A Stimulus-Centric Algebraic Approach to Sensors and Observations

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Abstract. The understanding of complex environmental phenomena, such as deforestation and epidemics, requires observations at multiple scales. This scale dependency is not handled well by today's rather technical sensor definitions. Geosensor networks are normally defined as distributed ad-hoc wireless networks of computing platforms serving to monitor phenomena in geographic space. Such definitions also do not admit animals as sensors. Consequently, they exclude human sensors, which are the key to volunteered geographic information, and they fail to support connections between phenomena observed at multiple scales. We propose definitions of sensors as information sources at multiple aggregation levels, relating physical stimuli to observations. An algebraic formalization shows their behavior as well as their aggregations and generalizations. It is intended as a basis for defining consistent application programming interfaces to sense the environment at multiple scales of observations and with different types of sensors.

1 Introduction

Sensor networks have become an important technology for observing physical phenomena. Their application scenarios include environmental and health monitoring, disaster management, early warning systems, precision agriculture, as well as home security [1]. Currently, most research is focused on technical issues. This includes work on hardware, operation systems, and signal processing [2], but also algorithmic aspects about how to reduce power consumption [3] and communication costs [4]. In contrast, this paper investigates sensors from an ontological perspective.

The understanding of complex phenomena, such as deforestation and epidemics, requires environmental sensor networks [5] observing at multiple scales. This scale dependency is not handled well by today's rather technical sensor definitions and therefore also in the derived models. For instance, to understand the impact of deforestation on the local fauna, it is necessary to track the path of individuals as well as the path of populations within a biotope. Movement patterns of individuals reveal information about change in territory and foraging, while the changed behavior of one population impacts the behavior of others. At the scale of the population, a sensor network should produce a single trajectory based on the tracks of the individual animals. Current definitions of sensors, sensor systems, and sensor networks are too technical to capture these abstractions of observations. For example, the definition of geosensor networks as 'distributed ad-hoc wireless networks of sensor-enabled miniature computing platforms that monitors phenomena in geographic space' [6] does not admit animals as sensors. It restricts the notion of sensors and sensor networks to technical devices and the message transmission to wireless communication.

In our work, we extend the second part of Nittel's definition by focussing on the scale dependency of observation regarding various sensor aggregation levels. Our main contribution is an algebraic specification of sensors. It provides a unified view on sensors at different scales, i.e., at different spatial, temporal and thematic granularity of observed phenomena. Our approach bridges between the sensor-centric Sensor Model Language (SensorML) [7] of the Open Geospatial Consortium (OGC) and the user-centric Observations & Measurements (O&M) [8] specification by focusing on stimuli as objects of sensing. We also include human sensors which are the key to volunteered geographic information [9].

The remaining paper is structured as follows. First, we give an overview of related work. We then propose to define sensors as information sources at multiple scales, relating physical stimuli to observations. An algebraic formalization shows their aggregations, compositions, and generalizations. We provide various examples from real applications of sensors and sensor systems to demonstrate our approach. The paper closes with conclusions and an outlook to future work.

2 Related Work

Current sensor models and definitions are designed from a technical perspective. In the engineering community, sensors are defined as devices that produce analog signals based on the observed phenomenon. These signals are converted to digital signals by analog-to-digital converters (ADCs). Sensor networks comprise a large number of sensor nodes 'that are densely deployed either inside the phenomenon or very close to it' [10]. A taxonomy of distributed sensor networks based upon different criteria such as input or communication could be found in [11]. Sgroi et al. [12] developed a set of well defined services and interface primitives for programming of ad-hoc wireless sensors and actuator networks. The SensorML specification [7] defines a common model for all kinds of sensor related processes, whereas a sensor is defined as a process entity capable of observing a phenomenon and returning an observed value. Our work is similar to [12,7] but is focused on the ontological view on sensors. Additionally, we provide a unique ontological view on sensors on different scales and include humans and animals as sensors.

There are several topics of current research on sensor networks. A lot of work has been done on reducing the in-network communication cost to reduce energy consumption by reducing the amount of data [4,13,14] or optimizing the data collection path [15]. As GSNs usually monitor dynamic phenomena in space, in-network detection of changes or events regarding the observed phenomenon is also investigated [16]. Another issue currently addressed is the localization of sensors in geosensor networks [17]. As the amount of data has to be reduced for further processing, several abstraction mechanisms for the sensor observations are presented [18]. Recently, Goodchild [9] proposed to extend geosensor networks to include humans either as sensor platforms or as sensors themselves. These human sensor networks could serve as the basis for the Volunteered Geographic Information enabled by Web 2.0 technologies. An example in this context is the bird post application (`www.birdpost.com`) which enables its users to report bird sightings or to search for bird sightings by location or characteristics.

To enable the web based exchange of geosensor data and the integration of sensor data into spatial data infrastructures, OGC's Sensor Web Enablement (SWE) initiative provides a framework of standards for the realization of a Sensor Web. Following Botts et al. [19] a Sensor Web refers to web accessible sensor networks and archived sensor data that can be discovered and accessed using standard protocols and application programming interfaces (APIs). Research on the Semantic Sensor Web [20] investigates the role of semantic annotation, ontologies, and reasoning to improve discovery on the Sensor Web [21]. It combines OGC's vision of a web of sensors with the reasoning capabilities of the Semantic Web. Besides discovery, a semantic layer would improve interoperability between sensor networks and would help to make sensors situation aware. A method for linking geosensor databases with ontologies has been presented by Hornsby [22]. An ontological analysis of the OGC standards on observations and measurements has been done by Probst [23]. However, the integration of semantics into sensor networks and sensor applications is still a challenging research task and a thoroughly defined model for sensors from an ontological perspective is currently missing.

3 An Algebraic Approach to the Aggregation of Sensors

In this section we introduce algebraic specifications for sensors, sensor systems, and sensor networks as well as for their aggregation and generalization. For lack of space and to improve readability we focus on particular aspects, leaving others (especially details about location, time, and signal processing) aside. The evolving, executable source code, specified using the functional language Haskell[3], is available online at `http://musil.uni-muenster.de/gsn09hs`.

3.1 Stimuli and their Observation

Our knowledge about the real world is based on observations. This includes observations about endurants such as a single zebra [24] or perdurants (also called occurants [25]) such as the dispersion of diseases like the dengue fever.

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[3] Introductions to the Haskell language, as well as interpreters and compilers can be found at `http://www.haskell.org`.

However, in most cases what is observed are not such particulars themselves but physical processes [26] related to them. We call those physical processes *stimuli* for which we have sensors. For instance sound waves within a certain frequency range become stimuli when they reach the human ear; they reveal something about particulars in the real world. We learn about particulars like walls from their echoing of sound waves. In this case the stimulus is created by the sensor itself, e.g., by an active sonar. In case of passive sensors such as human ears or passive sonars, the stimulus are the sound waves caused by a certain event (see figure 1). Another example is the problem of monitoring dengue fever. To make predictions about the future spread of this disease we observe the presence of eggs of *aedes aegypti* [27], the transmitters of dengue fever. We have several sensors to make this observation. For instance, we can detect the reflected light (stimulus) using our eyes (sensor) or the resistance from the solid surface (stimulus) with our sense of touch (sensor). In this case, a perdurant (the spread of a virus disease) is forecasted by observing another perdurant, namely the presence of eggs of the transmitting mosquito in a given region.

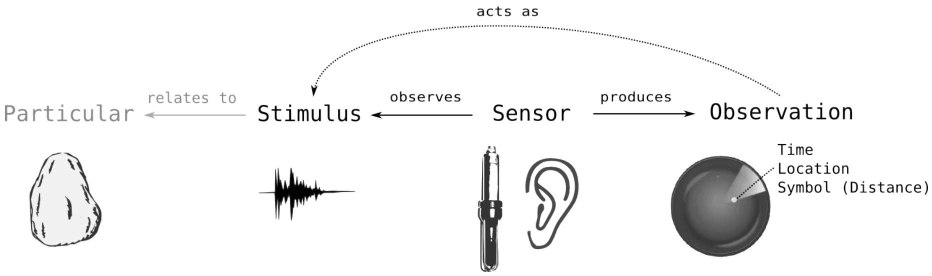

Fig. 1. Particulars such as a stone (hitting a water surface) can only be observed by stimuli which are related to them. The sensor has no knowledge about the particular itself (indicated by the greyed out color). Stimuli can only be defined with respect to a specific sensor. For example, the sound waves from the impact of the stone hitting the water surface are stimuli for human ears or a (passive) sonar. Stimuli are located and timed. For instance, the impact produces sound waves for a certain amount of time spreading from the location where the stone hits the surface in radial direction. While the stimulus acts as input to the sensor, the output is an observation. Such observations can be stimuli for other sensors (as in SensorML [7], though stimuli and observations are not not distinct types in SensorML), e.g., to produce a terrain model.

Note that we only require minimal assumptions about reality here. All information about reality is derived from observations and depends on sensors (including the human sensory system). In contrast to the user-centric view taken in OGC's O&M specification [8], our view focuses on stimuli as objects of sensing. At the same time, it abstracts from the technical, sensor-centric view of the

SensorML specification [7]. In this way, our view bridges between SensorML and O&M [8].

Listing 1.1. Stimuli as observable spatio-temporal referenced processes.

```
0  class LOCATED item where
1          getLocation :: item -> Location
2
3  class TIMED item  where
4          getTime :: item -> Time
5
6  data Process = SoundWave | EggReflection | Signal Observation |
7
8  data Stimulus = Stimulus Process Location Time
9
10 instance LOCATED Stimulus where
11         getLocation (Stimulus p l t) = l
12
13 instance TIMED Stimulus where
14         getTime (Stimulus p l t) = t
15
16 eggs = Stimulus EggReflection  'Porto Seguro' 04/2009
17 sound = Stimulus SoundWave theSonarsLocation now
```

Line 16 shows one specific stimulus, the occurrence of eggs of *aedes aegypti* in the Brazil city Porto Seguro in April 2009 (detected by the reflection of the eggs). This example also shows that we constrain the temporal and spatial resolution by the spatio-temporal extent of the stimulus. The behavior of stimuli is defined by the data type Stimulus specified in line 8-14. We model this extent of stimuli by introducing the type classes Timed and Located (line 0-4) which provides location and time on an abstract level.

We use a broader definition of Observation here than the one proposed by OGC [8]. Observations, as sensor results, are spatio-temporally referenced symbols provided to a user or for further processing (line 18-25). Symbols are observable signals and hence can be perceived by sensors again. Such symbols range from a count such as an integer for the number of eggs to complex symbols such as *mostly cloudy with occasional rain* in case of weather conditions. In the first case, an egg count is an observation where the human vision acts as sensor (line 27 & 30). In the second case, the literal *mostly cloudy with occasional rain* produced by the weather station is perceived by the human eyes acting as sensors (see figure 1). The result time and location of the observation may differ from those of the stimulus. Their georeferencing is up to the sensor (see below). Note that observations are processes (line 6) and can act as stimuli for other kinds of sensors.

Listing 1.2. Observations as sensor results.

```
18 data Observation = Observe [Stimulus]
19
20 instance LOCATED Observation where
21         getLocation (Observe stimuli) =
22                         getLocation (last stimuli)
23
24 instance TIMED Observation where
25         getTime (Observe stimuli) = getTime (last stimuli)
26
27 eggCount = Observe [eggs]
28 echoImpact = Observe [sound]
29
30 countEggs = observe aHumansVision [eggs]
31 receiveEcho = observe aSonar [sound]
```

3.2 Sensors

The Sensors type class (line 32-34) defines the behavior of kinds of sensors by providing the *observe* function (line 33). It maps from stimuli to observations. An example for a sensor is a heart frequency sensor attached to an animal. In this case, the location is not georeferenced and of minor interest. The implementation of the observe function is up to the specific kind of sensor. It captures how the stimulus is transformed to a digital signal, processed, and finally mapped to the symbol. This behavior should be described using standards such as SensorML. Geosensors are kinds of sensors delivering an observation with georeferenced location (line 38). An example is the EggSensor type for counting the eggs of *aedes aegypti*. The observations of the EggSensor contain a georeferenced location. Sensors are mounted on platforms (line 41) which provide an ID and a tracking function for their location. For instance, human eyes are placed on the human body, while a multi-spectral camera is mounted on a satellite.

Listing 1.3. Sensors mapping stimuli to observations.

```
32 class LOCATED sensor => SENSORS sensor where
33         observe :: sensor -> [Stimulus] -> Observation
34         observe sensor = Observe
35
36 data Sensor = Sensor Platform Process
37
38 data Location = GeoLocation Coordinates Epsg |
39                 BioLocation Organ Id | ...
40
41 data Platform = Platform Id (ClockTime -> Location)
```

Aggregation Sensors can be aggregated to sensor systems or sensor networks by using the *addSensor* operation (line 43). The *getSensor* operation (line 44) can be used to access a single sensor interface of the sensor aggregation to retrieve its observations.

A SensorSystem aggregates sensors (line 49-59) which are mounted on the same platform. An example is an aggregation of heart frequency and blood pressure sensors to provide the overall cardiac condition of an animal.

A GeoSensorSystem contains at least one geosensor defining the georeferenced locations of its observations. An example is a weather station (line 65,66) consisting of a thermometer and a barometer which are all georeferenced.

Listing 1.4. Sensors systems as sensor aggregations.

```haskell
42 class SENSORSYSTEMS sensorsystem where
43     addSensor :: Sensor -> sensorsystem -> sensorsystem
44     getSensors :: sensorsystem -> [Sensor]
45
46 data SensorSystem = SensorSystem Platform [Sensor]
47 aHumansSenses = SensorSystem aHuman [Hearing, Vision ,...]
48
49 instance SENSORSYSTEMS SensorSystem where
50     addSensor (Sensor platform2 stimulus)
51       (SensorSystem platform1 stimuli) =
52       if platform1 == platform2 then SensorSystem platform1
53         (stimulus : stimuli)
54       else error ”incompatible␣platform”
55     getSensors (SensorSystem platform [stimulus]) =
56         [Sensor platform stimulus]
57     getSensors (SensorSystem platform stimuli) =
58         (Sensor platform (head stimuli)) :
59           getSensors (SensorSystem platform (tail stimuli))
60
61 instance LOCATED SensorSystem where
62       getLocation (SensorSystem platform stimuli) time =
63           getLocation platform time
64
65 aWeatherStation = SensorSystem aPlatform
66                     [aThermometer, aBarometer, ...]
```

A SensorNetwork consists of a number of spatially distributed and communicating sensors or sensor systems. Instead of specific communication paradigms we only state that one can request the neighbors of a specific sensor. In an implementation of this specification the *getNeighbors* operation (line 71) could be realized by delegating to a corresponding operation of the sensor nodes. An example of a sensor network is a spatially distributed and connected group of animals carrying sensor systems of heart frequency and blood pressure sensors.

Listing 1.5. Sensors networks as sensor aggregations.

```
class SENSORS sensor => SENSORNETWORKS sensornetwork sensor where
    addSensor :: sensor -> sensornetwork sensor
                 -> sensornetwork sensor
    getSensors :: sensornetwork sensor -> [sensor]
    getNeighbors :: sensor -> sensornetwork sensor -> [sensor]
```

A GeoSensorNetwork is a sensor network whose nodes are all geosensors. For example, in the OSIRIS project [28], air quality sensors have been deployed on moving buses. These sensors taken together form a network for urban air quality monitoring, as they are spatially distributed and connected through wireless communication.

If a sensor system or a sensor network is a composition of sensors, all subsensors of the system or the network can only exist in it. One example for a composition of sensors is the human sensor system. The human eye cannot exist without the human body it belongs to.

Generalization Both, sensor systems and sensor networks can behave like single sensors by providing the observe function. Therefore, the proposed sensor aggregation realizes the *compositum* design pattern [29]. Thus, on different thematic, temporal or spatial scales a sensor aggregation can be generalized to a single sensor. The resulting symbol could be either a complex symbol containing single sensor symbols or a generalized symbol. In the example of the air quality monitoring network, if the sensor network is generalized to a single sensor, it either provides a value grid, a generalized value (e.g. an average) or a nominal value (e.g. 'smog'). The generalization defined by our sensor algebra affects the spatial and temporal resolution of the observation as well as the symbol resolution (as shown in the air quality example).

4 Conclusions and Further Work

In this paper we introduced an ontological definition of sensors at various scales. We provided algebraic specifications to show the aggregation, composition, and generalization of sensors. Our formalization is less restrictive in comparison to existing standards, and is more flexible in handling the heterogeneity of information sources. In contrast to more technical definitions, our approach explicitly includes human (and animal) sensors which play an important role in volunteered geographic information and environmental modeling.

A sensor implements a mapping from a physical stimulus to an observation. In contrast to the user-centric view taken in OGC's O&M specification and to the sensor-centric view in OGC's SensorML specification, our approach is stimulus-centric. It attaches the primary spatio-temporal context to the stimulus instead of the sensor. Geosensors differ from other sensors by providing additional georeferencing functionalities. This only requires minimal assumptions about reality, i.e., all information about reality is derived from observations and hence depends on sensors. Consequently, we do not need to make assumptions about objects (features of interest) at the sensor level. Observations can be stimuli for other sensors to enable more complex sensor processing chains. Sensors can be combined to sensor systems and networks. Depending on the thematic scale, these in turn can behave like a single sensor or a (spatially distributed) collection of sensors. The symbols of the aggregated sensors can be combined and generalized to create more complex symbols.

Further work will focus on defining more detailed algebraic specifications for the aggregation and generalization of sensors to reason about the resulting symbols and symbol systems. While geosensors rely on spatial reference systems to locate an observation, semantic reference systems [30] are necessary to reference complex symbols used by the sensor [31]. Such referencing, called *grounding*, is also required for the measurement procedure to fix the way how stimuli are mapped to observations.

The algebraic specifications developed in the paper will serve as a basis for defining a consistent application programming interface (API) to sense the environment at multiple scales of observations and with different devices. This involves work on defining a taxonomy of sensor types and relations between them. The API will allow for abstracting from specific sensor interfaces. It will focus on types of sensors and kinds of observations – making it a meta API.

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