Towards Knowledge-Driven Symptom Monitoring & Trigger Detection of Primary Headache Disorders

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ABSTRACT

Headache disorders are experienced by many people around the world. In current clinical practice, the follow-up and diagnosis of headache disorder patients only happens intermittently, based on subjective data self-reported by the patient. The mBrain system tries to make this process more continuous, autonomous and objective by additionally collecting contextual and physiological data via a wearable, mobile app and machine learning algorithms. To support the monitoring of headache symptoms during attacks for headache classification and the detection of headache triggers, much knowledge and contextual data is available from heterogeneous sources, which can be consolidated with semantics. This paper presents a demonstrator of knowledge-driven services that perform these tasks using Semantic Web technologies. These services are deployed in a distributed cascading architecture that includes DIVIDE to derive and manage the RDF stream processing queries that perform the contextually relevant filtering in an intelligent and efficient way.

CCS CONCEPTS

• **Information systems** → **Decision support systems**; • **Applied computing** → *Health care information systems*; • **Computer systems organization** → Distributed architectures.

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KEYWORDS

knowledge-driven, RDF Stream Processing, Semantic Web, headache classification, headache trigger detection, symptom monitoring

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1 INTRODUCTION

Headache disorders are experienced by many people around the world [10]. Existing headache disorders are classified in the International Classification of Headache Disorders, third edition (ICHD-3) [7]. For each disorder, it defines diagnostic criteria that are the international standard used by doctors in headache diagnosis. Primary headache disorders are those for which the headache and associated symptoms are not a symptom of an underlying disease or condition [7]. Migraine, cluster headache (CH) and tension-type headache (TTH) are the most common primary headache disorders [7].

In current clinical practice, the follow-up of patients with headache attacks happens during a consultation of a patient with his or her doctor. Follow-up and diagnosis of the patient's headache disorder is therefore only based on intermittent subjective data, self-reported by patients during an oral discussion or through existing mobile headache apps such as Migraine Buddy [8]. This current practice is far from optimal. Therefore, the mBrain system [5] tries to move towards a more continuous, semi-autonomous and objective follow-up of headache patients, based on both self-reported data and objective physiological and contextual data.

The general goal of the mBrain system is to support both doctor and patient in the diagnosis and follow-up of the patient's headache disorder. To this end, data about the patient is collected through different services [5]. Physiological data is collected with the Empatica E4 wearable [6]. This data is consumed by in-house designed machine learning (ML) algorithms that can detect a user's activities, stress periods and sleeping periods. A mobile app allows users to keep a diary of their headache attacks and contextual events (e.g., medicine intakes, food intakes, mood), inspect the ML predictions in a timeline overview, and answer questions about the anticipation of headache attacks, stress, and other events.

Different services can contribute to achieving the goal of the mBrain system. This includes the classification of headache attacks, as well as the detection of potential headache triggers. For the former, knowledge exists from ICHD-3 about diagnostic criteria for the classification of a headache disorder [7]. To this end, relevant data is collected via the mBrain app's diary. Moreover, outputs of the ML algorithms can also detect symptoms relevant for classification. Similarly for trigger detection, lots of data is available from the app and ML algorithms to detect certain triggers. In addition, knowledge on headache triggers of patients is available from the patient himself as well as rule mining services. To perform the given tasks in a context-aware manner, the available data needs to be intelligently consolidated and analyzed. Given the heterogeneous nature of the different sources of knowledge and collected real-time data, semantics are the ideal approach for this [2].

In this paper, a demonstrator of the knowledge-driven services of the mBrain system is presented. These services are built with Semantic Web technologies, involving the mBrain ontology, RDF stream processing (RSP) and stream reasoning. It includes DIVIDE [3] to derive and manage efficient context-aware stream processing queries. The focus is on the knowledge-driven monitoring of symptoms and other relevant events for headache follow-up and classification, as well as the detection of headache triggers.

2 SYSTEM ARCHITECTURE

The architecture of the knowledge-driven mBrain system follows a cascading reasoning approach [4], since this allows for an efficient distribution of the different semantic tasks across the network. It consists of a local and a central part. An overview of the knowledge-driven mBrain system architecture is shown in Figure 1.

The local components should be running on a gateway in the patient's home. The semantic local component is an RDF Stream Processing Engine, filtering any data on its input streams according to the registered continuous queries. These queries are managed by the central DIVIDE component. Events are sent to the processed streams by the Semantic Mapper. This component semantically annotates all inputs through the mBrain ontology, which is further discussed in Section 3. This mapper receives its inputs from two sources on the patient's smartphone. First, it takes all self-reported events in the mBrain app as input. This includes headache attack registrations, as well as other events such as food intakes. Second, the outputs of the ML algorithms are sent as inputs to Semantic Mapper. These outputs are activity, stress and sleep events predicted based on the raw physiological and accelerometer data collected & streamed by the Empatica E4 wearable over the smartphone.

The central components of the knowledge-driven part of the mBrain architecture are deployed on the mBrain back-end server system. In a real-life scenario, this server system will be hosted by a hospital. This server system contains a Knowledge Base (KB) with the mBrain ontology, including all relevant contextual information of users in the system. This KB is used by the Central Reasoner, a semantic reasoner system that processes the outputs of the local RSP engines. As will be explained in the use case scenarios in Section 4.1, this will include ongoing headache attacks that need to be classified by the reasoner, detected triggers and detected symptoms relevant to the classification of a headache attack. Outputs of the Central Reasoner include classification results and detected triggers. They are sent to the Application Back-end, which represents the other non-semantic components in the mBrain system. This component can then act upon the reasoning results, in any implemented way. It could for example generate notifications in the mBrain app or forward the results to a dashboard for the doctor. When contextual information changes from within the Application Back-end, these updates are also forwarded the KB.

DIVIDE [3] is the server component responsible for managing the queries on the local RSP engines. To derive which queries need to be executed, it performs semantic reasoning on the domain knowledge and context relevant to the associated person, which is contained in the KB. It listens to contextual updates in the KB, which trigger the query derivation process. This way, the evaluated RSP queries are always relevant to the current context, and do not require any more reasoning. DIVIDE fully automates the process of deriving the queries and updating them at the RSP engines.

3 MBRAIN ONTOLOGY

To achieve the semantic tasks in the mBrain system, the mBrain ontology has been designed [5]. It contains domain knowledge in the headache domain relevant to mBrain. This includes the ICHD-3 classification hierarchy of headache disorders and attacks, and the concepts to semantically describe headache attacks and their properties based on ICHD-3. Moreover, it is connected to the DAHCC (Data Analytics for Health and Connected Care) ontology [9]. This in-house designed ontology has different modules to semantically describe a monitored person, wearables, sensors, and ML predictions.

4 DEMONSTRATOR

The system architecture described in Section 2 is used to perform different knowledge-driven tasks in the mBrain system. This section zooms in on the use case scenarios of some of these tasks that will be the subject of the presented demonstrator. Moreover, an overview is given of any external material relevant to this demonstrator.

In terms of technologies, the RSP engine used within the mBrain system is C-SPARQL [1]. The Central Reasoner and Knowledge Base are deployed with Apache Jena [11].

4.1 Use case scenarios

The demonstrator focuses on the three main tasks of the knowledge-driven mBrain system: monitoring of contextual events (symptoms) during headache attacks, monitoring of headache triggers based on user anticipation, and real-time headache classification.

4.1.1 Closer monitoring of contextual events during headache attacks. When a patient is experiencing a headache attack, it might be interesting to closely monitor several contextual events such as symptoms associated to the attack. This could for example give

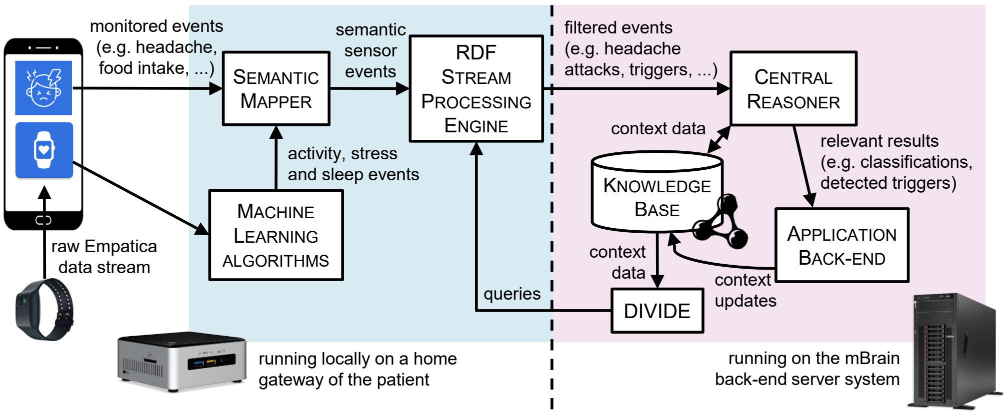

Figure 1: Architecture of the knowledge-driven services of the mBrain system

relevant insights to validate a headache classification and further refine a patient's diagnosis. To allow this in a semantic system with DIVIDE, the context of a patient in the KB should include information on when a headache attack is occurring, and the patient's (probable) diagnosis. The former can be known through the Empatica E4 wearable which contains a button that patients should push whenever a headache attack is starting.

In the mBrain ontology, performing this monitoring is made possible through the definition of headache attack statistics. The generic query that *could* do such monitoring is presented in Listing 1. It monitors any symptom during a headache attack that can be detected by a property associated to an event type in the patient's stream. An example of this is given in Listing 2 (lines 2–12): it defines restlessness as a typical associated symptom of cluster headache, which can be detected when an activity event has an activity index value exceeding the defined threshold for restlessness. To only retrieve relevant symptoms, i.e., symptoms associated to the disorder the patient is diagnosed with, semantic reasoning should be done using the definitions in lines 15–24 of Listing 2.

In the mBrain system, the generic query in Listing 1 is *not* deployed. Instead, with DIVIDE, this generic query can be converted during the query derivation to a simple RSP filtering query yielding a similar blank node of type `RelevantHeadacheAttackStatistic` instead in its CONSTRUCT clause, and with only the triples in lines 36–41 of Listing 1 in its WHERE clause. In this query, the query variables `?p`, `?event_type`, `?prop`, `?threshold`, `?symptom`, `?attack` and `?disorder_type` of the WHERE and CONSTRUCT clauses are substituted by DIVIDE during the query derivation. This query would be outputted and registered on the local RSP engine of the patient when the other triples in the WHERE clause of the generic query (lines 14–31) are fulfilled in the patient's context.

Listing 1: Generic SPARQL query that can detect the occurrence of any headache attack statistic. For simplicity, prefix declarations of the mBrain & DAHCC ontologies are omitted.

```
1  CONSTRUCT {
2    _:a a :HeadacheAttackStatistic ;
3        :detectedSymptom ?symptom ;
4        saref-core:relatesToProperty [ a ?prop ] ;
5        saref-core:hasValue ?v ;
6        saref-core:hasTimestamp ?t ;
7        :associatedToEventType [ a ?event_type ] ;
8        :associatedToHeadacheAttack ?attack ;
9        :associatedToDisorder [ a ?disorder_type ] ;
10       :associatedToPatient ?p . }
11 FROM <http://contextaware.ilabt.imec.be/stream>
12 FROM <http://contextaware.ilabt.imec.be/context.rdf>
13 WHERE {
14   # a patient has a headache attack
15   ?p a saref4ehaw:Patient ; :hasHeadacheAttack ?attack .
16
17   # a disorder is defined with an associated symptom
18   ?disorder a ?disorder_type ;
19             :hasAssociatedSymptom ?symptom .
20   ?disorder_type rdfs:subClassOf :HeadacheDisorder .
21
22   # a headache attack symptom can be detected by a
23   # threshold on a property associated to an event type
24   ?symptom a :HeadacheAttackSymptom ;
25       :isDetectedByUpperThreshold [
26           a :RegularThreshold ;
27           saref-core:hasValue ?threshold ;
28           :forProperty [ a ?prop , :EventProperty ;
29               :associatedToEventType
30                       [ a ?event_type ] ] ] .
31   ?prop rdfs:subClassOf :ConditionableProperty .
32
33   # an event of the given type is present in the
34   # patient's event stream, with a value for this
35   # property higher than the defined threshold
36   ?p saref4ehaw:hasEvent [ a ?event_type ] ;
37      :hasAssociatedPropertyValue ?pv ;
38      saref-core:hasTimestamp ?t .
39   ?pv saref-core:relatesToProperty [ a ?prop ] ;
40       saref-core:hasValue ?v .
41   FILTER (xsd:float(?v) >= xsd:float(?threshold)) }
```

4.1.2 Monitoring of headache triggers based on user anticipation. Different events can trigger a headache attack. Sources of knowledge on headache triggers for a patient can be the patient himself, or rule mining services that learn the association between headache attacks and contextual events. Some triggers such as stress, physical exercise, sleep deprivation or skipping of meals can be detected by RSP queries combining the domain knowledge and context in the KB with the mBrain event stream. With DIVIDE, specific queries can be defined that detect these triggers. An example for of an RSP query for a patient with a stress trigger is given in Listing 3. By using DIVIDE, context-awareness can be easily introduced in this query, e.g., the action state, window size & frequency, or required event

Listing 2: mBrain ontology definitions relevant to the detection of a RelevantHeadacheAttackStatistic

```
# Turtle syntax
:_ClusterHeadache a :ClusterHeadache ;
    :hasAssociatedSymptom :Restlessness .
:ClusterHeadache rdfs:subClassOf :HeadacheDisorder .
:Restlessness a :HeadacheAttackSymptom ;
    :isDetectedByUpperThreshold [
        a :RegularThreshold ;
        saref-core:hasValue "5"^^xsd:integer ;
        :forProperty :_ActivityIndex ] .
:_ActivityIndex a :ActivityIndex ;
    :associatedToEventType [ a :Activity ] .
:ActivityIndex rdfs:subClassOf :EventProperty .

# Manchester syntax
:ClusterHeadachePatient ≡ saref4ehaw:Patient and
    :hasHeadacheDisorder some :ClusterHeadache
:ClusterHeadacheAttackStatistic ≡
    :HeadacheAttackStatistic and
    :associatedToDisorder some :ClusterHeadache
:RelevantClusterHeadacheAttackStatistic ≡
    :ClusterHeadacheAttackStatistic and
    :associatedToPatient some :ClusterHeadachePatient
:RelevantClusterHeadacheAttackStatistic ⊑
    :RelevantHeadacheAttackStatistic
```

Listing 3: Example RSP query that detects stress as a known trigger for a given patient

```
CONSTRUCT {
    _:a a :HeadacheAlarm ; :relatedDuration ?d ;
        :relatedToTrigger [ a :StressTrigger ] ;
        :targetedAt entity:patient138 . }
FROM STREAM <http://contextaware.ilabt.imec.be/stream>
    [RANGE 60m STEP 5m]
WHERE {
    # patient has a stress event of at least 5 minutes
    entity:patient138
        saref4ehaw:hasEvent [ a DAHCC:Stress ] ;
        saref4ehaw:activityDuration ?d .
    FILTER (xsd:float(?d) >= xsd:float(300)) }
LIMIT 1
```

duration in this filtering query could be dependent on whether the patient is anticipating an event of the type associated to a known headache trigger for him or her. This anticipation is part of the patient's context in the KB through the mBrain data collection. When a trigger is detected by the local RSP engine, the Central Reasoner could generate a headache alarm and send it to the Application Back-end which can convert it into a mobile mBrain notification.

4.1.3 Real-time headache classification. Besides the contextual monitoring use cases described in the previous sections, the knowledge-driven components of mBrain are also responsible for performing real-time classification of headache attacks, based on both information reported by the patient and possible headache attack statistics detected through the RSP queries described in Section 4.1.1. Initial versions of semantic queries that classify an individual headache attack as migraine, CH or TTH are constructed based on the diagnostic criteria for these disorders in ICHD-3 [5, 7].

4.2 External material

A general video of the mBrain study can be found at https://www.youtube.com/watch?v=wvTY9y-TFZw. It explains the basics of mBrain, allowing for a better understanding of the broader context of its knowledge-driven services. The code of DIVIDE can be found at https://github.com/IBCNServices/DIVIDE. Resource files of the DAHCC ontology, to which the mBrain ontology connects, can be found at https://github.com/predict-idlab/DAHCC-Ontology.

5 CONCLUSION

This paper presents a demonstrator of the knowledge-driven monitoring services used within the mBrain project. mBrain tries to move towards continuous, semi-autonomous, objective follow-up and classification of primary headache disorders based on a combination of self-reported and physiological & contextual data. The architecture of the knowledge-driven mBrain services consists of State-of-the-Art components built on Semantic Web technologies, including DIVIDE to manage the RSP queries that perform the relevant monitoring. This monitoring includes the real-time detection of symptoms during headache attacks, which is useful for classifying and diagnosing headaches, and headache attack triggers.

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