

Semantic interoperability in sensor applications

Making sense of sensor data

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Abstract—Much effort has been spent on the optimization of sensor networks, mainly concerning their performance and power efficiency. Furthermore, open communication protocols for the exchange of sensor data have been developed and widely adopted, making sensor data widely available for software applications. However, less attention has been given to the interoperability of sensor networks and sensor network applications at a semantic level. This hinders the reuse of sensor networks in different applications and the evolution of existing sensor networks and their applications. The main contribution of this paper is an ontology-based approach and architecture to address this problem. We developed an ontology that covers concepts regarding examinations as well as measurements, including the circumstances in which the examination and measurement have been performed. The underlying architecture secures a loose coupling at the semantic level to facilitate reuse and evolution. The ontology has the potential of supporting not only correct interpretation of sensor data, but also ensuring its appropriate use in accordance with the purpose of a given sensor network application. The ontology has been specialized and applied in a remote patient monitoring example, demonstrating the aforementioned potential in the e-health domain.

Keywords—semantic interoperability, sensor networks, ontology, examinology, semantic sensor networks

I. INTRODUCTION

Sensor networks (SN) are technically highly developed in terms of performance and power efficiency, amongst others, however remain tightly coupled with specific sensor applications (SA) as closed stovepipes. We aim at developing open sensor networks, allowing sensor applications to choose amongst different SN components. This should foster reuse and stimulate innovation. This has motivated our research in the semantic interoperability of the SN/SA domain.

A sensor delivers the same bits of data independent of the application domain, but this data can have distinct purposes in different domains. For example, heartbeat can carry an indication of health in the care domain or an indication of performance potential in domains of sports or entertainment. This example shows that semantic interoperability requires not only sharing of data and concepts, but also positioning them in the specific purpose of the application for their appropriate use.

Ontologies have been acknowledged in the literature as a means to achieve interoperability between systems at semantic level [1]. An ontology is a conceptualisation of real-world

phenomena [2], so we need to investigate which concepts should be included in an ontology to achieve semantic interoperability between sensor networks and sensor applications, and what is required to direct their appropriate use. Furthermore, we want to be able to reuse parts of our ontology in different domains, but also to specialise our ontologies for specific applications in a certain domain. We are particularly interested in the application of our ontology to remote patient monitoring application in the e-health domain. Finally, loose coupling has been acknowledged as a means to achieve open systems, so we need to investigate its application in a semantic interoperability architecture.

This paper introduces, justifies and discusses our ontology, ContoExam, and shows its role in the system architecture. We show that by its application, open sensor networks emerge that can be loosely coupled with open sensor applications, enabling semantic interoperability in and across different SN/SA domains.

Our case is set in the domain of remote patient monitoring (RPM). These RPM applications endeavour for (a) increased quality of life by empowering patients to extend care & cure remotely and (b) improved quality of medical treatment, by providing information to the health care professional to improve decision making. Examples of such cases have been described by [3-5] and report positive effects on either or both of the mentioned endeavours. Still, re-use of (parts of) tailor-made applications, such as presented by [6], is hardly reported for these systems. This loss of efficiency will only grow with the technological progress being made in SNs and will hinder both endeavours. We advocate that the results of our work can alleviate this impediment, signifying the relevance of our research.

Presently some work can be identified that relates to our work, notably about ontologies for interoperability [7], [8], sensor semantics [9-16] and contextual awareness [17-19]. We distinguish from this research by taking an approach that integrates observations and their circumstances, with an architectural foundation to secure a loose coupling between SN and SA at the semantic level.

This paper is further organised as follows: Section II presents our conceptual model of semantic interoperability in sensor applications. Section III presents our architectural design. Section IV shows how our architecture holds in practice by presenting a case. Section V discusses some related work. Finally, Section VI draws our conclusions.

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II. CONCEPTUAL MODEL OF SEMANTIC INTEROPERABILITY

A. Semantic interoperability

Interoperability is defined as the ability of a system or product to work with other systems or products without special effort on the part of the customer¹. “Without special effort” refer to loose coupled systems. *Semantics* of data refer to its meaning that abstracts from reality as a *conceptualisation* that refers to the reality that is being observed [20]. *Semantic interoperability*, then, relates to sharing a conceptualisation by communicating its representation as a string of bytes, that, with minimal mutual dependency, leads to appropriate interpretation. That has two implications: a) Both communicating peers are expected to establish a similar comprehension of the state of affairs in the world (i.e. the observed reality) when assessing the shared string of bytes and to show reactive behaviour that is considered appropriate given their purpose and their scope². We further advocate that b) in open environments, semantic interoperability requires adherence, *at the semantic level*, to the architectural principles of separation of concerns and transparency. Semantic standards, such as *openEHR* [7] or HL7v3 RIM [21] in eHealth, do address these principles, for instance, by differentiating between the information model and the implementation model. As a result, different implementations of one of those standards remain interoperable with each other. Unfortunately none of these principles are addressed at the semantic level though, obstructing the semantic interoperability between different semantic standards.

What is considered *appropriate* can only be established at design time when the application is being analysed and modeled with respect to the enterprise’s operational business goals and the task of the user that the application is considered to support. Semantic interoperability, therefore, not only refers to passive representation of meaning in the data but requires support for the active, context-aware interpretation of the data into domain incentives as well. Only then applications are able to make appropriate decisions. For example, in RPM, semantic interoperability then implies that (a) the sensor that provides heart rate pulses should be able to abstract this observation in terms of a concept about *examined reality*, such as the frequency of occurrences of a certain event. Vice versa, the RPM application should be able (b) to comprehend such representation of examined reality in its own semantic framework, i.e., as a patient observation about heart rate, formally defined as the number of contractions of the cardiac ventricles per unit of time. Yet, a heart rate reading of, say 104BPM, in itself is insufficient to act upon and only when (c) embedded in contextual awareness, such as the subject being an adult or infant, at rest or running on a treadmill, it provides the necessary information to appropriately interpret the data to allow reasoning about a high or normal heart rate reading.

B. Coping with prior knowledge

Before a SA is able to appropriately use data originating from a SN, it requires *prior knowledge* about the details of the

SN and its environment that is typically only available at design time. Whether that prior knowledge refers to the driver details of the applied sensor, to details about how to convert voltage into a blood pressure value, or to assumptions about its operating environment, the knowledge often remains implicit and tacit, as well as specific for each distinct sensor-enabled application. Semantic interoperability requires this prior knowledge to become (i) explicit, so that it can be addressed and applied elsewhere; (ii) tangible, so that its relevance can be addressed by any SA at runtime; and (iii) standardised, so that it can be re-used by others. Studer [22] defines an ontology as “a formal, explicit specification of a shared conceptualization”. Therefore an ontology is suitable to capture this prior knowledge because it represents a specification that is *formal* (machine-processable), and *explicit* about a conceptualisation that is being *shared*, i.e. referring to consensus between communicating peers. We therefore focus on the development of an ontology to describe the prior knowledge about the act of making observations. To that end we draw from the science of examinations [10], and integrate these concepts with concepts around context and situation [23]. The resulting ontology, best described as a domain abstract language, describes precisely yet in an abstract way the act of making context-aware examinations. Before putting it into practice in a specific domain, it requires customisation into a precise but concrete specification of that domain’s universe of discourse (UoD). This is done by constraining it on the basis of knowledge ontologies, in our case GALEN³ or SNOMED⁴.

C. Conceptual model

Fig. 1 depicts a general sensor system, positioned in the RPM domain. We identified the following four interrelated semantic perspectives one can take when addressing prior knowledge:

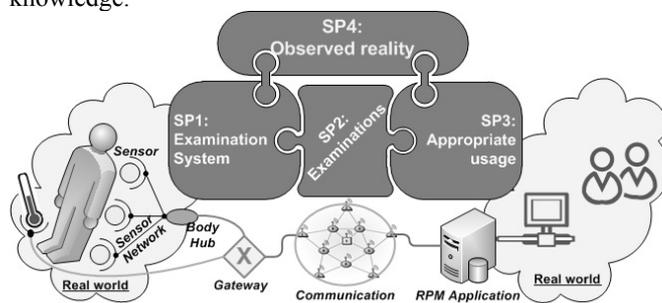


Fig. 1. Semantic perspectives of examinology on an RPM application

SP1: An examination system perspective, related to all concepts for acquiring and producing a sample of an examination, i.e., a shared conceptual model about instrument characteristics, principles of examination, devices involved and properties about the examination system itself;

SP2: An examination perspective, related to the result of the act of examining something, i.e., a shared conceptual model about examinations, the property values to expect and their qualifying properties such as, e.g., accuracy;

¹ IEEE Standards Glossary, available at <http://www.ieee.org/>, accessed Sep 28th, 2012

² Adapted from CEN/ISO-13606, <http://www.en13606.org/the-ceniso-en13606-standard/semantic-interoperability>, accessed Sep 28th, 2012

³ openGALEN. (2012) Available:<http://www.opengalen.org>, accessed Sep 28th, 2012

⁴ SNOMED-CT. (2011) Available:<http://www.ihtsdo.org/snomed-ct/>, accessed Sep 28th, 2012

- SP3: A usage perspective, related to all concepts involved in using information on consumed examinations to support a user task, i.e., a shared conceptual model about what is to be observed, the conditions that apply, the various protocols to follow, the quality criteria to meet and the contextual aspects of relevance;
- SP4: An observed reality perspective, related to the reality that the other perspectives are speaking about, i.e., a shared conceptual model about specific characteristics of the domain, such as properties and quantities, their relation to available standards, and a coherent set of properties, quantities and units that are considered relevant.

III. ARCHITECTURAL DESIGN OF SEMANTIC INTEROPERABILITY

We first identify semantic requirements before introducing concepts about examinology and context, which are subsequently constrained into a domain-specific UoD. We finalise this Section with architectural considerations.

A. Requirements

For each semantic perspective the semantic requirements have been derived from RPM cases, in hospitals [3-5] as well as at home [6], [24-26], and by evaluating requirements from the semantic sensor initiative [27]. The scope of our requirements analysis has been determined by the following situations: (i) One or more SNs, with dynamically changing variety of quantities and properties, biomedical, environmental and patient activity sampling alike; (ii) establishing patient-situation awareness and aggregating sensed data into application-relevant patient-status indicators; (iii) feeding clinical decision support applications real-time with relevant patient status indicators; (iv) making patient observations according to well-defined protocols. From these we derive semantic concerns in sensor systems as the ability to *explicitly* (a) express examinations of properties about entities, uniformly, regardless of medium (visual, acoustic, textual), source (lab, field or clinic) and method (objectively measured parameters, subjective indicators such as validated self-assessments, mathematically derived parameters) (SP1, SP2); (b) relate examinations to unambiguous and controlled domain vocabularies such as LOINC and SNOMED-CT in eHealth (SP4); (c) include context about the examinations that potentially influence their appropriate use such as patient activity, time of day, location of subject or examination, environmental (SP3); (d) relate domain properties, such as used in epilepsy, to other system of properties such as the ISQ, including transformations of their property values (SP3, SP4); and (e) state how measurement procedures influence appropriate use of data (SP3).

B. Examinology

The ‘International vocabulary of metrology – Basic and general concepts and associated terms (VIM)’ [28] deals with metrology, defined as the science of measurement and its application. However, the Joint Committee for Guides in Metrology limits its use to quantities, i.e., properties having a magnitude. This is a major impediment for its use in, amongst others, biomedical sciences, where properties without magnitude, such as blood type or level of abdominal pain, need to be measured. This has been recognised by [10] that introduces the term ‘Examinology’ to denote “the science of examinations, comprising both ‘nominal examinology’ and

‘metrology’ relating to both ‘nominal property’ and ‘quantity’, respectively”. The work also suggests definitions and explanations of concepts and terms related to nominal examinations. Dybkaer [11] defines an ‘Ontology on Property’ (OP) that unites ‘nominal property’ and ‘quantity’ as specialisation of a single superordinate concept ‘property’, depending on whether it constitutes a magnitude or not, as depicted in Fig. 2. In a similar way this work unites the metrological concept ‘measurement’ with the examinological concept ‘nominal examination’ into a single superordinate concept ‘examination’, represented in Fig. 3.

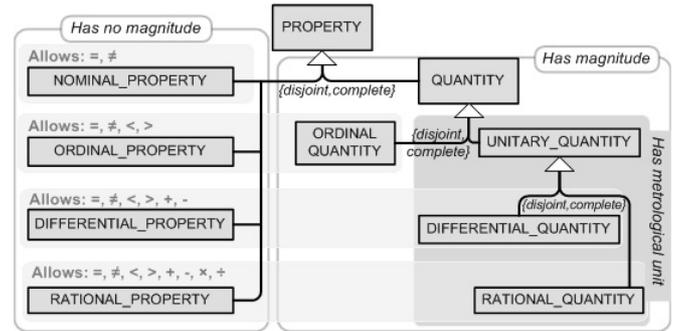


Fig. 2. Generic conceptual model of ‘property’ (from [11]), differentiating (i) between quantities and properties on the basis of having a magnitude, and (ii) between characterisations about allowed comparisons

We have taken the main concepts of the above ontologies and blended them into one single superordinate ontology as stepping stone towards the ContoExam ontology. To that end Fig. 3 also depicts how the concept ‘examination’ represents a conceptualisation of the examinological reality that an ‘examination system’ provides for an ‘examination result’, including its expected ‘examination uncertainty’, according to an ‘examination method’, for instance, specifying about how many ‘examined property values’ must be obtained to calculate an ‘examination result’.

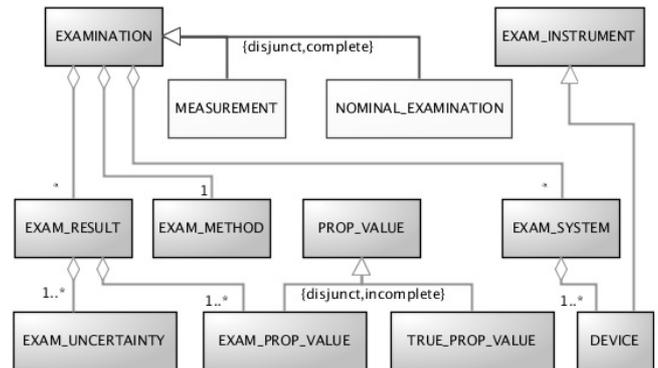


Fig. 3. “Examination” (adapted from [11]) as (i) superordinate concept uniting metrological ordinal “measurement”s and examinological “nominal examination”s, and as (ii) compound concept expressing an “examination system”, an “examination method”, and “examination result”(s).

Based on these concepts we can express abstractions such as: “A sensor provides examination results of an examinand in accordance to an examination procedure, including metrological properties such as accuracy”; and “A quantity is part of a system of quantities and is expressed in terms of a unit that is part of a corresponding system of units”. Furthermore, related definitions provide guidelines for processing property

values, especially concerning the comparable nature of properties and quantities as shown in Fig. 2. From this figure it becomes clear, for instance, that establishing an order between nominal properties is meaningless since these can only be tested for equality. This provides us with the ability to meet requirements (a) and (d), while we can express measurement procedures as required by (e).

C. Context

We consider context to influence the conceptualisation of the state of affairs that is intended to be captured. The approach taken in [27] is based upon [2], and reports about the foundational language constructs that are required in order to be able to construct contextual cues. To that end it defines the distinguishing concepts *entity* and *context*; the latter representing what can be said about the former, however without assuming primary context types as in [17]. Context does not exist by itself and is existentially dependent on a bearer, either a spatial or an intangible entity. Now consider the definition of an examinological *property*, as provided by [10] as the “inherent state- or process-descriptive feature of a system including any pertinent components”. By this definition a *property* is only meaningful with respect to a *system* (“demarcated part of the perceivable or conceivable universe, material or immaterial”, [ibid.]), and is existentially dependent on it. In short, a property inheres on a system as context inheres on its bearer, the entity. This leads us to the conclusion, depicted in Fig. 4, that in a conceptual model, the *property* should be considered as *context* to the *system* that is considered as an *entity*, both terms in their examinological definition.

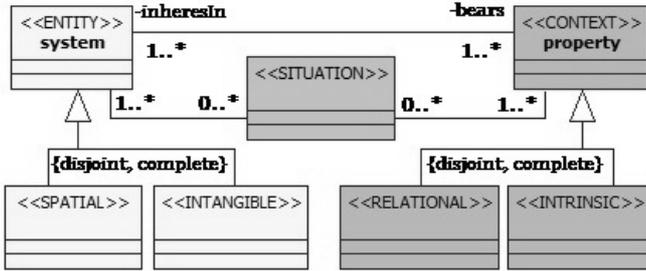


Fig. 4. Foundational language concepts to construct context of an entity or a situation, here how properties inhere in systems (adapted from [19]).

In our RPM case, for example, a statement that “the electrocardiogram (ECG) represents the conduction of the cardiac nervous tissue” is depicted in Fig. 5 as specialization of the concepts shown in Fig. 4. Similarly, one can express that spatial entity ‘ECG electrode’ has a property context expressing the ‘site location’. Furthermore, a lead (originating from a pair of electrodes) can view the heart from different angles, depending on site locations of the electrodes. A lead can then be expressed as relational context since it inheres on a multitude of entities, i.e. two electrodes.

Many clinical protocols prescribe that the situational context around a patient observation must be recorded, such as patient position or exertion state. This can be considered as yet another examination of a property, and can be expressed similarly as depicted in Fig. 5 as the state of the patient. This provides us with the ability to express the subject and circumstances of the measurement, meeting requirements (a) and (c).

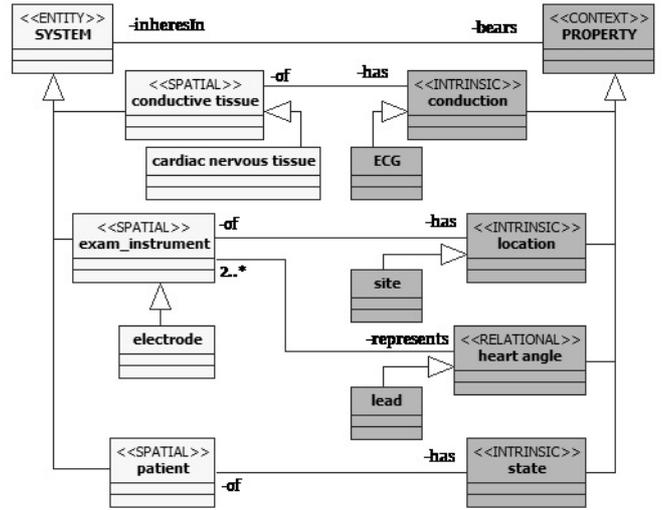


Fig. 5. Example of use of the context concept.

D. Constraining by domain vocabulary

By integrating concepts about context and examinology we thus far developed a domain abstract language that requires customisation into a precise but concrete specification of the domain’s UoD. The abstract concept of *property* can subsequently be constrained into a concept that is meaningful for the domain, such as the pattern of a heartbeat. This can be done by applying domain vocabularies, exemplified in Fig. 6. Next, examinology defines concepts to specify a *system of properties* (SoP), the very fundamental one being the well-known International System of Quantities ISQ. Similarly, one can define its own SoP in which each property can either be expressed by a quantity of the ISQ, or, if the property does not express a magnitude, it can be defined as nominal, ordinal, differential or rational property. This results in the ability to explicitly scope semantics to one’s own domain-specific UoD. In our RPM case, we draw from medical nomenclatures and ontologies such as SNOMED, LOINC, and similar, to facilitate the unambiguous definition of a coherent SoP that specifically relates to the Cardiovascular system (CVS).

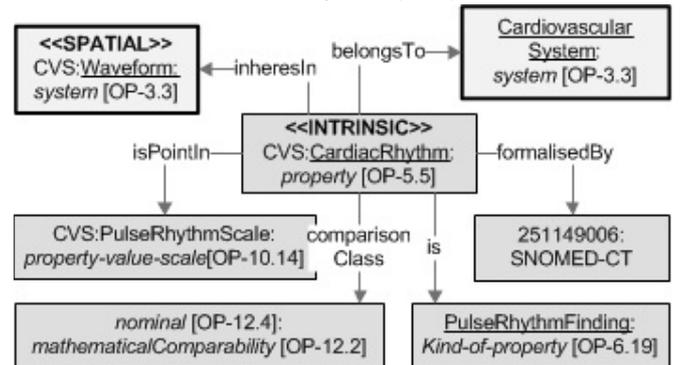


Fig. 6. Example of constraining a *property* into a domain-specific CVS:CardiacRhythm, where underlined words represent formalised SNOMED terms, italic words represent examinological concepts, and CVS refers to a user-defined namespace (here: cardiovascular system)

As pointed out in [29], an ECG recording session is a complex event, constituted by which consists of many observations. Each observation measures an electrical potential

difference (ISQ:EPD) around a human’s body surface, representing a conduction of the cardiac nervous tissue. The combination of several pairs of electrodes results in a *lead* representing an ISQ:EPD. Other properties are derived from that, such as augmented limb lead (aVR), QRS complex, P wave or RR interval, all belonging to the CVS SoP. The conceptualisation of this CVS SoP would then contain concepts such as ⁵ *rational property* (OP-12.7): CVS:ECG-lead→SNOMED-257467001; *property* (OP-5.5): CVS:aVR→SNOMED-257474006; *kind-of-property* (OP-6.19): CVS:deflection→SNOMED-250865004; *Quantity equation* (VIM3-1.22): aVR=RA-½(LA+ LL); *property* (OP-5.5): CVS:lead-location→SNOMED-263565005 as well as references to *derived quantity* (VIM3-1.5): ISQ:ΔV and *derived unit* (VIM3-1.11): SI:voltage, the latter two belonging to the ISQ SoP but applied to define the CVS SoP. In this way, the abstract statement from Section III.B: “a Sensor provides examination results of an examinand in accordance to an examination procedure, incl. metrological properties such as accuracy” can be constrained to read “the ECG-lead provides a deflection of the +60° axis of the heart of 0.85 mV (±0.005)”. This provides the ability to meet requirements (b) and (d).

E. Semantic separation of concerns

Loose coupling is considered an important characteristic in order to achieve open system architectures. We focus on two architectural principles, i.e., separation of concerns and transparency (see Section III.F), and apply these in a semantic architecture.

Separation of concerns (SoC), in its classical sense, refers to decomposing a system into parts with as minimal functional overlap as possible. In general this implies to define distinct layers for data management, service provisioning and enterprise applications. Each of these functional layers locally store and manipulate data, for which semantics are due. We therefore advocate that the semantic architecture should consider functional SoC as orthogonal to semantic SoC. In Fig. 7, partly founded on [8], functional SoC is represented by the three vertical columns, and semantic SoC is depicted by the five abstraction layers. Furthermore, it shows that semantic interoperability has to apply both bottom-up as top-down. Firstly, the lowest layer, the repository schemata, represent semantics concerning the technological details about accessing data: reading sensor data; syntactical details of how data are addressed; specifics about storing a patient observation according to an *openEHR* [7] or HL7v3 RIM standards [21]; gathering results from self-report health assessments. Whether it relates to sensor networks, services or applications, its semantics are held hostage by the technology used and the design decisions made, varying from XML-schemata to binary data fields or ERD-diagrams and more. This is considered a fact-of-life and hence unavoidable. Secondly, the function-dependent ontology represents the semantics concerning system operation: driving the management, monitoring and control of all the data handling of the previous layer; coordinating the envelope’s various components in realising the specific functionality allocated to it considering its functional SoC. Due to the heterogeneity of the sources, this calls for a local abstraction to provide uniform and internal consensus about the

local meaning of data and its control. The abstracting envelope provides local semantics only and, therefore, shows local appropriate behaviour. This internal consensus also provides for syntactical interoperability between the abstraction envelopes. Thirdly, the domain-variant ontology layer, represents the semantics for communication outside the local envelope, and is responsible for providing a representation of the concepts that communicating partners share in their domain-specific UoD. This represents the meaning they share, and hence use during communication. For the subject RPM domain, this concerns semantics about, e.g., a heart rate of a patient, while for the water management domain it concerns, e.g., the water gauge of a dike segment. These semantics need to be able to evolve over time as technology improves or applications need to change by incorporating new use cases.

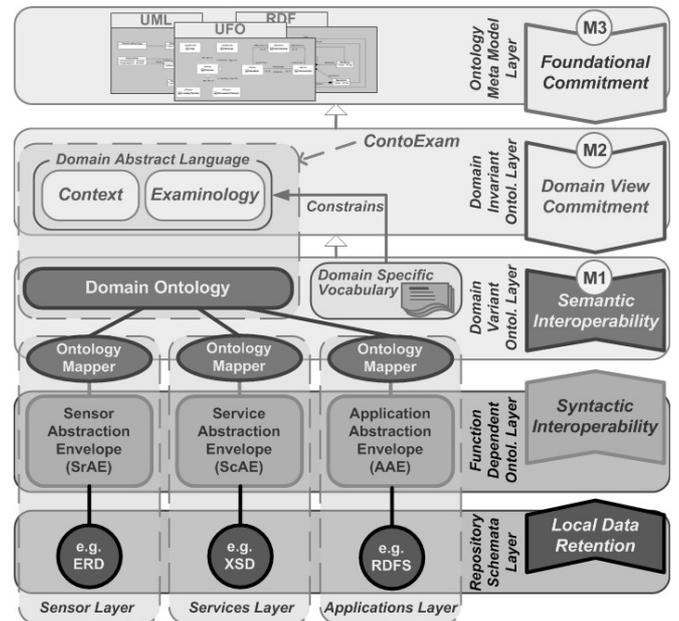


Fig. 7. Architectural design of semantic interoperability: data schemata are abstracted into local, function-dependent and envelope-uniform ontologies that map to one single, domain-variant ontology. Applying the four level modeling hierarchy pattern of the OMG, we can recognise the top three layers as the M3, M2 and M1 layers (from top to bottom). The domain ontology (M1) instantiates from the domain abstraction language (M2)

Fourthly, since “understanding something new requires a connection with something already known” [30], the subsequent domain-invariant ontology layer represents an abstract vehicle that is capable of formulating those shared concepts. These abstract semantics, however, remain stable when concepts in the lower level domain ontology change. This is the responsibility of both top layers: providing an abstract, stable, and semantically appropriate foundation, i.e. one domain abstract language, that describes the ontological commitment to the domain-specific state of affairs in the world, that is, the entities to which the primitives of a language commit [31]. We advocate that this is a two-step top-down approach: first the domain-independent foundational commitment must be defined, and then this can be instantiated into a domain commitment.

The ContoExam ontology fit into this architecture as follows: the domain abstract language, formulated in Sections III.B and III.C, represent the domain-invariant ontology model

⁵ We applied the following codification scheme: (nomenclature ‘-’ reference), where nomenclatures OP, VIM3 and SNOMED refer to [11], [27], and <http://www.ihtsdo.org/snomed-ct/>, respectively

committing to the domain view on the act of making examinations, and hence resides on the M2-layer. Section III.D describes how domain nomenclatures (e.g. SNOMED) are used to constrain the domain abstract language into the actual ontology describing the UoD to apply; both reside on the domain-variant M1-layer.

With semantic SoC, semantic interoperability: a) is designed to take place at the M1-layer; b) is being prepared at the ontology model and metamodel layers; c) requires syntactic interoperability; and d) is about data that is used appropriately in various functional envelopes.

F. Semantic transparency

Semantics can now be shared, and although we have introduced a semantic separation of concerns over five interrelated layers, it is not yet clear how interoperability with minimal mutual dependency can be achieved. For this we introduce *semantic transparency*. In service and object orientation, service transparency is being achieved by the architectural principle of information hiding. In this case, the information that is hidden from the external world relates to internal design decisions on how a component's function is achieved. In the semantic orientation, this 'information' should relate to design decisions about how an envelope comes to establish the 'intended' meaning, and 'being hidden' reflects the requirement that these design decisions do not apply prior knowledge about internals of other envelopes. We therefore define semantic transparency as the fact that the external world is agnostic about what is required for the subject envelope to establish local appropriateness from a globally shared conceptualisation. Here we use 'appropriate' to reflect that each envelope uses the conceived conceptualisation in its own right and according to its own purpose of existence, which is something different than demanding equal meaning over communicating peers. More pragmatically, the term designates that the concept that bears the semantics remains transparent for other envelopes. This implies an explicit separation between a local ontology from another local ontology, meaning that concepts from one local ontology do not proliferate to other local ontologies. This is where the ontology mappers from Fig. 7 come into play: to abstract from local syntax and connect to well-defined global syntax, while maintaining appropriate semantics. This requires the domain ontology to represent the quintessential UoD of all the local ontologies, which requires a conceptualisation over the domain-relevant state of affairs that is complete, lucid (without construct overloads), sound (without excessive constructs) and laconic (without redundant constructs) [31].

IV. CASE STUDY: PLUG-AND-PLAY MONITORING

The case has been built around a body sensor platform (BSP), described in detail by [32], on which several body sensor network applications are installed dynamically. The BSP is self-contained and designed to host multiple applications, sharing data with each other. For example, an ECG sensor is being used to support medical applications as well as to derive a heart rate to support a fitness application. The platform connects to back-end systems, like those of a hospital, when required. In the medical case study of the VITRUVIUS project⁶, a parameterised and personalised epileptic seizure detection algorithm uses heart rate to detect patient-specific

seizures. Motivated by this case study, we aimed for a design which is able to 1) dynamically handle deployment of applications and algorithms, 2) share data between multiple applications, and 3) handle different sensors and their configurations. Although the body sensor platform does not strictly apply service orientation, conceptually it does implement a sensor layer, a service layer and an application layer as depicted Fig. 7. The application layer may either reside on the BSP or on the back-end systems.

A. Original design

The original design is centred around a database that stores data generated by sensors or events derived by application components from sensor data. Since multiple applications can manipulate or share the same sensor data, a publish/subscribe pattern has been applied. The publisher notifies the subscribers about availability of new subscribed information, upon which the interested subscribers retrieve data from the database. The subscription method supports dynamic modifications of the subscription list. The configuration manager is responsible for verifying and serving the requests from the applications or other components. In order to handle sensors with several types of sensing data, and to allow sharing data among multiple applications, a simple ontology for sensor and data descriptions has been developed, which is realised by a set of database tables. These tables hold prior knowledge about potential configurations about (type of) sensors, such as shimmer EMG or temperature, derived data, possible operating states. These tables are pre-defined by the system engineer. When a new component registers, its specifics are activated by the configuration manager. Using the information from these tables, applications can interpret the data from sensors or generated by components. Any back-end system, such as a monitor or a domain decision support engine, is required to implement this common set of terminologies. They need to comply syntactically in order to establish data exchange and semantically in order to establish appropriate behaviour.

B. Role of ContoExam

From the perspective of semantic interoperability, the original application in the performed case study can be considered a legacy situation since semantics were not considered at the time of development. When introducing ContoExam, we decided to (a) not change any communication sequence flows unless deemed necessary, and (b) implement semantic transparency wherever possible. Consequently, most component logic remained identical, while all exchanged data were changed to apply ContoExam concepts. The ontology mappers from Fig. 7 became necessary to translate from and to local schemata, which is a function that was assigned to the configuration manager. For example, the following flow of events happens when new subscribed information becomes available:

- 1) The publisher (i.e., a sensor) notifies the subscriber (i.e., a decision support system) about new data. To specify the property it represents, its mapper includes a preconfigured cross-reference to the concerned property as defined in the subscribers SoP.
- 2) Besides the notification and the property, the database was extended to also provide a so-called measurementView to the endpoint that specifies the procedure required for fetching the actual data.

⁶ see: <http://vitruius-project.com/>; accessed Aug 30, 2012

- 3) The subscriber's mapper informs the subscriber in its own local terms about the availability of new data.
- 4) The subscriber decides to formulate a data request that its mapper transforms into the execution of the measurementView procedure.
- 5) The mapper's endpoint receives the measurementView, maps it onto the actual query to the central store and returns the raw data to the subscriber.

For reasons of performance, the endpoint that actually executes the procedure may be the sensor node itself, hence bypassing the configuration manager. However, these issues are considered as implementation details.

C. Lessons learned

Reflecting on the case study, the following observations can be made. We made no attempts to alter the design of the systems for the parts not related to semantic awareness. For instance, the central database that stores all produced data is still part of the system and still being queried for new sensor data; however, because of the introduction of an ontology mapper (see Fig. 7), the nature of these SQL queries is changed considerably as these are now being expressed in ContoExam terms. Within the scope of the case, no concept is missing to support original functional behaviour; in addition ContoExam can represent specific details about the sensor as well as their direct context of examination, leading to the conclusion that the Domain Ontology is complete for the subject UoD. Although examinology does not specifically represent domain concepts about patient observations and protocols, together with the concepts on context it indeed provides sufficient ground to be further constrained into an ontology that provides suitable support for *openEHR* domain artifacts. The availability of an application-defined 'set of kind-of-properties' (OP-13.17), representing the application's focus on observed reality, facilitates the description of which properties are measured by which instruments. In case no such information is available from the sensor layer, the ontology mapper of the application layer still knows about the type-of-properties that are produced by the sensor layer. From this information, and based on context information provided by the sensor layer (e.g., the site of measurement), the ontology mapper can establish which instruments represent what domain-specific property (e.g. lead-II of the ECG). Interestingly, it became clear though that foundational medical knowledge required to populate a domain-specific set of kind-of-properties (e.g. a set of cardiovascular properties), was not yet completely defined, at least not on the detailed level that was required. Hence, we had to design a small but significant part of the ontology. This underlines the need for knowledge ontologies to guarantee the completeness of the set of domain-specific concepts. Although we could define the semantics ourselves to still prove the concept, this stresses that *interoperability* is dependent on the completeness of the shared domain nomenclature.

Next, the ontology mappers appropriately function as tollgates to safeguard semantic transparency. Any newly introduced sensor from the sensor layer becomes semantically available for the service and application layers once its meaning was formally expressed, locally. This shows that reuse of a sensor solely depends on its mapping to application-specific definitions of the property about the subject it examines, whilst maintaining its metrological characteristics. Similarly, using appropriate medical knowledge, new properties such as, e.g., an

epileptic seizure can become available, easily and transparently, while maintaining a closed-world UoD and resulting in an agnostic view on the difference between physical and virtual sensors. Although not completely comparable to connecting a completely new application to the same SN, it nevertheless represents a strong indication of semantic reuse of existing SNs.

V. RELATED WORK

The work of Berges [8] addresses semantic interoperability by mapping local application ontologies to a canonical representation of domain knowledge. We draw from this work but distinguish from it due to our focus on the impact architectural principles have on achieving mutually transparent domain ontologies. From an application perspective, although our work, just like the work of Berges, draws from the *openEHR* information model [7], ours complements his in that we present an ontology about patient observations, since we are interested in the semantics around sensor applications. Several sensor languages have been proposed, such as SensorML [12], ECHONET [14], IEEE-1451 family [13], and Device Description Language (DDL) [33]. These languages mainly address only connectivity (i.e. control, access and syntax of the sensors and their data) and therefore fall short in supporting semantic interoperability with applications [16]. Contrarily, the Semantic Sensor Network (SSN) ontology [9] presents sensor semantics on a similar abstraction layer as our ContoExam ontology. However, it applies only that part from metrology that describes instrument properties, replacing the majority of the internationally agreed conceptualisation about the science of measurements with their Stimulus-Sensor-Observation (SSO) ontology design pattern [34]. Basically, this pattern is strongly biased and directed by an SSN architecture, presented in [27], instead of staying both independent and orthogonal, as I our work. In addition, their SSO pattern has deliberately been kept lightweight, minimalistic, and with a minimum of ontological commitments with the intent to act as a generic and reusable component for all kinds of observation-related ontologies. We have shown that at the semantic level, conversely, being abstract (as opposed to being generic) calls for a domain-agnostic yet precise representation of the process of examination, whilst being reusable calls for the ability to constrain the abstract representation into a domain-specific conceptualisation of the UoD. Another such initiative, the QUDT ontology [35], represents (only part of) VIM's metrology UoD and neglects the examinological properties without magnitude, as required by biomedical sciences.

Context-aware applications, finally, have been defined by Dey [17] who identifies primary context types for characterising the situation of a particular entity. Compton [27] takes an approach based upon [2], and reports about the foundational language constructs that are required in order to be able to construct contextual cues. This confirms the implicit assumption of Dey (*ibid.*), however, without assuming primary context types, remaining more generic. We prefer the latter approach, underlined by Daniele [19] who shows how these concepts can apply as founding elements to construct an abstract model capable of uniformly representing, amongst others, the proximity concept.

VI. CONCLUSIONS

We started this research with the question how *appropriate use of shared concepts* could be conceptualised into an

ontology, applied for semantic interoperability in the sensor networking domain. To that end we have developed an ontology (ContoExam) founded on examinology and context, and evaluated its use. We have shown that the property concept can be considered as the context of the measurement subject it inheres on, and how context can be used to further express situational awareness about the measurement, directing its appropriate use. In addition, we applied the principle of semantic transparency to share concepts without the need to adhere to external state of affairs. We developed an ontology that is both abstract enough for reuse while remaining sufficiently specific to be used as UoD. We showed that by specialising the examinology and context ontology for the RPM domain, a rigorous conceptualisation that facilitates a strict UoD is obtained. Our research demonstrates the effectiveness of ContoExam in RPM applications, especially in aspects that are not specific to the RPM domain. We therefore argue that this ontology can be applied to any other application domain that can be supported by sensory data, such as the Internet of Things, with comparable effectiveness, as long as specific ontologies for that domain have been established. Future work is required to validate this argument. Our research also shows that the architectural layers of semantic interoperability can be applied orthogonally to the usual SOA layers, allowing semantic concerns to be resolved independently from the technical architecture. Finally, our work shows that the architectural principles of separation of concerns and transparency provide similar guidance for semantic architectures as they do for technical architectures and functional designs.

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