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BCI Ontology: A Sensing and Acting Context-based Model for Brain-Computer Interaction

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Abstract. Key developments in wearable sensors, wireless networks, and distributed computing will largely enable Brain-Computer Interaction (BCI) as a powerful, natural and intuitive mainstream human-computer interaction in real-world activities. BCI systems annotate the sensed signals in order to classify the analysis of brain states/dynamics in diverse daily-life circumstances. There is no any complete and standardized formal semantic structure to model the BCI metadata annotations, which are essential to capture the descriptive and predictive features of the brain signals. We present the BCI Ontology (BCI-O): the first OWL 2 ontology that formalizes relevant metadata for BCI data capture activities by integrating BCI-domain-specific Sensing and Acting Models along with a novel Context Model for describing any kind of real/virtual environments. At its core, BCI-O defines a human-environment interaction model for any BCI, based on design patterns and primarily aligned to the SOSA/SSN, SAN –IoT-O– and DUL ontologies. Its axiomatizations aid BCI systems to implement an ontological overlay upon vast data recording collections to support semantic query constructions (to perform Adaptive BCI) and reasoning for situation-specific data analytics (to apply inference rules for Transfer Learning in multimodal classification).

Keywords: Brain-Computer Interaction • Ontology • Sensing-Acting Model • Context-based • Context-awareness • Internet of Things • M2M environments

1 Introduction

Recent advancements in BCI systems (sensors integrated with novel computing architectures) are enabling analyzing human brain states in real-world situations (augmented) with real-time data processing [1] [2]. A formal structure is needed to semantically characterize the descriptive and predictive data components of brain state multimodality analysis: a domain ontology for real-world multimodal BCI.

This paper introduces the BCI Ontology (BCI-O). At its core, it defines a human-environment interaction model inspired from Human-Computer Interaction (HCI) notions [3]. Relevant BCI metadata for context, multimodality (not only EEG), and event annotation tags, are depicted in its conceptual abstractions. BCI-O's Sensing and Acting Models are based on ontology design patterns found in standard upper ontologies, making it interoperable and easy to extend for any BCI system. Below are presented BCI-

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O's structure, design principle, ontology engineering, applications, and future work. Last, in the conclusions section, are described the main contributions.

2 Overview

Real-world multimodal BCI [1] may be decomposed into the following modeling aspects: wearing a set of sensors (*device*) and/or through actuators (*actuator*), human beings (*subject*) interact with an environment (*context*) while performing (*session*) real-world activities (*activity*), where stimuli (*stimulus*) triggered by *context*ual *event*s, are observed, recorded (*record*) and marked (*marker*) in the sensed multimodal (*modality*) BCI *data*.

At its core, BCI-O defines the conceptual components in any BCI through a bidirectional *subject-context* interaction model (a BCI *session* with *sensors*/*actuators*): a Sensing Model (*context* to *subject*) and an Acting Model (*subject* to *context*), as depicted in **Fig. 1**. The design principle underlying this interaction model is described in section 4. However, its structure can be summarized in the following way: the Sensing Model is based on the Stimulus-Sensor-Observation (SSO) Ontology Design Pattern (ODP) [4] and aligned to the SOSA/SSN upper ontologies [5], whilst the Acting Model is based on the Actuation-Actuator-Effect (AAE) ODP [6] [7] and aligned to both SOSA & SAN (IoT-O) [6] [8] upper ontologies.

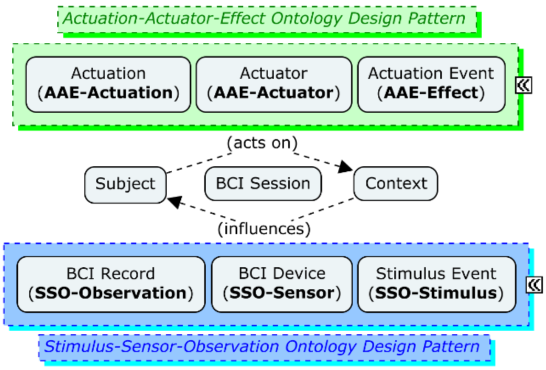

Fig. 1. Core BCI Interaction Model: Integration of a Sensing Model (context to subject, based on the SSO ODP and aligned to SOSA/SSN) and an Acting Model (subject to context, based on the AAE ODP and aligned to SOSA & SAN/IoT-O) for BCI data capture activities.

Two distinct conceptual domains are found in this model: BCI domain (observations, actuations, and interactions) and context domain (surroundings). The context domain concepts are based on the gaming architectural modeling of the Unity framework [9]. The BCI domain concepts were taken from the following semi-structured standard vocabularies and formats:

(1) *Extensible Data Format* (XDF) [10]: a general-purpose container format for multi-channel time series data with extensive associated meta-information stored as XML, called *XDF metadata schemes*. XDF is tailored towards bio-signal data (multi-modal data capture) but can easily hold data with high sampling rate (like audio) or high numbers of channels (like fMRI or raw video), as well.

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(2) *EEG Study Schema* (ESS) [11]: an XML-based specification that holds a metadata hierarchy for describing and documenting electrophysiological studies and their raw recorded data, in a format that is both machine and human readable.

(3) *Hierarchical Event Descriptor Tags for Analysis of Event-Related EEG Studies* (HED) [12]: defines a hierarchy of standard and extended descriptors for EEG experimental events that provides a uniform human- and machine-readable interface that facilitates the use of an underlying event-description ontology during EEG data acquisition, analysis, and sharing. HED tags may be used to mark and annotate all known events in an experimental session. As a classification system, HED is a *folksonomy* (also known as collaborative *tagging*), due that can be used collaboratively to create and manage tags for annotating and categorizing EEG-related events content. ESS is the companion specification of HED.

In the BCI domain, after collecting multimodal data from a *subject*, systems proceed to "annotate" the data with descriptive and predictive parameters. The **descriptive features** explain the "interaction model settings" of the data (see **Fig. 2**); whereas the **predictive features**, based on the data contextual event tagging, provide important input to classification models (data analytics) for adaptive BCI [2] (see **Fig. 3**). In the BCI domain, *context* correspond to the same concept as in HCI literature.

Due to its orientation on real-world BCI, the ontology main design objectives are:

1. **Target domain** – *BCI metadata*: define core, generic and relevant consensual concepts about BCI data capture activities.
2. **Target users** – *Focus*: develop a machine-readable BCI semantic model for software agents' interoperability. Special interest in pervasive M2M environments.
3. **Design principle** – *Structure* (based on ontology design patterns), and *Alignment* (following the intention of abstractions modeled in upper ontologies).
4. **Design criteria** – *Simplicity* (minimalistic model), *Extensibility* (easy to extend), and *Reusability* (reuse of relevant vocabularies from different knowledge domains, related to BCI).

BCI-O structure depicts a conceptual framework that BCI systems can extend and use in their implementations. The spec is available at the following open repositories:

Repository	Entry	Description
w3id.org	https://github.com/perma-id/w3id.org/tree/master/BCI-ontology	WWW URI
Linked Open Vocabularies	http://lov.okfn.org/dataset/lov/vocabs/bci	LOD
BioPortal	http://bioportal.bioontology.org/ontologies/BCI-O	BioMedical

Table 1. Open Repositories where BCI-O spec can be publicly accessed

BCI-O namespace is `<https://w3id.org/BCI-ontology#>`

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3 Ontology Structure

BCI-O concepts are grouped into several modules[1]. Each module represents a key topic that gives a consistent explanation of its correspondent functional aspect in the mentioned BCI interaction model. Following, are presented a brief description of the modules and their core concepts.

- **Subject**: defines a human being (*subject*) engaging in an *activity* and its associate state (*subject state*). *Subject* defines a person with certain attributes, equivalent to *Patient* in the HL7 standard.
- **Context**: captures the architectural description of a physical/virtual environment. Its modeling is based on [9]. A *context* is a sequence of *scenes*, each one of which depicts a collection of spatial-located entities (*objects*) interplaying (behavior: *methods*) with one another (temporality-based sequence of *event*s: change of state) in a specific way (see **Fig. 6**). These conceptual components able the structural, functional, and temporal complexity definitions of any environment. Under the *event* classification, BCI-O defines three key concepts that bind the contextual integration with its Sensing and Acting Models: *stimulus event* (a stimulus to the *subject*), *action* (issued by a *subject* while performing an *activity*), and *actuation event* (an effect –change of state– in the *context* as the result of an *actuation*).
- **Session**: represents the interaction between a *subject* and a *context* while performing (*session*) a single *activity*, under specific settings and conditions (the **descriptive data features**). A *session* groups both observations (multimodal measurement records: *record*) and *actuations*. **Fig. 2** depicts the core modeling for *Session*.
- **Sensing Model**: describes the contextual input data and events to the subject [6].
  - **Observations**: specific concepts aligned to the SOSA/SSN axioms for modeling Observations (the initial alignment was to the Skeleton of [13]). These are related to *record*s (a single observation), *modality* types ("mode of the data"), interpretation *aspect*s, *channeling* schema information, *recorded data* as sensor output streams (with a *data format* and an *access method*), and *stimulus event*s.
  - **Sensors**: specific concepts aligned to the SOSA/SSN axioms for modeling Sensors –under Observations– (the initial alignment was to the Device Module of [13]). These are related to *device*s, their *channeling* schema, and their *spec*s.
  - **System Capabilities**: specific concepts aligned to the SSN horizontal segmentation module for System Capabilities (the initial alignment was to the Measurement Capability Module of [13]). They are about *channel*s (logical components of a channeling schema spec's data structure model) and other *measurement properties*.

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1 Detailed class modeling diagrams and graphical depictions of the BCI-O architecture (structure, modules, and alignments) are documented in the Ontology Structure, Overview Presentation sections, and on each concept definition of the spec's human-readable version.

  - **Results**: specific concepts aligned to the SOSA axioms for modeling Results (the initial alignment was to the Data Module of [13]). They are *data block* and *recorded data*. *Actuation result* is also included in this module.

- **Acting Model (Actuation)**: unified concepts aligned to the SOSA and SAN axioms for modeling Actuations. This module depicts how the *subject* can interact with the *context* [6]. Its main concepts are *actuation* and *actuator*.
- **Annotation Tag**: *event marker*s (based on context stimuli –*stimulus events*–) and *response marker*s (based on machine learning *model*s) for annotations on specific *data segment*s (data tagging). These define the **predictive data features** (see **Fig. 3**), while the previously modules explain the **descriptive data features**.
- **Descriptor**: a *descriptor* defines an external resource set that extends and/or complements the description associated with relevant entities defined in BCI-O.
- **EEG**: concepts for EEG applications. Due to the common nature of EEG data, these subclasses represent EEG subtypes for *channel*, *device*, *modality* and *record*.

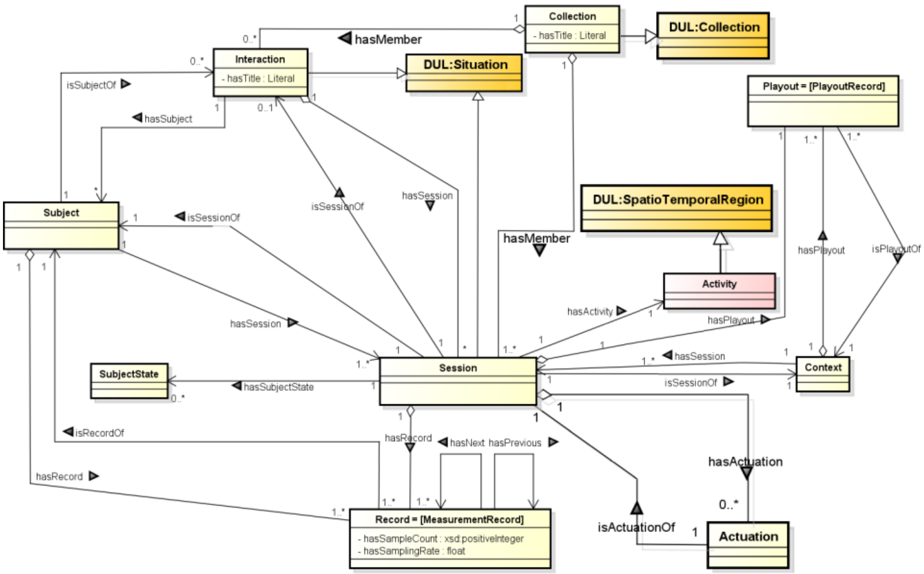

Fig. 2. A representational UML class diagram for the concept *Session*: the integration of the Sensing and Acting Models for BCI-O's descriptive data features.

The *instant* and *interval* concepts were borrowed from [14]. URI locators to external resources and raw data can be used as accessing and indexing purposes. BCI systems can express interoperable models extending BCI-O, which comes handy in M2M environments. The spec leaves open the way in which applications handle the semantic expressiveness level for measurement units, and the *sosa:Procedure* concept extension (for more details, refer to the General Remarks section of the spec's human-readable version).

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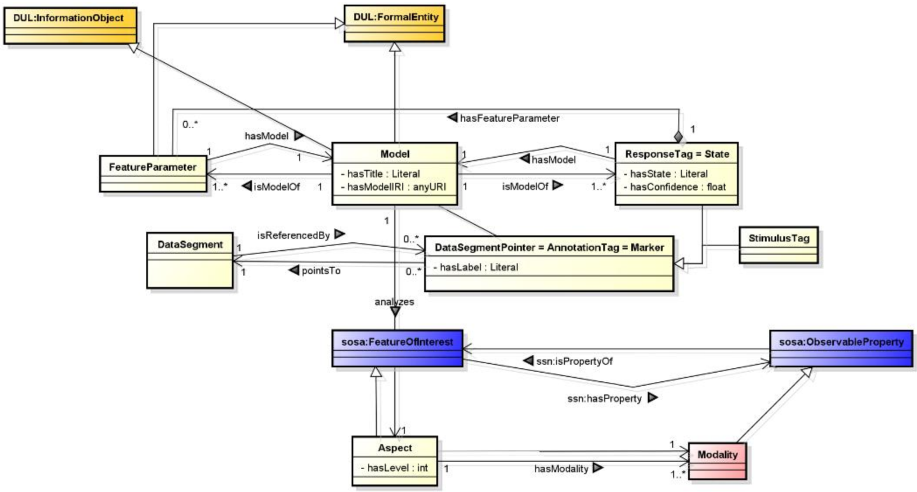

Fig. 3. A representational UML class diagram for the concepts *Marker* and *Model*: the key abstractions for BCI-O's predictive data features.

4 Design principle

Semantic Sensor Network (SSN) [13] [15] [5], along with its self-contained core ontology *SOSA* (*Sensor, Observation, Sample, and Actuator*) [5], is a standard framework ontology that BCI-O furtherly extends for the BCI domain. SOSA/SSN gives BCI-O the conceptual template and structure for both its Sensing and Acting Models, describing functional aspects of any BCI data capture activity.

4.1 Sensing Model: SOSA/SSN Ontologies & SSO Design Pattern

Besides of SSN general benefits [15], BCI-O's Sensing Model leverages from it in the following ways:

- BCI systems can be considered as specialized sensor networks [2]; SOSA/SSN helps to improve their semantic interoperability and integration.
- As a *Linked Sensor Data* standard, SSN helps to connect the IoT and the Internet of Services layers [15], which is of special interest to BCI in M2M environments.
- SOSA/SSN supports different views related to BCI systems architecture, which can be centered around: (1) Sensors (capabilities), (2) Observations (what was observed and how), and (3) Features and properties (how to observe them).
- SSN gives a foundation for describing sensor networks as Web apps: real-time data processing from *Web-of-Things* sensors; which is a characteristic of BCI systems.

SSN *Skeleton module* describes the *Stimulus-Sensor-Observation* (SSO) ontology design pattern [4] [16], which forms the top-level of SSN [15]. BCI-O's Sensing Model key concepts were first built aligned to SSO (following closely [15]), and later on, remapped to [5]. Not only SSO is suitable for event/situation based data logging but due

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to its generic and reusable structure, this pattern is intended for observation-related ontologies and for observation-based data on the Semantic Web [4]. Thus, it conforms a natural design structure for the BCI-O's Sensing Model.

4.2 Acting Model: SOSA + SAN ontologies & AAE Design Pattern (IoT-O)

BCI-O's Acting Model is based on the *Actuation* and *Actuator* abstractions. In the IoT community, the *Semantic Actuator Network* (SAN) has been proposed as an upper ontology for IoT-O (IoT ontology) [6]. SAN is built around the *Actuation-Actuator-Effect* (AAE) ontology design pattern [6] [7].

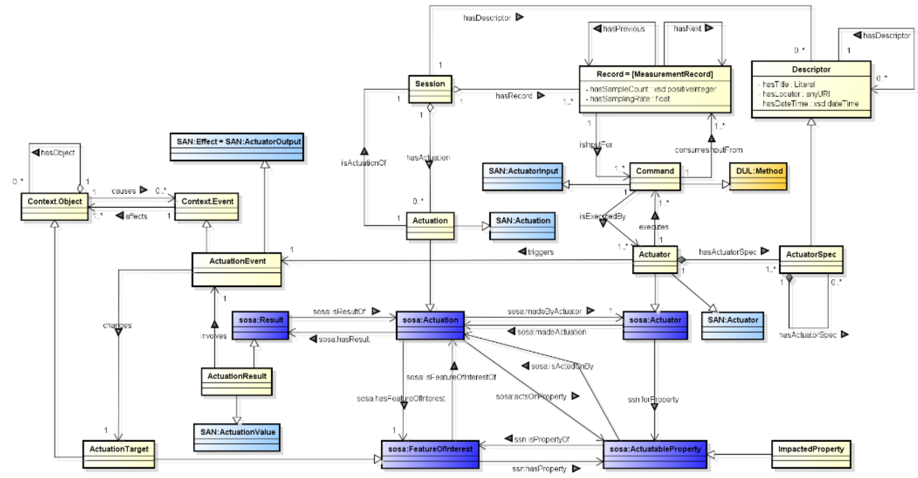

Fig. 4. BCI-O's Acting Model: alignment to SOSA/SSN.

BCI-O's Acting Model integrates carefully both standard axiomatization models for actuations, developed by W3C/OGC [5] and IoT [6] [8] communities. Thus, its structure follows closely the AAE ODP while aligning to SOSA/SSN and SAN. As part of the BCI-O's Acting Model development, we raised[2] the issue[3] to the W3C Spatial Data on the Web Working Group [17], regarding the mapping of SOSA/SSN to AAE ODP, due of their structural resemblance. **Fig. 4** shows BCI-O's Acting Model alignment perspective to SOSA/SSN, while **Fig. 5** presents its alignment perspective to SAN (IoT-O) following the AAE ODP.

2 <https://lists.w3.org/Archives/Public/public-sdw-comments/2017Apr/0038.html>

3 <https://www.w3.org/2015/spatial/track/issues/187>

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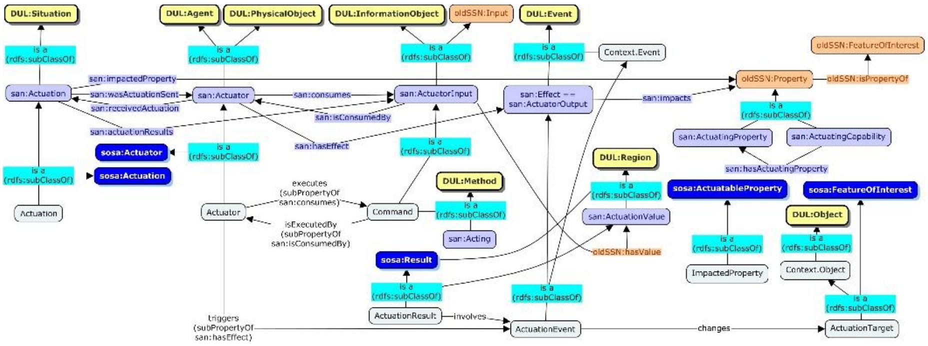

Fig. 5. BCI-O's Acting Model: following the AAE ODP and alignment to SAN (IoT-O).

4.3 Design approach: ontology alignments

BCI-O's basic design principle can be depicted as a three-layered architecture of an ontology library [18], with the following structure: the foundational layer (DUL), the core layer (SOSA/SSN + SAN), and the domain layer (BCI-O). Thus, as an example, the *participation* foundational design pattern [16] fits in the following way:

- [objects] `DUL:Object` → *sosa:Sensor* → *Device*.
- [objects] (`dbp:Person` [19] | `DUL:NaturalPerson`) → *Subject*.
- [events] `DUL:Event` → *ssn:Stimulus* → *StimulusEvent*.
- [events] `DUL:Event` → *sosa:Observation* → *Record*.
- [spatial-temporal location] `DUL:Situation`→ (*Session* | *Context* | *Context.Scene*).

Based on the SSO ODP, the domain level concepts of the Sensing Model were specialized initially from the SSN *Skeleton module*, following a similar alignment scheme that this one had with DUL, as explained in [15]. Due to its alignment with the initial SSN version, BCI-O was documented as part of the analysis on the usage of SSN [20], as one of the ontologies (concept producers) that reuse SSN. Subsequently, BCI-O's Sensing Model was re-aligned to the *Dolce-Ultralite* (DUL) *Alignment Module* of the SOSA/SSN Vertical Segmentation[4]. SSO-based core alignments are:

- *Stimulus*: A detectable change in the environment that triggers the sensors to perform observations. BCI-O defines *StimulusEvent* aligned to *ssn:Stimulus*.
- *Sensor*: An object that performs observations to measure certain observable properties. SSO defines sensors as the composite abstraction of sensing devices. BCI-O defines *Device* aligned to *sosa:Sensor*.

[4] The complete axiomatization re-alignments are described in the General Remarks » Mappings to SOSA/SSN section of the spec's human-readable version.

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- *Observation*: A multi-dimensional event that captures information about the stimulus, sensor, its output and the spatial-temporal specification of the sensing activity. Due to its constraints, BCI-O defines *Record* aligned to *sosa:Observation*.

Based on the AAE ODP, the domain level concepts of the Acting Model were aligned initially to SOSA/SSN. Afterwards, they were integrated with proper alignments to SAN (IoT-O), following closely their axiomatization satisfiability (see **Fig. 4** and **Fig. 5**). BCI-O's AAE-based core alignments are:

- *Actuation*: Carries out a procedure to change the state of the *Context* using an *Actuator*. BCI-O defines *Actuation* aligned to both *sosa:Actuation* and *san:Actuation*.
- *Actuator*: A device that is used by, or implements, an *Actuation* that changes the state of the *Context*. BCI-O defines *Actuator* aligned to both *sosa:Actuator* and *san:Actuator*.
- *Effect*: Any kind of physical modification (an effect on the *Context*) induced by an *Actuator* (a characteristic of its nature, as an agent that has an effect on the context). BCI-O defines *ActuationEvent* aligned to *san:Effect*.

Direct alignments to DUL were considered carefully evaluating the scope and intent for each concept, which led to properly define class hierarchies and disjoint axioms.

4.4 Context Model: Unity's Gaming High-Level Modeling Architecture

BCI-O’s Context Model was built based on relevant abstractions curated from the gaming architectural modeling of the Unity framework [9]. The following figure shows its representational UML class diagram.

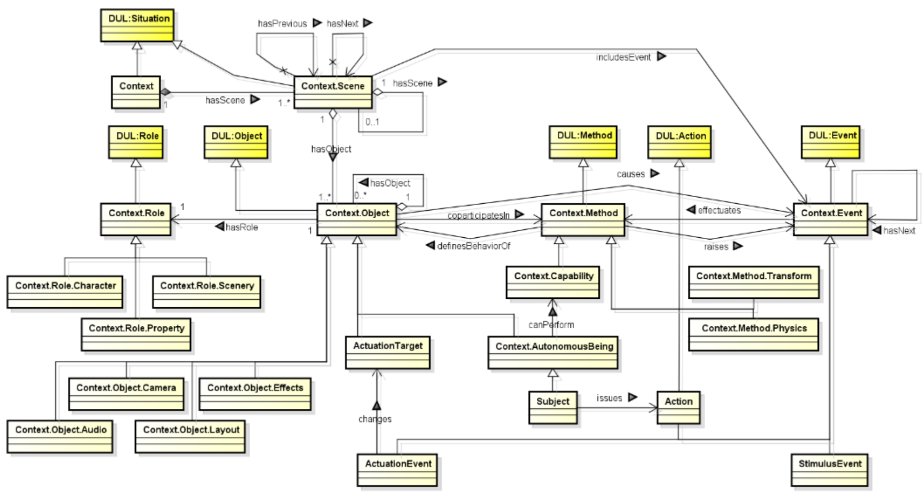

Fig. 6. BCI-O’s Context Model: based on Unity's Gaming High-Level Modeling Architecture.

In order to be consistent in the BCI-O's overall structure and intention, the Context Model core concepts were properly aligned to DUL.

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5 Ontology Engineering

A *proto-ontology* was initially developed as part of a pervasive on-line BCI system [2] [1], based on the project specs and incremental Software Engineering tasks. Later, it was generalized and expanded through a modeling process [21] described below.

Two fundamental and general representational aspects were considered for the **domain modeling**: BCI and physical/virtual environments (contexts). The contextual aspect was focused on explain the relevant component architecture of any environment for BCI (context-awareness), by abstracting the high-level concepts and relations found in [9]. The BCI aspect focused on categorizing the entities in any interaction through structured metadata. BCI interaction model complexity was addressed as follows: (a) major players and flows were clearly identified based on HCI notions; (b) their characterizations were formalized following open BCI vocabularies; and, (c) additional/complementary design considerations, taken from [22] and especially from [23], were incorporated in a top-down approach to model the *Annotation Tag* module and related concepts. Common concepts, such as time intervals, were defined as datatype properties, in order to ease the modeling to BCI systems. However, if required, BCI-O applications could add more semantic expressiveness for the representation of time stamps and intervals, using directly [14].

The modeling and its spec were assessed several times until they reached a stable status. Below, are presented important aspects of the followed construction process:

- Proto-ontology's project: (1) specification (requirements), (2) conceptualization and formalization (analysis & design), (3) Implementation (dev. & deployment).
- A hybrid modeling style was used: (1) verbal/semi-structured (BCI vocabularies), (2) logic-based (upper ontologies), (3) structural -object- (Unity framework [9]).
- Level of detail for BCI-O: conceptual and logical model.
- Pattern-based architecture for the Sensing and Acting Models: SSO, AAE.
- Non-ontological resource application: context domain (Unity dictionary), video coding domain (MPEG-7 MDS glossary), and time domain (OWL-Time glossary).
- Ontology design pattern reuse and alignment: Sensing and Acting Models.
- Ontological resource reuse: SOSA/SSN, SAN (IoT-O), DUL, dbp [19].
- Ontology restructuring: special focus on pruning and modularization.

Ontology authoring and quality were carefully looked during the overall process of building the BCI-O spec. Thereby, best practices found in the SSN and IoT-O specs were taken as proper guidelines for its structure and documentation.

The construction rules applied in the BCI-O development were:

1. Identify relevant BCI metadata terms to be included. They should have major “impact” to BCI activity/data annotation and machine-launched semantic search.
2. Determine domain and scope of concepts, keeping the model simple and stable.
3. Define class hierarchies and design rules, following closely BCI vocabularies.

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4. Find prominent ontologies from which we could apply ontology design patterns [16] to directly align the term definitions: SOSA/SSN and SAN (IoT-O).
5. If necessary, establish equivalence relations with other related terms of interest.

5.1 Semantic Annotations

During the ontology development, some terms from popular vocabularies were included to enrich the BCI-O concepts metadata as annotation properties, such as:

- Dublin Core Metadata Terms (DC and DCMIType)[5],
- SKOS Simple Knowledge Organization System[6],
- VANN: A vocabulary for annotating vocabulary descriptions[7], and
- Open.vocab.org8.

Besides of their minimal semantic commitment, these annotations are well-known Web-oriented representations that aim to reuse and share ontological concepts and their descriptions. Guidelines[9] were carefully followed while incorporating the annotations into the BCI-O spec.

SKOS lexical labels (*prefLabel*) and *Note*s documentation properties[10] (such as *definition*, *scope note*, *editorial note* and *change note*) were included into the spec to distinct and structure properly the different content nature for each BCI-O concept.

5.2 Axioms' Satisfiability

BCI-O's satisfiability was checked in different validation points immediately after including and modifying various axioms, such as disjoint concepts, and DUL/SAN alignments. The reasoner *HermiT v1.3.8* was used. As part of the ontology engineering process, a detailed log was kept with all the results and durations of each satisfiability checkpoint.

5.3 Publishing the spec: versions, linked data engine and modeling tools

The spec was developed in three versions (each with related XML documents):

1. Base version: an (OWL 2) RDF/XML document with the complete modeling structure and content, plus embedded HTML formatting and text-handling rules.
2. HTML version: a set of XSL 3 documents with XPath 3 functions and a companion XML configuration document to handle the base-to-HTML transformation.

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5 <http://dublincore.org/documents/dcmi-terms/>

6 <http://www.w3.org/2004/02/skos/core#>

7 <http://purl.org/vocab/vann/>

8 <http://open.vocab.org/terms/>

9 <http://dublincore.org/documents/profile-guidelines/#appc>, <https://www.w3.org/TR/void/#dublin-core>

10 <https://www.w3.org/TR/skos-reference/#labels>, <*#notes>

3. (OWL 2) RDF/XML version: an XSL 3 document strips off from the base-version the HTML formatting, to generate a clean and proper machine-readable document.

A simple *linked data engine* was developed to handle some specialized linked data services for the spec, including serving (dispatching and generation) the proper HTML and RDF/XML versions and URI entry-points to different user agents.

A **w3id.org** identifier was registered as its namespace URI definition. A basic content negotiation server-side script was developed to serve properly the different versions of the spec. The BCI-O spec was published in the *LOV* registry on 2016-11-08. The modeling and ontology tools used were: (1) Astah Community Modeling Tool; (2) IHMC CmapTools [24]; and, (3) *Protégé* v5.2.0 [25].

6 Applications

As mentioned, BCI-O *proto-ontology* was developed in a joint project between NCTU (PET Lab) and UCSD (SCCN), with the U.S. Army Research Laboratory, Translational Neuroscience Branch [2] [1]. As an application for a proof of concept system, the *proto-ontology* was used in order to make sure that big data sets were semantically searchable for high-level processing via BCI metadata definitions. The *proto-ontology* was successfully used further in heterogeneous BCI datasets coming from different applications[11], such as stress and fatigue neuroimaging [1], car driving tests, and multimodal mobile brain imaging. Another application is described in the paper on the Neuromonitoring VR/AR Goggle [26].

Moreover, the BCI-O spec's HTML version presents two early applications (including their correspondent RDF graph model):

- The CerebraTek® νPod Ontology [12], applied to glaucoma diagnostics using mfSSVEP, and
- ESS+HED Standards Ontology for BCI-O[13], as an ontological overlay for the ESS v2.0 and HED v2.0 EEG data sharing tools.

7 Future work

BCI-O models subject-context interactions while focusing on monitoring the brain dynamics. In a long-term, we would like to take BCI-O as the basis towards generalizing a semantic model to describe how any human body bio-signal (not only from the brain) can be monitored and made to interact with computing interfaces. Initially, this work would lead to BCI-O's generalization towards a "*Bio-signal Computer-Interaction Ontology*". This modeling task is planned to be one of the main development drivers in the future, for a set of ontological frameworks to capture the different bio-signal markers and technological interfaces for the entire human body: organs (brain, heart, liver, etc.) and systems (nervous, integumentary, endocrine, etc.).

11 <http://brc.nctu.edu.tw/>

12 <http://bci.pet.cs.nctu.edu.tw/ontology?cerebratek_nupod.owl>

13 <http://bci.pet.cs.nctu.edu.tw/ontology?ESS_HED.owl>

Currently, there is an ongoing effort on proposing some extensions to the SOSA/SSN W3C Recommendation [27]. We are following closely the new proposed concepts and relationships and given our feedback from the BCI-O perspective in their ongoing discussions: special interest for issue #1028 regarding the "*Homogeneity of an ObservationCollection*" [14]. BCI-O will be updated accordingly following the structure/alignments of these extensions, after the proposal becomes stable.

Last, some BCI applications keep part of their metadata store in standard relational database systems. As an aside project, we are planning to work on an OWL 2 QL profile [28] version of BCI-O, so that those relevant metadata sets can be queried through a restrictive (intersection of RDFS and OWL 2 DL) version of BCI-O via a simple rewriting mechanism (section 3 of [28]).

8 Conclusions

As a foundational model for real-world BCI, BCI-O will become an important tool to aid large-scale BCI data analytics models and processes, due primarily to its OWL 2 formal structure. Semantic reasoning based tasks of BCI-O's axiomatizations enable BCI systems to carry out two major jobs:

- Apply inference rules to aid machine learning techniques, such as feature-based Transfer Learning (Adaptive Deep Learning), in online multimodal (EEG) classification [29].
- Perform Adaptive BCI (train and refine brain state prediction and classification models) [2], based on relevant data sets constructed through semantic data queries.

Another key contribution of BCI-O is its novel Context Model. This one associates the *context* architectonic definition with the data recordings (SOSA/SSN-based observations), making BCI systems to be semantically *context-aware* for real/virtual-world situations. Thus, it gives a semantic foundation for Augmented BCI applications, assisting ambient intelligence's settings in sensor systems for any kind of BCI.

As a domain ontology for BCI sensors[15] and actuators[16], with a special interest in real-time IoT M2M environments, BCI-O allows:

- Semantically informed BCI analytics of sensor/actuator data patterns: unambiguous searchability, similarities, simulations, and predictions.
- Semantic interoperability (based on its alignments): easy integration, reusability, and extensibility into the Linked Data world for all kind of BCI.

In general, its axiomatizations enable BCI systems to apply Semantic Web technologies for data analysis, as a form of a semantic middleware for BCI sensor/actuator networks.

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[14] <https://github.com/w3c/sdw/issues/1028>

[15] BCI-O's Sensing Model for sensing and sensors, as well as for linked sensor data.

[16] BCI-O's Acting Model for semantic feedback, control, and actuation.

References

[1] K. Mcdowell, C. T. Lin, K. S. Oie, T. P. Jung and e. al., "Real-World Neuroimaging Technologies," *IEEE Access*, vol. 1, pp. 131-149, 2013.

[2] J. K. Zao, T. T. Gan, C. K. You and et.al., "Pervasive Brain Monitoring and Data Sharing based on Multi-tier Distributed Computing and Linked Data Technology," *Frontiers in Human Neuroscience Journal [Research Topic: Towards a New Cognitive Neuroscience: Modeling Natural Brain Dynamics],* vol. 8, p. 370, 03 June 2014.

[3] P. Brey, "The Epistemology and Ontology of Human-Computer Interaction," *Minds and Machines,* vol. 15, no. 3, pp. 383-398, 2005.

[4] K. Janowicz and M. Compton, "The Stimulus-Sensor-Observation Ontology Design Pattern and its Integration into the Semantic Sensor Network Ontology," in *In The 3rd Int. workshop on Semantic Sensor Networks 2010 along with the 9th Int. Semantic Web Conf*.

[5] W3C Spatial Data on the Web WG & OGC, "Semantic Sensor Network (W3C Recommendation 19 October 2017)," 19 October 2017. [Online]. Available: https://www.w3.org/TR/vocab-ssn/.

[6] N. Seydoux, K. Drira, N. Hernandez and T. Monteil, "IoT-O, a Core-Domain IoT Ontology to Represent Connected Devices Networks," in *Knowledge Engineering and Knowledge Management: 20th Int. Conference, EKAW 2016*, Bologna, Italy, 2016.

[7] N. Seydoux, "The "Actuation-Actuator-Effect (AAE)" design pattern," 20 02 2015. [Online]. Available: http://ontologydesignpatterns.org/wiki/Submissions:Actuation-Actuator-Effect.

[8] N. Seydoux, M. Ben Alaya, K. Drira, N. Hernandez and T. Monteil, "The "Semantic Actuator Network (SAN)" ontology," [Online]. Available: http://lov.okfn.org/dataset/lov/vocabs/SAN.

[9] Unity, "Unity's Gaming Modeling Architecture Manual," 2016. [Online]. Available: http://docs.unity3d.com/Manual/index.html.

[10] C. Kothe and C. Brunner, "XDF (Extensible Data Format)," [Online]. Available: https://code.google.com/p/xdf/. [Accessed 2014].

[11] SCCN, "EEG Study Schema (ESS)," August 2013. [Online]. Available: http://sccn.ucsd.edu/wiki/ESS; http://www.eegstudy.org/.

[12] N. Bigdely-Shamlo, K. Kreutz-Delgado, M. Miyakoshi, M. Westerfield, T. Bel-Bahar, C. Kothe and K. Robbins, "Hierarchical event descriptor (HED) tags for analysis of event-related EEG studies," October 2013. [Online]. Available: http://www.hedtags.org/.

[13] W3C, "Semantic Sensor Network (SSN) Ontology," 2011. [Online]. Available: http://www.w3.org/2005/Incubator/ssn/ssnx/ssn.html.

[14] OGC & W3C, "Time Ontology in OWL (W3C Recommendation 19 October 2017)," 19 October 2017. [Online]. Available: http://www.w3.org/TR/owl-time/.

[15] W3C SSN Incubator Group, "Semantic Sensor Network XG Final Report," 28 June 2011. [Online]. Available: http://www.w3.org/2005/Incubator/ssn/XGR-ssn-20110628/.

[16] A. Gangemi, "Ontology Design Patterns for Semantic Web Content," in *In Gil, Y., Motta, E., Benjamins, V., Musen, M., eds.: The Semantic Web – ISWC 2005. Volume 3729 of Lecture Notes in Computer Science.*, Springer Berlin / Heidelberg, 2005.

[17] W3C Spatial Data on the Web Working Group, "Semantic Sensor Network Ontology (Wiki)," W3C, [Online]. [Accessed 2017]. Available: https://www.w3.org/2015/spatial/wiki/Semantic_Sensor_Network_Ontology.

[18] A. Gangemi, F. Fisseha, J. Keizer, J. Lehmann, A. Liang, I. Pettman, M. Sini and M. Taconet, "A Core Ontology of Fishery and its Use in the FOS Project," in *Proceedings of the EKAW*04 Workshop on Core Ontologies in Ontology Engineering*, 2004.

[19] DBpedia, "wiki.dbpedia.org : About," 2016. [Online]. Available: http://dbpedia.org/.

[20] W3C Spatial Data on the Web WG & OGC, "On the usage of the SSN ontology —W3C Document 28 May 2018—," 28 May 2018. [Online]. Available: https://w3c.github.io/sdw/ssn-usage/. [Accessed 2018].

[21] G.-P. A., F.-L. M. and C. O., Ontological Engineering: with examples from the areas of Knowledge Management, e-Comm. and Semantic Web, London: Springer, 2004, p. 401.

[22] P. Salembier and S. J. R., "MPEG-7 multimedia description schemes," *IEEE Transactions on Circuits and Systems for Video Technology,* vol. 11, no. 6, pp. 748-759, 2001.

[23] J. Hunter, "Adding Multimedia to the Semantic Web: Building an MPEG-7 Ontology," in *Proceedings of the 1st Int. Conf. on Semantic Web Working (SWWS'01)*, CA, USA, 2001.

[24] A. J. Cañas, G. Hill, R. Carff and et.al., "CmapTools: A Knowledge Modeling and Sharing Environment," in *Concept Maps: Theory, Methodology, Technology. Proceedings of the 1st Int. Conf. on Concept Mapping.*, Pamplona, Spain, 2004.

[25] M. Musen, "The Protégé project: A look back and a look forward," *AI Matters. Association of Computing Machinery Specific Interest Group in Artificial Intelligence.*, vol. 1, no. 4, June 2015.

[26] J. K. Zao, T.-P. Jung, H.-M. Chang and et.al., "Augmenting VR/AR Applications with EEG/EOG Monitoring and Oculo-Vestibular Recoupling," in *Foundations of Augmented Cognition: Neuroergonomics and Operational Neuroscience: 10th Int. Conf., Held as Part of HCI Int. 2016*, Toronto, Canada, 2016.

[27] W3C Spatial Data on the Web WG & OGC, "Extensions to the Semantic Sensor Network Ontology —W3C Editor's Draft 28 May 2018—," May 2018. [Online]. Available: https://w3c.github.io/sdw/proposals/ssn-extensions/.

[28] W3C, "OWL 2 Web Ontology Language Profiles (Second Edition) —W3C Recommendation 11 December 2012—," December 2012. [Online]. Available: https://www.w3.org/TR/owl2-profiles/. [Accessed 2017].

[29] C. S. Wei, Y. P. Lin, Y. T. Wang, T. P. Jung, N. Bigdely-Shamlo and C. T. Lin, "Selective Transfer Learning for EEG-Based Drowsiness Detection," in *2015 IEEE International Conference on Systems, Man, and Cybernetics*, 2015.