Semantic Matchmaking & Mediation for Sensors on the Sensor Web

Christian Malewski, Arne Bröring, Patrick Maué and Krzystof Janowicz

***Abstract*—With myriads sensors out there, the manual matching of their characteristics and constraints is not feasible anymore and requires a detailed understanding of sensor metadata and observed properties. Thus, Plug & Play like approaches that ease the matching of sensors to Web services have become popular in Sensor Web Enablement research. Simple matching, however, tends to exclude too many potentially relevant sensors if not accompanied by mediators as well, e.g., to convert between measurement units. In extending the state of the art, we introduce our current implementation of a rule system that supports complex mediation and mappings, and, thus, aims to achieve a real Plug & Play for the Sensor Web.**

***Index Terms*—Semantic Matchmaking, Semantic Mediation, Semantic Sensor Web, Semantic Sensor Network Ontology, Semantic Web Rule Language, Sensorbus, Sensor Plug & Play**

I. Introduction

THIS WORK presents an approach for the automated integration of in-situ and proximal sensors [1] and services on the Sensor Web. A Sensor Web is an infrastructure that enables the interoperable usage of sensor resources by providing services for *discovery*, *access*, *tasking*, as well as *eventing & alerting* [2]. The presented work focuses on the mediation between sensors and Web services in the context of sensor Plug & Play.

Standards and technologies such as the Universal Serial Bus enable Plug & Play integration of hardware sensing devices with computer systems on a lower communication level. However, to integrate sensors with a Sensor Web requires going beyond the connection of the hardware device as provided through a driver mechanism. In applications such as disaster management, flood early warning systems, or environmental monitoring, the integration of sensors with models and simulations plays a crucial role. The Sensor Web Enablement (SWE) standards Observations & Measurements (O&M) [3] and Sensor Observation Service (SOS) [2] are examples for data or service models that serve as generic foundations of application specific models. Sensor Plug & Play means that a new sensor, not registered with the Sensor Web, needs to be automatically registered at SWE services which have announced interest in the sensor's characteristics.

To give an example, in an oil spill scenario, such as the *Deepwater Horizon* disaster in 2010, an SOS should be able to subscribe for the retrieval of oceanographic sensor observations from the 'Gulf of Mexico' to monitor relevant properties. Therefore, the service should be able to declare interest in sensor data for the feature 'Gulf of Mexico' and observed properties such as 'sea water salinity' or 'fluorescence'. The key challenge is to assure that the characteristics advertised by a particular sensor match those required by a Web service. A sensor may characterize itself by stating its identifier, serial number, or model name, but also *thematic*, *temporal*, *spatial*, and *measurement capability* attributes may be specified.

Central thematic characteristic of a sensor are the observed property (e.g., water temperature) and the unit of measure (e.g., Kelvin). Temporal characteristics include the calibration time or the deployment period of a sensor. Spatial characteristics are the current position of a sensor, or a geographic region it observes. Sensor capabilities are composed of properties, such as accuracy or measurement range. Matching sensor characteristics with the requirements of a service is challenging and requires suitable mediation techniques; a detailed analysis of these matching challenges has been described in [4]. Until recently, sensor mediation has only been realized for a limited set of sensor properties, namely the observed property and the unit of measure. Spatial and temporal characteristics or sensor capabilities have attracted little attention and have not been fully examined. Thus, this paper extends the spectrum of sensor characteristics that have been considered until recently.

II. Background

The notion of the *Sensor Web* was largely influenced by the developments of OGC's SWE initiative, however, there are also other implementations complying with the Sensor Web idea, for instance Sensorpedia[1], SensorMap with its underlying

Manuscript received October 07, 2012; revised December 06, 2012. This work has been financially supported by the project *Flexible and Efficient Integration of Sensors and Sensor Web Services* funded by the ERDF program for NRW (contract number N 114/2008), the EC funded project *ENVISION* (contract number 217951), as well as the 52°North *Initiative for Geospatial Open Source Software*.

C. Malewski is now with the Fraunhofer Institute for Computer Graphics Research IGD, Fraunhofer Str. 5 D-64283 Darmstadt, Germany (christian.malewski@igd.fraunhofer.de).

A. Bröring is now with the 52°North Initiative for Geospatial Open Source Software GmbH, Martin-Luther-King-Weg 24 D-48155 Münster, Germany (a.broering@52north.org).

P. Maué is with the Computer Sciences Corporation (CSC), Ettore-Bugatti-Straße 6-14, D-51149 Cologne, Germany (pmaue@csc.com).

K. Janowicz is with the Geography Department, University of California, SantaBarbara 5806 Ellison Hall, Santa Barbara (jano@geog.ucsb.edu)

[1] http://www.sensorpedia.com

SenseWeb infrastructure[2], or Cosm[3].

Data and service models of the Sensor Web achieve syntactic interoperability, but lack semantic interoperability [5]. Hence, several attempts have been done to integrate the Sensor Web and the Semantic Web (e.g. [6]).

The Semantic Web is a concept to extend the Web. It comprises mechanisms to make the meaning of Web content machine-processable. For this purpose natural language resources are complemented with semantic keywords that are structured in ontologies [7]. The World Wide Web Consortium (W3C) has developed the Web Ontology Language[4] (OWL) to model ontologies. OWL provides mechanisms to generate explicit knowledge from existing facts, so called reasoning. Reasoners, such as Pellet[5] interpret ontology statements and perform consistency checking or classification of instances.

However, there exist statements that cannot be expressed in OWL. Therefore OWL ontologies can be extended with rules. One attempt for a rule language is the Semantic Web Rule Language (SWRL)[6]. SWRL rules are Horn-like rules. They consist of an antecedent and a consequent statement, which says that for all individuals the antecedent expression is valid, the consequent formulation is also valid. SWRL can be extended with several built-ins, such as the ability for mathematical operation. Thus it can be utilized to formulate matching rules for sensor attributes and support semantic sensor matchmaking.

Gomez et al. [8] present an approach for sensor metadata matchmaking. Two separate ontologies are maintained: one stores concepts of a well-known set of sensor and platform models. The other contains a fixed set of task descriptions along with the respective requirements. A third ontology integrates the previous two by aligning tasks to devices able to accomplish the latter. For sensor matchmaking, a subsumption reasoning process is performed first to detect possible sensor-platform combinations suitable for a mission. Afterwards, sensor individuals are allocated through a sensor catalogue.

Tran et al. [9] present an ontology containing sensor types as well as spatial and temporal properties to compose similar sensor assets. Spatial relations are based on the Region Connection Calculus (RCC) [10]; temporal relations are based on Allen's Interval Algebra (AIA) [11]. For comparison, syntactic sensor descriptions are mapped to a semantic representation based on an ontology that can be seen as the predecessor of the W3C Semantic Sensor Network (SSN) ontology [13]. RCC and AIA are computed from discrete values and integrated to the ontology afterwards. Sensor descriptions are then aligned via semantic subsumption reasoning. Subsumption reasoning detects whether two OWL concepts are related through a sub-class relation [5].

Pschorr et al. [14] propose an approach for semantic sensor discovery by filtering spatial attributes encoded in Linked Data documents using SPARQL[7] queries. The discovery process relies on a reverse geocoding service using the Geonames gazetteer[8]. The similarity of two named places is inferred by the distance of the sensor's current position.

In difference to the above approaches, here, a broader spectrum of sensor attributes is taken into account. Integration of matching rules into the previous version of a sensor Plug & Play approach [2] aims to add flexibility and reduce human effort in matchmaking sensors. Additionally our approach performs matchmaking from concrete values for sensor characteristics. Thus an ontology that relates tasks to sensors is not required.

III. An Ontology For Sensor Mediation

This section illustrates the structure of the ontology (referred to as *Sensor Mediation (SM) ontology*) developed for our approach. The SM ontology is aligned with the SSN ontology where possible to obtain semantic interoperability within the sensing domain and imports secondary ontologies that contain further knowledge (e.g. the QUDT[9] ontology for unit of measure conversion). The SM ontology is categorized into four modules, namely the main module, the spatial module, the temporal module, and the sensor capability module. Each of them contains a pre-defined set of sensor attributes modeled as OWL concepts. Fig. 1 sketches the modules and their specific sensor attributes. Sensor attributes are separated into two disjoint subsets, the required (prefix Req) concepts representing service requirements and the advertised (prefix Adv) concepts modeling the sensing devices' metadata.

The **main module** comprises the sensor description's central components. This is the AdvSensingDevice, an atomic sensor observing exactly one physical property and providing numerical data with one unit of measure on the advertised side. Atomic sensors are usually grouped into a sensor system (AdvSystem). A required sensor (ReqSensingDevice) represents service constraints for one observed property. These constraints must be met by an atomic sensor in order to be mediated and automatically registered at the Web service.

The **temporal module** contains two attribute types. The calibration time determines the time instant, that describes when a calibration procedure is finished and the sensor's initial capabilities are restored. The deployment time of a sensor is understood as the duration a sensor remains deployed in the field.

The **spatial module** comprises concepts and relations to model a sensor's observation area as either a named spatial feature or a bounding box. The concept ObservationArea represents a two dimensional region, in which all measurements of a sensor are supposed to be located.

The **sensor capability module** encapsulates all attributes qualifying or limiting a sensor's observation procedure. Three

[2] http://atom.research.microsoft.com/senseweb3/sensormap
[3] http://cosm.com
[4] http://www.w3.org/TR/owl-features
[5] http://clarkparsia.com/pellet
[6] http://www.w3.org/Submission/SWRL
[7] http://www.w3.org/TR/rdf-sparql-query
[8] http://www.geonames.org
[9] http://www.qudt.org

categories are pre-defined and aligned to one of the SSN ontology concepts OPERATINGRANGE, SURVIVALRANGE, and MEASUREMENTCAPABILITY. Each of them comprises a set of properties, such as accuracy, measurement range or storage temperature range.

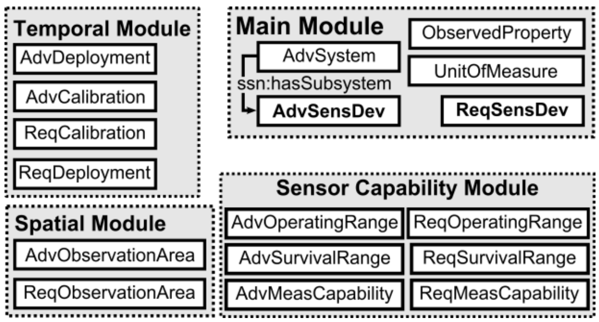

Fig. 1. The four modules of the Sensor Mediation Ontology. Concepts are separated in two disjoint subsets for advertised (Adv) and required (Req) sensor. Advertised (required) concepts in the main module are connected via concept relations to all advertised (required) concepts in the other modules.

IV. A SEMANTIC MEDIATION MECHANISM FOR THE SENSOR WEB

This section describes a mechanism for the automatic semantic mediation of sensors and Sensor Web services.

The mediation process consists of two main steps, (I) the concept creation and (II) the semantic matchmaking. In the first step, the sensor metadata or the service requirement description, are translated into corresponding individuals of the SM ontology and stored internally by the mediator. In the second step, the created ontological description is automatically compared to all existing descriptions of the opposite set, i.e., a new description of sensor characteristics required by a service is compared to all registered descriptions advertised by connected sensors, and vice versa.

The first step of the mediation process is triggered when a new sensor or service registers through a messaging protocol (e.g., via eXtensible Messaging and Presence Protocol[10] or Advanced Message Queuing Protocol[11]), where messages can be exchanged between the mediator and the sensors / services. These are the CONNECTSENSOR, CONNECTSERVICE, and MEDIATE messages. Examples of these messages are given below. The syntax is intentionally kept simple and self-explanatory (a '*' is used to separate message parts).

The CONNECTSENSOR message allows for registering a sensor at the mediator. It carries only one argument, which is the URL of sensor metadata document:

```
ConnectSensor * http://server.org/sensor.xml
```

This document contains a detailed description of the sensor and is encoded in compliance with the SWE standard SensorML [15]. The SensorML syntax needs to be complemented with semantic annotations that allow for a correct mapping from SensorML into the SM ontology.

The SUBSCRIBESERVICE message registers a service with the mediator. In the example of Listing 1, a service subscribes with the mediator by requiring that the observed property of the sensor is some quantity related to temperature. For this a concept[12] of an already existing ontology such as NASA's SWEET ontology[13] is used. The unit of measure is Kelvin. Accuracy is restricted to ±10 °C. Additionally the sensor should observe within the city of Muenster, Germany. The service restriction itself is formatted with JavaScript Object Notation[14].

```
ConnectService * http://www.myserver.com/sos *
  { http://sweet.jpl.nasa.gov/..#TemperatureRelatedQuantity":
    { "uom": "http://sweet.jpl.nasa.gov/...#Kelvin",
      "measCap": {"ssn:Accuracy" : "max": "10" , "min": "-10",
                  "uom": "http://sweet.jpl.nasa.gov/...#degCel"},
      "obsArea": "Muenster, Germany}
```

Listing 1. Example of a CONNECTSERVICE message

After creation and insertion of OWL individuals for sensor characteristics or service requirements the comparison is automatically started. The reasoner performs subsumption reasoning on observed properties and interprets a set of SWRL rules. In the main module, a MATCHESOBSERVEDPROPERTY relation is detected through subsumption reasoning due to the structure of utilized secondary ontologies (e.g. SWEET). If the property observed by a sensor is equal or a sub-concept of what the service requires, the according matching relation is added. In order to detect whether two units of measure match, four cases are possible: The advertised unit of measure…

1. is equal to the unit required by the service.
2. is derived from the unit required by the service.
3. is the base unit of the unit required by the service.
4. and the required unit are derived from the same unit.

In all the four cases a MATCHESUNITOFMEASURE relation is detected. The last three cases require an instruction for a service adapter to convert a measured value from one unit of measure into a related unit of measure (e.g. from Kelvin to Celsius degree). This instruction is appended to the MEDIATE message. The service adapter interprets this instruction and converts the measured value accordingly before data insertion.

In the temporal module, a MATCHESDEPLOYMENTTIME relation is derived whenever the advertised deployment time interval fully contains the required deployment time interval. Relations between calibration times are interpreted in a different way. The reasoner detects a MATCHESCALIBRATIONTIME relation whenever the advertised time instant lies within a time duration specified in the service requirement description from the present date. For instance, a duration of one year would be matched by 15-Nov-2011, if today was the 15-Oct-2012. Determining a minimal interval of one day, the mediation process has to be repeated every 24 hours.

The matching relation between required and advertised observation area in the spatial module are divided into two

[10] http://xmpp.org/xmpp-protocols/rfcs
[11] http://www.amqp.org

[12] http://sweet.jpl.nasa.gov/1.1/property.owl#TemperatureRelatedQuantity
[13] http://sweet.jpl.nasa.gov/ontology
[14] http://www.json.org

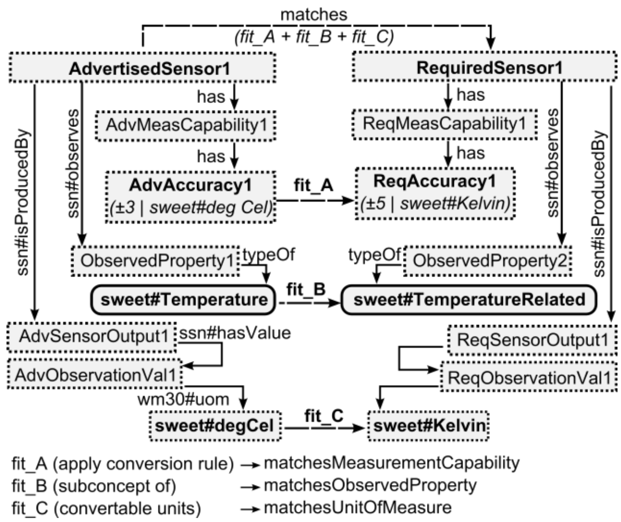

Fig. 2. Matchmaking between advertised and required sensor description. Arrows indicate concept relations. Some concept names are abbreviated. When all required sensor attributes are fitted, a complete match is detected. Not required attributes are fitted by default.

sub-relations, the MATCHESOBSERVATIONAREA and the MATCHESPARTLYOBSERVATIONAREA relation. Several services, such as Nominatim[15] for OpenStreetMap[16], provide the functionality to return a well-structured document for a requested place name including its spatial coordinates, places it is contained in, or its minimal bounding rectangle. These services can be utilized, as done in [14] to convert a spatial place name into a set of coordinates. Four comparison combinations are then possible to compare the advertised…

1. spatial feature with the required bounding box.
2. spatial feature with the required spatial feature.
3. bounding box with the required spatial feature.
4. bounding box with the required bounding box.

The MATCHESOBSERVATIONAREA relation is determined if the advertised area lies completely within the required area (Egypt lies in Africa), since all possible observation locations are included within the restricted region. The MATCHESPARTLYOBSERVATIONAREA relation indicates a weaker match. The reasoner derives this relation when the required area contains only a part of the advertised area. In the latter case, the required observation area's bounding box is appended to the MEDIATE message as an instruction for the service adapter. The service adapter performs a spatial inclusion test for each location of each observation before the measurement is submitted to the corresponding service. This assures for mobile sensors that only observation's in the requested area are considered.

Three different matching relations, namely MATCHESSURVIVALRANGE, MATCHESOPERATINGRANGE, and MATCHESMEASUREMENTCAPABILITY, are detected in the sensor capabilities module. When an advertised sensor fits all restrictions for one of the above attribute types the corresponding relation is derived by the reasoner. It is necessary to define rules for every property, for instance accuracy or measurement range, since they show distinct behaviors during unit conversion. Comparing, for example, the accuracy of a thermometer of ±3 °C with a minimum accuracy of ±4 Kelvin required by a service, the values need to be converted using merely the conversion multiplier (1.0) from Celsius degree to Kelvin.

If a measurement range of ±3 °C is compared with a required measurement range of ±4 Kelvin, no match is detected. The conversion addend (273.15) between °C to Kelvin needs to be considered as well. Corresponding SWRL rules for sensor capability match detection include concepts and individuals from additional ontologies that model unit of measure resources. Similar to matching rules for the MATCHESUNITOFMEASURE relation four matching rules are required for each sensor capability type.

The same procedure is performed for the MATCHESSURVIVALRANGE and MATCHESOPERATINGRANGE. When all properties required by a Web service (e.g. survival temperature range) that belong to the survival range set are met by a sensor, the according match is detected. The match detection for the MATCHESOPERATINGRANGE relation works similar.

Fig. 2 illustrates an example. Individuals of sub-concepts of the SSN ontology have been created by the mediator for the advertised and required sensor description. Observed properties do match due to a sub-concept relationship. A match for the unit of measure is also detected, since Celsius degree and Kelvin are convertible. The accuracy values do match as well.

When all sub-matches have been successfully detected, a sensor is considered as matching the service requirements. If an attribute type is not restricted by a service the according matching relation is detected by default. The mediator then sends a MEDIATE message to service and sensor. The message states which advertised sensor output relates to a property required by a certain service. It establishes the connection of sensor and service by advising the sensor at which service it shall register. Optionally, the message can contain the above mentioned conversion formula or bounding box that need to be considered by the service. Listing 2 shows a MEDIATE message that advises the service with the given URL the requested temperature related properties. Unit conversion instruction and bounding box coordinates are encoded in JSON.

```
Mediate
  * http://myserver.org/sensor/s1.xml
  * http://mySensorWebService.org
  * http://sweet...#Temperature
  * {add: 273.15, sub: 0, mult: 1, div: 1}
  * {n:52.06007,e:7.77437,s:51.84021,w:7.4738}
```

Listing 2. Example of a MEDIATE message.

V. IMPLEMENTATION AND PERFORMANCE

The mediation component is implemented in Java using the Pellet API[17] and the OWL API[18]. We implemented a testing

[15] http://wiki.openstreetmap.org/wiki/Nominatim
[16] http://openstreetmap.org
[17] http://clarkparsia.com/pellet

class[19] to demonstrate performance of the mediation process. In several test iterations an exemplary CONNECTSERVICE message is sent to the mediator. Each iteration registers a varying number of metadata documents[20] at the mediator that describe simulated advertised wind speed sensors. These metadata documents assume a virtual regular sensing grid located in the area of Germany. The measurement properties accuracy, resolution and measurement range are given for each virtual sensor, varying in values and unit of measure. The temporal attributes deployment and calibration date is also stated in each metadata document. The mediation process has been executed on an Intel Core i5-2500K 3.3 GHz CPU with 8 GB RAM. Fig. 3 illustrates the time needed for each iteration (vertical axis), where the horizontal axis shows the number of considered sensor metadata documents.

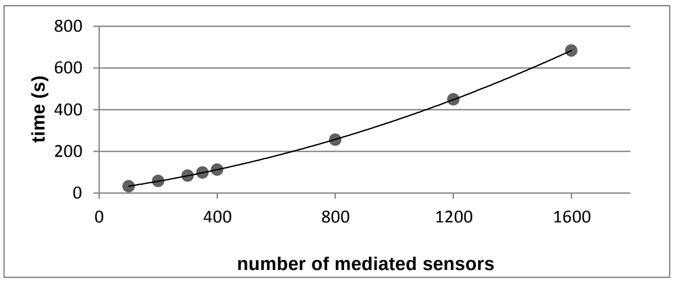

Fig. 3. Performance of sensor mediation. The fitting line increases constantly when adding more sensor metadata documents to process.

The fitting line increases constantly when adding more sensor metadata documents. For 100 metadata documents the mediation process lasts about 32 seconds. When 1600 sensors are available the mediation process takes more than 11 minutes. This behavior reflects the implementation strategy. When mediating a connecting service, OWL triples for each connected sensor system are iteratively injected into the SM ontology, tested against the SWRL rules using Pellet Reasoner and removed afterwards. One of two major time consuming sub-processes is reasoning over the separated measurement capability module ontology. It lasts about 44 % of the overall mediation duration. This is due to the interpretation of SWRL rules for a huge set of OWL individual triples imported from the QUDT unit ontology (>10900 OWL axioms). The second major time consuming process is reasoning over the composed main, temporal and spatial modules that takes about 53 % of the overall reasoning process. Here the QUDT unit ontology is also considered. These two sub-processes can be sub-divided in the actual reasoning process performed by Pellet (about 25 %) and searching for derived matching triples (about 75 %). Subsumption reasoning over the SWEET ontology takes constant time of less than 30 seconds. The time needed for parsing the metadata documents is neglectable. The time for parsing and instantiating the ontology objects is not considered, since it is included in a pre-processing step. In an alternative implementation strategy all sensor triples were added to the ontology first and then tested against the SWRL rules collectively. Although the latter strategy needs less time for the reasoning process the process runs out of storage space when adding more sensor triples. Thus, a trade-off is necessary to the cost of processing time in order to achieve scalability. However, in the context of long term connection between a service and a sensor the needed time for mediation is acceptable and can be split to multiple parallel processes.

VI. DISCUSSION AND CONCLUSION

Our solution combines subsumption reasoning and rule based reasoning for sensor metadata mediation. In contrast to previous work [16], sensing entities and their attributes are modeled as individuals rather than concepts. This facilitates the use of semantic rule languages such as SWRL. We developed a set of SWRL rules for every sensor attribute type according to its specific behavior. Concepts and rules are composed to a modularized Sensor Mediation ontology. The majority of concepts are aligned to the SSN ontology. This ensures a favorable level of interoperability among the semantic sensing domain. Due to the plethora of sensor models and manufacturers the presented collection of sensor attribute types is not claimed to be complete. It rather adds a certain degree of flexibility to restrict requirements for Sensor Web services and therefore extends the functionality of previous versions of the mediator.

Regarding the temporal module, two matching strategies have been conceptualized and applied. These strategies differ from suggested approaches in [9] and [16], where it is proposed to detect similarity among temporal attributes based on AIA relations. In the context of real time comparison merely the current status of a sensor is considered. Thus, potential similarities of advertised and required sensors (e.g. overlapping deployment time intervals) are ignored. The matching conditions are rather determined to containment relations, where the current time is integrated to the respective matching rules. If required these matching strategies can be adapted and applied to temporal attributes with similar characteristics.

A sensor's observation area is considered as the major spatial attribute. The present concept detects containment relations among features specified through place name and features specified through simple geometries. Although approaches exist [14] that make use of semantic filters on spatial attributes, the presented concept utilizes external knowledge bases to retrieve the exact geometries of a named place. As a result these two spatial feature categories can be examined for matches. The matchmaking component dynamically builds an internal knowledge base that contains spatial features. These spatial features are not only provided with topological relations but also linked with their respective geometry.

Matchmaking on sensor measurement, survival and operating capabilities is achieved by reduction of complexity of these sensor attributes. Properties are assumed to be available as a single value or as a value interval since sensor capabilities are often listed in data sheets in that way. Based on this assumption, difference in behavior of a set of distinct

[18] http://owlapi.sourceforge.net
[19] https://svn.52north.org/svn/swe/incubation/SensorBus/trunk/52NSensorbus/ test/org/n52/sensorbus/mediation/MediatorTest.java
[20] http://giv-swsl.uni-muenster.de/SensingDevice

capability types is identified and considered in the matchmaking process. Additionally, on-the-fly conversion of values with related units has been realized.

A central characteristic of the presented concept is that a match between an advertised and required sensor is detected when all attributes of a web service restriction are met. Additionally all matches are detected with precise boundaries. In cases where a sensor's deployment time ends just before the required deployment interval is finished, no match is detected.

Thus, in a future version of a sensor metadata matchmaker the involvement of similarity needs to be investigated in depth. This would improve the mediation by offering ranking information for the matchmaking among entities of same attribute types and over the entire set of attributes.

The approach also relies on secondary ontologies for unit of measure conversion and observed property matchmaking. This strategy is dependent on correctness and reusability of the used ontologies. In a future version of the mediator a central ontology could be maintained that merges several other ontologies as proposed in [5].

The approach discusses matchmaking of in-situ sensor attributes. Although matchmaking of characteristics, such as deployment period or observation area is applicable in a remote sensing domain straightaway, discussion of other capabilities (e.g. resolution) or the submission of measurements would be a starting point for future work.

References

[1] P. M. Teillet, "Sensor webs: A geostrategic technology for integrated earth sensing," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 3, no. 4, pp. 473–480 , 2010

[2] A. Bröring, J. Echterhoff, S. Jirka, I. Simonis, T. Everding, C. Stasch, S. Liang, and R. Lemmens, "New generation sensor web enablement," *Sensors*, vol. 11, no. 3, 2652–2699, 2011. Available: www.mdpi.com/1424-8220/11/3/2652/pdf

[3] S. Cox, "OGC Implementation Standard 10-025: Observations and Measurements - XML Implementation, Version 2.0.0," Open Geospatial Consortium, 2010.

[4] A. Bröring, K. Janowicz, C. Stasch, and W. Kuhn, "Semantic challenges for sensor plug and play," *Web and Wireless Geographical Information Systems*, vol. 5886, 72–86, 2009, Springer Berlin Heidelberg.

[5] S. S. Durbha, R. L. King, S. K. Amanchi, S. Bheemireddy, and N. H. Younan, "Standards-based middleware and tools for coastal sensor web applications," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, , vol. 3 no. 4, 451–466, 2010

[6] A. Sheth, C. Henson, and S. S. Sahoo, "Semantic sensor web," *Internet Computing, IEEE*, vol. 12, no. 4, 78–83, 2008

[7] J. Domingue, D. Fensel, and J. A. Hendler (Eds.), "Handbook of semantic web technologies", vol. 1. Springer Verlag Berlin Heidelberg, 2011

[8] M. Gomez, A. Preece, M. P. Johnson, G. De Mel, W. Vasconcelos, C. Gibson, A. Bar-Noy, K. Borowiecki, T. La Porta, D. Pizzocaro, H. Rowaihy, G. Pearson, and T. Pham, "An ontology-centric approach to sensor-mission assignment." *Knowledge Engineering: Practice and Patterns*, 347 – 363, 2008, Springer Berlin Heidelberg

[9] K. N. Tran, M. Compton, J. Wu, and R. Gore, "Semantic sensor Composition", *The 3rd International workshop on Semantic Sensor Networks*, 2010

[10] J. Renz, "Qualitative spatial reasoning with topological information," Springer Verlag Berlin Heidelberg, 2002

[11] J. F. Allen, "Maintaining knowledge about temporal intervals," *Communications of the ACM*, vol. 26, no. 11, 832–843, 1983

[12] H. Neuhaus and M. Compton, "The semantic sensor network ontology," *AGILE Workshop on Challenges in Geospatial Data Harmonisation*, Hannover, Germany, 1–33, 2009

[13] M. Compton, P. Barnaghi, L. Bermudez, R. Garcia-Castro, O. Corcho, S. Cox, J. Graybeal, M. Hauswirth, C. Henson, A. Herzog, V. Huang, K. Janowicz, W. D. Kelsey, D. Le Phuoc, L. Lefort, M. Leggieri, H. Neuhaus, A. Nikolov, K. Page, A. Passant, A. Sheth, and K. Taylor, "The SSN ontology of the W3C semantic sensor network incubator group," *Web Semantics: Science, Services and Agents on the World Wide Web*, 2012

[14] J. Pschorr, C. Henson, H. Patni, and A. Sheth, "Sensor discovery on linked data", *Proceedings of the 7th Extended Semantic Web Conference, ESWC2010*, Heraklion, Greece, vol. 30, 2010

[15] M. Botts, "OGC Implementation Specification 07-000: OpenGIS Sensor Model Language (SensorML)", Open Geospatial Consortium, 2007

[16] A. Bröring, P. Maué, K. Janowicz, D. Nüst, and C. Malewski, "Semantically-enabled sensor plug & play for the sensor web," *Sensors*, vol. 11, no. 8, 7568–7605, 2011

Christian Malewski received the B.Sc. and M.Sc. degree in geoinformatics from the University of Münster, Germany, in 2013. He is a Research Assistant with the Fraunhofer Institute for Computer Graphics Research IGD, Darmstadt, Germany.

His research interest includes the semantic sensor web and semantic interoperability of spatio-temporal data.

Arne Bröring received his PhD in geoinformatics from the ITC Faculty of the University of Twente, Netherlands. Currently, he works as a research software engineer at 52°North.

He is actively participating in the development of Sensor Web Enablement standards at the Open Geospatial Consortium and is the chair of the Standards Working Group for the Sensor Observation Service. His research interests range from Web-based infrastructures for sensors as well as mobile- and location-based systems to Citizen Science, Participatory Sensing, the Internet of Things, the Semantic Web, as well as visualization of sensor/geo data.

Patrick Maué received his PhD in geoinformatics from the University of Münster, Germany for his research on place name recognition in user-generated content on the Web.

He was involved in various research projects about the use of Semantic Web technologies for the discovery and integration of geospatial Web services. His current research interests are the analysis and visualization of real-time data streams in the context of Big Data and applications for geographic information for service and process integration. He works as application architect with the Computer Sciences Corporation (CSC).

Krzystof Janowicz holds a PhD in geoinformatics from the University of Münster, Germany. Currently he is an Assistant Professor at the University of California, Santa Barbara.

He is the community leader of the 52°North semantics community and one of the two Editors-in-Chief of the Semantic Web journal. His research interest includes geo-semantics, Linked Data, and the Semantic Web, location-based services and location-based social networks, similarity and analogy reasoning, as well as geographic information retrieval.