1. INTRODUCTION

This work\(^1\) enables an automated integration of sensors and services on the Sensor Web. The Sensor Web is defined as an infrastructure which enables the interoperable usage of sensor resources by providing services for (1) discovery, (2) access, (3) tasking, as well as (4) eventing & alerting [2]. The notion of the Sensor Web has been largely influenced by the developments of OGC’s Sensor Web Enablement (SWE) initiative [3], however, there are also other implementations complying to the Sensor Web idea, such as Sensorpedia [4], SensorMap with its underlying SenseWeb infrastructure [5], SensorBase [6], or Cosm\(^2\) (formerly known as Pachube).

Approaches such as USB enable the integration of a hardware sensing device with computer systems on the lowest level. However, to integrate sensors with the Sensor Web, one needs to go beyond the connection of the hardware device as provided through a driver mechanism. In applications such as disaster management, early warning, or environmental monitoring, the integration of the sensor with the model of a specific application plays a crucial role. The SWE standards Observations & Measurements (O&M) [7] and Sensor Observation Service (SOS) [8] are examples for data or service models that serve as generic foundations of application specific models.

Sensor Web services shall be able to subscribe for sensors based on their characteristics. For 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 data for the ‘Gulf of Mexico’ to monitor an oil spill. Therefore, it declares interest in sensor data for the feature ‘Gulf of Mexico’ and properties observed by sensors such as ‘sea water salinity’ or ‘fluorescence’. The key challenge here is to assure that the characteristics advertised by a sensor match those required by a service. A sensor may characterize itself by stating its identifier, name, or model number, but also spatial, temporal, and thematic characteristics may be specified.

2. A SEMANTIC MEDIATION MECHANISM FOR THE SENSOR WEB

To cope with the above described challenges, this section describes a mechanism for the automatic semantic mediation of sensors and Sensor Web services. The approach is based on an encapsulated component, the mediator\(^3\). The mediator acts as a central component on the Sensor Web, or within a local Sensor Web infrastructure. It allows Sensor Web services and sensors to register and it realizes their correct integration via semantic mediation. Therefore, sensors can advertise their characteristics, and services can specify requirements regarding sensors, based on which the mediator computes possible matches. Through some means of communication (e.g., via XMPP or AMQP) messages can be exchanged between the mediator and the sensors / services. Those are the ConnectSensor, SubscribeService, and Mediate message. Examples of those messages are given below. The syntax is intentionally kept simple and self-explanatory (a ‘*’ is used to separate message parts).

The ConnectSensor message allows to register a sensor at the mediator. It carries only one argument, which is the URL of a metadata description document of the sensor (see Listing 1 for an example). This metadata document contains a detailed description of the sensor and is encoded conform to

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\(^1\)This short paper extracts and extends work from our previous article [1] by encapsulating a stand-alone mechanism for the semantic mediation on the Sensor Web.

\(^2\)http://cosm.com

\(^3\)The mediator concept has been implemented as open source software as part of the 52°North Sensor Bus project; http://52north.org/sensorBus.
the SWE standard SensorML [10]. This SensorML document needs to be semantically annotated, so that the mediator is able to gather the meaning of the contained information. Listing 2 shows an excerpt of such a SensorML document that describes the output of a sensor. In this case, the sensor observes temperature, semantically annotated by a concept from the SWEET ontology [11], and provides those measurements in degree Celsius, as defined by the according UCUM [12] code.

Listing 1. Excerpt of the used SensorML document.

```
<sml:output name="temp">
  <swe:Quantity
    definition="http://sweet.jpl.nasa.gov/1.1/property.owl#Temperature">
    <swe: uom code="Cel" />
  </swe:Quantity>
</sml:output>
```

Listing 2. Excerpt of the used SensorML document.

The SubscribeService message is sent to register a service at the mediator. Besides the service’s endpoint URL, required sensor characteristics can be passed as arguments of the message in key-value pairs. In the example of Listing 3, a service subscribes at the mediator by requiring that the observed property of the sensor is some quantity related to temperature\(^4\) and the unit of measure is Kelvin (‘K’ is the according UCUM code).

Listing 3. Example of a SubscribeService message.

```
SubscribeService * http://mySensorWebService.org
* observedProperty
* http://sweet.jpl.nasa.gov/1.1/property.owl
  #TemperatureRelatedQuantity
* unitOfMeasure
* K
```

After a new sensor or service has registered, the mediator starts the mediation process, which consists of two main steps, (1) the concept creation and (2) the semantic matchmaking. In the first step, an ontological description of the advertised or required characteristics, respectively, are created. These ontological descriptions are based on W3C’s SSN ontology [13] and stored internally by the mediator. In the second step, the created ontological description is automatically compared to all existing descriptions, 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. This automatic comparison is done by injecting the new ontological description into the existing ontology maintained by the mediator. Then, the mediator triggers a subsumption reasoner to reclassify the ontology. Thereby, only in case the advertised sensor characteristics are reclassified as equivalent to or as subconcept of the required sensor characteristics. In consequence, a match is inferred and the sensor can be linked with the service.

Figure 1 illustrates an example. Subconcepts of the SSN ontology have been created by the mediator for the advertised and required sensor description. External terms from the SWEET ontology are used to describe the observed properties of both sensor descriptions. They do match, due to a subclass relationship. However, for the unit of measure, individuals for Celsius and Kelvin were added, which results in a mismatch. The service cannot directly ingest measurements from the advertised sensor, since the utilized unit does not comply with what it expects.

Our approach deals with such mismatches by relying on SWRL rules with associated conversion formulas. These rules are part of the ontology and are executed during reasoning. They automatically attach conversion formulas, e.g., for unit or data type conversions, as properties to the individuals of the advertised sensor description. In the above example, a conversion formula for calculating Kelvin values from degree Celsius is attached. The formula is encoded in executable MathML and needs to be applied to the sensor values before insertion.

After finalizing the second step, and in case the matchmaking was successful, the mediator sends a Mediate message to service and sensor. The message states which advertised sensor output relates to a property required by a certain service. Thereby, it establishes the connection of sensor and service by advising a sensor at which service it shall register. Optionally, the message can contain a conversion formula which needs to be applied by the service. In the example of Listing 4, a Mediate message is shown that advises the service with the given URL to a consume the temperature data from the specified sensor for the requested temperature-related properties. Additionally, a MathML conversion rule is defined, that needs to be applied by the service to transform from Celsius measurements to Kelvin.

Listing 4. Example of a Mediate message with conversion rule.

```xml
Mediate
  * http://myserver.org/sensor/s1.xml
  * http://mySensorWebService.org
  * http://sweet.jpl.nasa.gov/1.1/property.owl
    #Temperature
    http://sweet.jpl.nasa.gov/1.1/property.owl
    #TemperatureRelatedQuantity
  * <math>
    <mrow>
      <mi>VAL</mi>
      <mo>=</mo>
      <mi>273.15</mi>
    </mrow>
  </math>
```

3. CONCLUSIONS AND OUTLOOK

This paper outlines an approach for performing semantic mediation on the Sensor Web between sensors and services. This
mediation is done through the creation of ontological descriptions and semantic matchmaking. For specifying the ontological sensor description, the W3C SSN ontology acts as a basis. While here the SWEET ontology was used to represent environmental phenomena, also other domain ontologies can be incorporated. For mediating between non-matching concepts, SWRL rules can be added to the ontology which link to executable conversion formulas.

So far, the design of the mediation mechanism relies on subsumption reasoning to compute the matching. All major reasoners offer such taxonomic reclassification functionality. However, the design also allows the usage of other reasoning methodologies, e.g., semantic similarity measurement. This would improve the mediation by offering ranking information for the matchmaking [14]. The developed mechanism is similar to formerly developed approaches for the semantic matchmaking of client requirements against Web service capabilities (see e.g., [15, 16]). The mediation mechanism proposed here, is optimized for the matchmaking of sensors and services on the Sensor Web.

In the future, the approach will be extended to better support reasoning on quantitative sensor characteristics. So far, the mediator sorts values of quantities and quantity ranges of characteristics such as accuracy, precision, or survival range as ordered or nested concepts into the ontology. This sorting logic has to be computed by the mediator in the creation phase to prepare for the reasoning step. Alternatively, this could be delegated to the reasoner by modeling the quantities as individuals and using SWRL rules to select the correct sensors for a requesting service.

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5. REFERENCES


