigieg, N. Morrison, B. Smith, C. J. Mungall, S. E. Lewis, The environment ontology: contextualising biological and biomedical entities, J. Biomed. Semant. 4 (2013) 43. URL: https://doi.org/10.1186/2041-1480-4-43. doi:10.1186/2041-1480-4-43.

[4] R. Raskin, M. Pan, Semantic web for earth and environmental terminology (sweet), in: Proc. of the Workshop on Semantic Web Technologies for Searching and Retrieving Scientific Data, volume 25, 2003.

[5] C. Shimizu, K. Hammar, P. Hitzler, Modular ontology modeling, Semantic (2021). In Press.

[6] A. Gangemi, V. Presutti, Ontology design patterns, in: S. Staab, R. Studer (Eds.), Handbook on Ontologies, International Handbooks on Information Systems, Springer, 2009, pp. 221–243. URL: https://doi.org/10.1007/978-3-540-92673-3_10. doi:10.1007/978-3-540-92673-3_10.

[7] K. Hammar, V. Presutti, Template-based content ODP instantiation, in: K. Hammar, P. Hitzler, A. Krisnadhi, A. Lawrynowicz, A. G. Nuzzolese, M. Solanki (Eds.), Advances in Ontology Design and Patterns [revised and extended versions of the papers presented at the 7th edition of the Workshop on Ontology and Semantic Web Patterns, WOP@ISWC 2016, Kobe, Japan, 18th October 2016], volume 32 of *Studies on the Semantic Web*, IOS Press, 2016, pp. 1–13. URL: https://doi.org/10.3233/978-1-61499-826-6-1. doi:10.3233/978-1-61499-826-6-1.

[8] C. Shimizu, S. Stephen, A. Barua, L. Cai, A. Christou, K. Currier, A. Dalal, C. K. Fisher, P. Hitzler, K. Janowicz, W. Li, Z. Liu, M. S. Mahdavinejad, G. Mai, D. Rehberger, M. Schildhauer, M. Shi, S. S. Norouzi, Y. Tian, S. Wang, Z. Wang, J. Zalewski, L. Zhou, R. Zhu, The KnowWhereGraph ontology, Journal of Web Semantics (2023). Under review.

[9] Z. Liu, Z. Gu, T. Thelen, S. G. Estrecha, R. Zhu, C. K. Fisher, A. D'Onofrio, C. Shimizu, K. Janowicz, M. Schildhauer, et al., Knowledge explorer: exploring the 12-billion-statement knowwheregraph using faceted search (demo paper), in: Proceedings of the 30th International Conference on Advances in Geographic Information Systems, 2022, pp. 1–4.

[10] C. Shimizu, R. Zhu, G. Mai, C. K. Fisher, L. Cai, M. Schildhauer, K. Janowicz, P. Hitzler, L. Zhou, S. Stephen, A pattern for features on a hierarchical spatial grid, in: IJCKG'21: The 10th International Joint Conference on Knowledge Graphs, Virtual Event, Thailand, December 6 - 8, 2021, ACM, 2021, pp. 108–114. URL: https://doi.org/10.1145/3502223.3502236. doi:10.1145/3502223.3502236.

[11] C. Shimizu, R. Zhu, M. Schildhauer, K. Janowicz, P. Hitzler, A pattern for modeling causal relations between events, in: Proceedings of the 12th Workshop on Ontology Design and Patterns (WOP 2021), co-located with the 20th International Semantic Web Conference (ISWC 2021) : online, October 24, 2021, volume 3011, 2021, pp. 38–50.

[12] S. Stephen, C. Shimizu, M. Schildhauer, R. Zhu, K. Janowicz, P. Hitzler, A pattern for representing scientific taxonomies, in: V. Svátek, V. A. Carriero, M. Poveda-Villalón, C. Kindermann, L. Zhou (Eds.), Proceedings of the 13th Workshop on Ontology Design and Patterns (WOP 2022) co-located with the 21th International Semantic Web Conference (ISWC 2022), Online,

October 24, 2022, volume 3352 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022. URL: https://ceur-ws.org/Vol-3352/pattern3.pdf.

[13] C. Shimizu, P. Hitzler, C. F. V. II, A pattern for modeling computational observations, in: V. Svátek, V. A. Carriero, M. Poveda-Villalón, C. Kindermann, L. Zhou (Eds.), Proceedings of the 13th Workshop on Ontology Design and Patterns (WOP 2022) co-located with the 21th International Semantic Web Conference (ISWC 2022), Online, October 24, 2022, volume 3352 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022. URL: https://ceur-ws.org/Vol-3352/pattern5.pdf.

[14] C. Shimizu, Q. Hirt, P. Hitzler, MODL: A modular ontology design library, in: K. Janowicz, A. A. Krisnadhi, M. P. Villalón, K. Hammar, C. Shimizu (Eds.), Proceedings of the 10th Workshop on Ontology Design and Patterns (WOP 2019) co-located with 18th International Semantic Web Conference (ISWC 2019), Auckland, New Zealand, October 27, 2019, volume 2459 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2019, pp. 47–58.

[15] F. Knibbe, J. Herring, J. Abhayaratna, M. Bonduel, M. Perry, N. J. Car, S. J. D. Cox, T. Homburg, GeoSPARQL Ontology, OGC Standard, OGC, 2021. Https://opengeospatial.github.io/ogc-geosparql/geosparql11/index.html.

[16] R. Battle, D. Kolas, GeoSPARQL: enabling a geospatial semantic web, Semantic Web Journal 3 (2011).

[17] graphdb, GraphDB, http://graphdb.ontotext.com/, 2023.

[18] K. Janowicz, A. Haller, S. J. Cox, D. Le Phuoc, M. Lefrançois, Sosa: A lightweight ontology for sensors, observations, samples, and actuators, Journal of Web Semantics 56 (2019) 1–10.

[19] 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.

[20] H. Wagner, S. Weibel, The dublin core metadata registry: Requirements, implementation, and experience, J. Digit. Inf. 6 (2005). URL: https://journals.tdl.org/jodi/index.php/jodi/article/view/70.

[21] D. Brickley, L. Miller, Foaf vocabulary specification 0.91, 2007.

[22] S. Sahoo, D. McGuinness, T. Lebo, PROV-O: The PROV Ontology, W3C Recommendation, W3C, 2013. Http://www.w3.org/TR/2013/REC-prov-o-20130430/.

[23] H. Rijgersberg, M. van Assem, J. L. Top, Ontology of units of measure and related concepts, Semantic Web 4 (2013) 3–13. URL: https://doi.org/10.3233/SW-2012-0069. doi:10.3233/SW-2012-0069.

[24] UNDRR Hazard definition and classification review (Technical Report)., https://www.undrr.org/publication/hazard-definition-and-classification-review, 2021.

[25] D. Kontokostas, H. Knublauch, Shapes Constraint Language (SHACL), W3C Recommendation, W3C, 2017. Https://www.w3.org/TR/2017/REC-shacl-20170720/.

[26] R. Zhu, C. Shimizu, S. Stephen, L. Zhou, L. Cai, G. Mai, K. Janowicz, M. Schildhauer, P. Hitzler, SOSA-SHACL: shapes constraint for the sensor, observation, sample, and actuator ontology, in: IJCKG'21: The 10th International Joint Conference on Knowledge Graphs, Virtual Event, Thailand, December 6 - 8, 2021, ACM, 2021, pp. 99–107. URL: https://doi.org/10.1145/3502223.3502235. doi:10.1145/3502223.3502235.

[27] D. Garijo, WIDOCO: A wizard for documenting ontologies, in: C. d'Amato, M. Fernández, V. A. M. Tamma, F. Lécué, P. Cudré-Mauroux, J. F. Sequeda, C. Lange, J. Heflin (Eds.), The Semantic Web - ISWC 2017 - 16th International Semantic Web Conference, Vienna, Austria, October 21-25, 2017, Proceedings, Part II, volume 10588 of *Lecture Notes in Computer Science*, Springer, 2017, pp. 94–102. URL: https://doi.org/10.1007/978-3-319-68204-4_9. doi:10.1007/978-3-319-68204-4_9.

[28] The KnowWhereGraph Schema, The KnowWhereGraph schema, https://stko-kwg.geog.ucsb.edu/lod/ontology, 2023.
[29] C. Shimizu, P. Hitzler, Automatically generating human readable documentation for ontology design patterns, in: O. Seneviratne, C. Pesquita, J. Sequeda, L. Etcheverry (Eds.), Proceedings of the ISWC 2021 Posters, Demos and Industry Tracks: From Novel Ideas to Industrial Practice co-located with 20th International Semantic Web Conference (ISWC 2021), Virtual Conference, October 24-28, 2021, volume 2980 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021. URL: http://ceur-ws.org/Vol-2980/paper305.pdf.
[30] The KnowWhereGraph Ontology, The KnowWhereGraph ontology, https://stko-kwg.geog.ucsb.edu/lod/ontology.ttl, 2023.
[31] kwg-site, Knowwheregraph, https://knowwheregraph.org/, ????