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Interoperability in IoT Through the Semantic Profiling of Objects

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ABSTRACT The emergence of smarter and broader people-oriented IoT applications and services requires interoperability at both data and knowledge levels. However, although some semantic IoT architectures have been proposed, achieving a high degree of interoperability requires dealing with a sea of non-integrated data, scattered across vertical silos. Also, these architectures do not fit into the machine-to-machine requirements, as data annotation has no knowledge on object interactions behind arriving data. This paper presents a vision of how to overcome these issues. More specifically, the semantic profiling of objects, through CoRE related standards, is envisaged as the key for data integration, allowing more powerful data annotation, validation, and reasoning. These are the key blocks for the development of intelligent applications.

INDEX TERMS Machine-to-machine communications, Internet of Things, Semantic Web, interoperability, mashups.

I. INTRODUCTION

The *Internet of Things* (IoT) will bring into the Internet all kind of devices (e.g., sensors able to record physical observations) that will be accessible at any time, from any place. Exposing objects as Web resources means that they can serve multiple applications, rather than being dedicated to a single application as in the past, and these are also expected to interact with each other to achieve common goals. As these objects become increasingly connected, there will emerge new intuitive ways of interacting with them, and the smart environments they create. There is a valuable lesson to be learned here: we should move towards thinking "smart" about people and not only about objects [1].

For smart and people-oriented IoT applications to emerge, interoperability at the data and knowledge levels is necessary, where semantic technologies have a major role. The reality, however, is that IoT has stumbled into vertical data silos, and little to no integration between data exists. There are already some initiatives offering objects as Web resources, and a lot of data from multiple sources is being shared, but there is no integration between them at a fundamental level. This is mainly caused by IoT applications being deployed by single providers, mostly in a bottom-up manner: sensors, gateways, services and applications. Controlling everything allows providers to build and maintain their proprietary solutions, but vertical silos are created and no integration with others exists. This limits the arising of applications benefiting from multiple devices and data-streams, which may have interactive capabilities, and moving towards valuable knowledge at higher levels.

Although some work on building semantic IoT architectures exists, it mainly focuses on annotating arriving sensor data at gateways (e.g., using the W3C Semantic Sensor Networks ontology and/or domain-specific ontologies), which is not enough to achieve a high-degree of interoperability. This solution promotes different approaches, which will be adopted at different gateways, as no standardized annotation process exists (it is domain dependent too). A sea of non-integrated data scattered across data-silos continues to exist. Also, although organizations managing IoT messaging protocols (for data transport) are working on the standardization of sensor data representation, the efforts are advancing in the direction of creating silos. That is, such data representations end up having a data-model that is incompatible with others. Besides all these problems, current approaches do not fit well into *Machine to Machine* (M2M) requirements, as data annotation has no knowledge on the M2M interactions behind arriving data. Such awareness is essential for increasingly connected experiences, and can only be achieved if objects are able to communicate the way they operate and their ongoing interactions, when others (objects or people) want to discover such information.

This article discusses how the *Constrained RESTful Environments* (CoRE) related standards can become the key

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semantic driver for data integration in multiple domains, M2M included. More specifically, how these can be used to discover an embedded object's functionality and for the semantic profiling of objects, according to their interaction patterns. Semantic profiling allows for a deeper understanding of data being stored and manipulated, meaning that systematic and rigorous approaches to a specific problem can be adopted. Also, correlation with profiling efforts in other objects/applications becomes easier. Semantic reasoners, able to infer logical consequences from a set of premises, can be used to build new semantically enriched connections between objects.

It should be emphasized that a profile-aware annotation of data will allow for intelligent knowledge extraction schemes to be adopted, due to context sensitivity, and better validation of data. Such an architecture provides, therefore, the basis for smart applications to emerge. People can always be the final data analysts, decision makers and/or process controllers.

II. IoT STANDARDS AND HOW TO ACHIEVE INTEROPERABILITY

Smart and connected objects are heterogeneous, having different sizes, power, processing capabilities, mobility patterns, connectivity ranges, and various functionalities. For this reason IoT involves many intertwined standards.

A. LOWER LAYER STANDARDS

There are several physical connectivity/communication standards used for IoT, which include WiFi, IEEE 802.15.4, Bluetooth for personal area and low-power wireless networks [2], [3], Z-Wave for home automation [4] and *Long-Term Evolution Advanced* (LTE-A) for extended coverage [5]. More specific communication technologies include *Radio-Frequency IDentification* (RFID), *Near Field Communication* (NFC) and *Ultra-Wide Bandwidth* (UWB) [6].

In respect to device management protocol standards, *Modbus* is used for industrial automation systems, establishing master-slave/client-server communications, while *Open Mobile Alliance Lightweight M2M* (OMA LWM2M) is more oriented for M2M or IoT device management [7].

Solving interoperability at these lower layers is difficult, as existing physical communication standards and device management protocols were designed for domain-specific applications with very distinct requirements and features.

B. HIGHER LAYER STANDARDS

Due to the success and ubiquity of IP-based technologies, a convergence towards an all IP-based communication stack emerged, as a way to allow objects to have Internet addresses. In 2007, the *Internet Engineering Task Force* (IETF) concluded the standardization process of *IPv6 over Low-Power Wireless Area Networks* (6LoWPAN) enabling IPv6 over very constrained networks [8]. Besides this initiative, another IETF working group called *Routing Over Low-power and Lossy-networks* (ROLL) was created, focusing on routing issues for low power and lossy networks. The main outcome of this group was the *Routing Protocol for Low power and lossy networks* (RPL) [9]. These are standardization efforts around the IEEE 802.15.4 standard.

At the application layer there are also multiple messaging standards for data transport. Within IETF, the CoRE working group has focused on the development of a resource-oriented application framework so that data can be stored, retrieved and manipulated using a client-server protocol: the *Constrained Application Protocol* (CoAP), a data transport standard intended to provide RESTful services in constrained nodes and networks [10]. Another relevant messaging protocol is the *Message Queue Telemetry Transport* (MQTT), standardized in 2013, that uses a publish/subscribe model [11]. Both CoAP and MQTT were designed for low power and network constrained devices, so the choice really depends on the application. MQTT can be used to publish messages from one node to many interested nodes, while CoAP can be used to trigger predefined functions at nodes.

C. SOLVING THE INTEROPERABILITY PROBLEM

As previously stated, solving the interoperability at lower layers is difficult due to the existing communication and device management standards, which were designed for domain-specific applications with distinct features. One possibility is to solve interoperability at the application level, bypassing the challenge of bridging lower layer protocols. However, different messaging protocols (at the application layer) also possess unique characteristics and are adequate for different types of applications, which have heterogeneous needs regarding processing and energy consumption.

The key for interoperability relies, therefore, on the data and knowledge level. For this reason, some sensor-related data standards emerged, such as: *Observations and Measurements* (O&M) and *Sensor Markup Language* (SenML), to represent observations/measurements and sensors/processes, and the *Sensor Observation Service* (SOS) for the querying of observations and sensor meta-data [12], [13]. However, gateways still need to semantically annotate all SenML data for interoperability, and such annotation comprises no underlying knowledge on the M2M interactions behind arriving data. The following sections discuss a way of addressing this issue.

III. SEMANTIC TECHNOLOGIES IN IoT

Semantic technologies allow computers to understand the meaning of data and, therefore, to process data properly and make inferences. For this reason, applying semantic Web technologies to IoT becomes a critical enabler for the integration of data and future development of smart IoT applications and services, in a variety of domains.

A. SEMANTIC WEB – KEY BUILDING BLOCKS

When using semantic Web technologies to create data stores, build vocabularies and write rules to handle data, we aim to extract new knowledge from cohesive data integration, such that collaborative/intelligent applications can be developed.

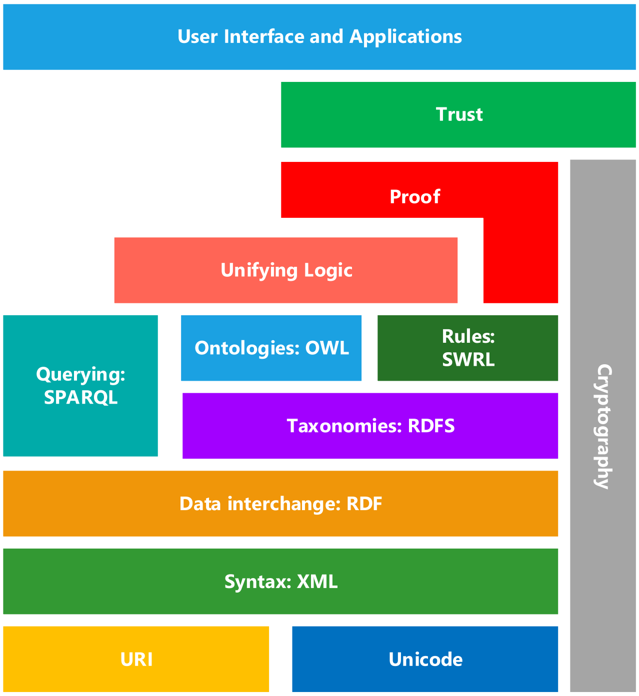


FIGURE 1. The building blocks of semantic Web technologies (*adapted from https://www.w3.org/2007/Talks/0130-sb-W3CTechSemWeb*).

As shown in Figure 1, linked data can be empowered by technologies such as RDF, RDFS, OWL, SPARQL, and SWRL:

1) RESOURCE DESCRIPTION FRAMEWORK (RDF)

RDF is a data model (not a data format) with a choice of syntaxes for storing data files (serialization formats: RDF/XML, Turtle, N-Triples). Facts are expressed as three-part statements known as triples. The three parts are called: subject, predicate, and object (i.e., the identifier of the thing/resource being described, the property name, and the property value). To prevent misunderstandings, when combining data from different sources, subjects and predicates must belong to namespaces given by *Uniform Resource Identifiers* (URIs).

2) RDF SCHEMA (RDFS) AND WEB ONTOLOGY LANGUAGE (OWL)

Resources and properties in triples may use existing/shared URIs so that data can be more easily connected with each other. Existing taxonomies/vocabularies are stored using RDFS and ontologies using OWL. RDFS has limited expressiveness, when compared with OWL; e.g., for sensors, the *Semantic Sensor Network* (SSN) ontology has been defined in [14].

3) SPARQL PROTOCOL AND RDF QUERY LANGUAGE

A language designed to query data across diverse data sources, whether the data is stored natively as RDF or viewed as RDF via middleware. A variety of SPARQL processors are available for running queries against both local and remote data.

4) SEMANTIC WEB RULE LANGUAGE (SWRL)

An OWL-based rule language that allows users to write rules that can be expressed in terms of OWL concepts, providing more powerful deductive reasoning capabilities than OWL alone.

B. SEMANTIC WEB – PENDING ISSUES

The *Linked Open Data* (LOD) is a movement for organisations to make their data available in a machine-readable format. As the major barrier for the deployment of linked data is the difficulty that data publishers have in choosing which vocabularies to use, the *Linked Open Vocabularies* (LOV) initiative emerged so that a catalogue of reusable vocabularies becomes available. Although these initiatives are relevant for the integration of data, some issues remain unsolved:

- Validation of new data – Currently it is mainly reduced to RDF data validation. Other components, like reasoning, are expected to have a relevant role in solving violations and in categorizing data relevance.
- Data privacy – Preventing unauthorised access to data and ontological knowledge is a critical requirement. Privacy-related issues are expected to become very important as ontology-based technologies are integrated into mainstream applications.
- Data source reliability – Confidence on the sources of information should be quantified, such that highly reliable sources have more impact than poorly reliable ones, without discarding information.

Some researchers argue that an unified reasoning mechanism (or unified logic) becomes necessary to know if data is reliable, accurate and trustworthy. However, this can potentially limit data integration and future developments. As the semantic Web focuses mostly on publishing disaggregated (but meaningful) data for consumption by applications, the developers/users are the ones that should ultimately say which data is considered trustworthy. Thus, comprehensive mechanisms to determine if data is reliable, accurate and trustworthy, are of paramount importance.

C. SEMANTIC IoT ARCHITECTURES AND CHALLENGES

Gateways can be used to assist legacy devices that do not have the capacity to interact with the Internet on their own. These gateways can help settle the heterogeneity between devices and the Internet, and to provide APIs for interaction with multiple types of devices. This is illustrated in the Figure 2. Therefore, the semantic annotation of sensor data (at gateways) using taxonomies/vocabularies/ontologies is one way of providing interoperability between IoT vertical silos, as services can exploit information (through APIs) for further analysis. However, this can still be a painful task, as existing architectures are scattered and focused on solving particular problems, requiring translations between specific protocols. Sometimes, meticulous work at gateways is necessary for just a bit of integration for a domain-specific application. Also, the annotation comprises no knowledge on

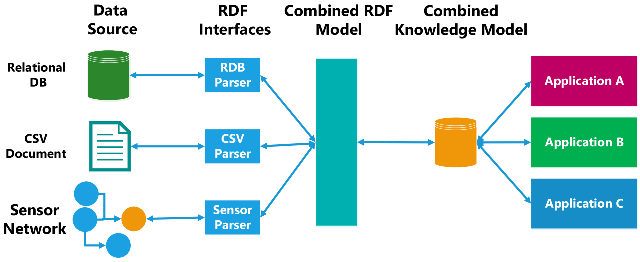


FIGURE 2. An example of the semantic connections inside a typical gateway.

the M2M interaction behind arriving data, meaning that these approaches do not fit M2M requirements. In summary, these proposals are not enough to deal with the sea of IoT data spread throughout multiple data silos, and do not provide a common, open and multi-application platform.

Besides the just mentioned challenges, mechanisms to determine if data is reliable, accurate and trustworthy become necessary in semantic IoT applications, as discussed above. We believe that all of these issues can be better solved if embedded semantic profiles are built using CoRE related standards as support. Pending issues can be better solved, as the answer for interoperability comes from the inside of networks/objects, while having the advantage of being a standard-based approach. A common, open and multi-application approach is, therefore, being proposed. This is developed in the next sections.

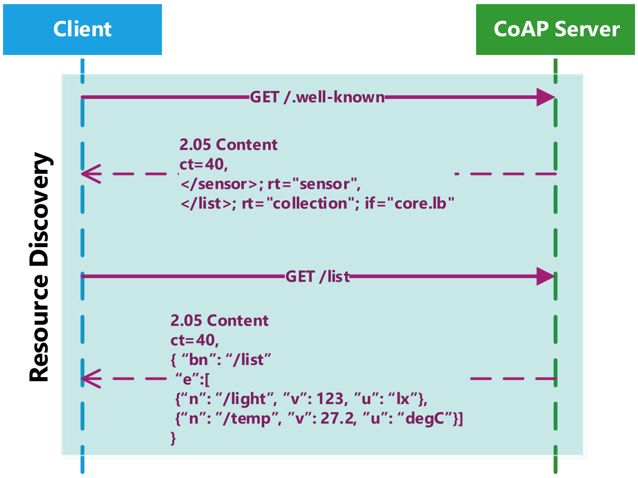
IV. CoRE FRAMEWORK

The CoRE working group, within the IETF, focused on the development of a resource-oriented application layer framework for data to be stored, retrieved and manipulated following the REST architectural style.

A. CoRE RELATED STANDARDS

CoRE standards include CoAP, a REST-based transfer protocol specified in [10], and a set of related information standards. CoRE Link-format is the standard for Web linking that allows the discovery of resources hosted by constrained nodes [15]. The discovery of resources is very important for machine application clients to be able to adapt to different resource organizations without previous knowledge of the specific data structures hosted by the connected things. For discovery, a default entry point "*/.well-known*" is defined and the Internet media type "*application/link-format*" is assigned to CoRE Link Format payloads.

A set of Interface Types for resource design is now on an ongoing standardization process in [16]. These Interface Types allow a server to compose and organize resources, and a client to discover and determine how to consume such resources. Collections can be defined for resource organizations and various forms of bulk interactions. Another key concept, specified in [17], is Link Binding. This defines a new link relation type to create a dynamic link between resources over which to exchange state updates. More specifically, resource states are binded together, such that updates to one are sent over the link to the other. CoRE Link Format representations are used to configure, inspect and maintain Collections and Link Bindings. Together, these can be used in the composition of Function Sets and Profiles for resource organization.



```
GET /.well-known
```

```
2.05 Content
ct=40,
</sensor>; rt="sensor",
</list>; rt="collection"; if="core.lb"
```

```
GET /list
```

```
2.05 Content
ct=40,
{ “bn”: “/list”
 “e”:[
 {“n”: ”/light”, ”v”: 123, ”u”: “lx”},
 {“n”: ”/temp”, ”v”: 27.2, ”u”: “degC”}]
}
```

FIGURE 3. Resource discovery followed by the creation of a Collection.

For nodes to be able to go to sleep, a *Resource Directory* (RD) entity can be used [18]. This entity would host descriptions of resources held on other servers, allowing lookups from others. An RD supports Web interfaces for the discovery of directory servers, registration, update and removal of resource descriptions, lookup of resources, and group maintenance.

B. RESOURCE DISCOVERY EXAMPLE

Figure 3 shows a resource discovery example. Parameter "*ct*" defines the Content-Format (e.g., 40 refers to application/link-format), "*rt*" is used to assign an application-specific semantic type (e.g., "*temperature*", "*http://sweet.jpl.nasa.gov/2.0/phys. owl#temperature*") and "*if*" is used to specify the interface used to interact with the resource (e.g. ,"*sensor*", "*http://www.example.org/myapp.wadl#sensor*").

After resources have been discovered, a second step is used to GET the Collection named "*</list>*". In this case, a single SenML data object including multiple resource values is returned. The linked batch (*if*="*core.lb*") is an interface type that allows Collections to be dynamically managed according to the control of a Web client. Thus, a client discovering the "*if*" link attribute is able to consume resources based on its knowledge on Interface Types and, in this sense, an Interface Type acts as a selector for a high-level functional abstraction.

V. INTEROPERABILITY THROUGH CoRE-BASED SEMANTIC PROFILING OF OBJECTS

As discussed above, the key for interoperability in IoT relies on the data and knowledge level. The higher the knowledge of the context, the greater the effectiveness of data

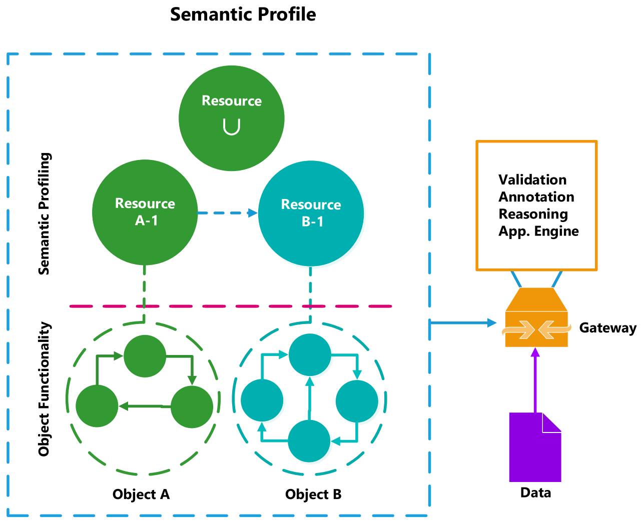


FIGURE 4. CoRE-based semantic profiling framework.

annotation, crucial for further inference and development of smarter applications. Besides this, any approaches should fit M2M requirements. For this reason, the semantic profiling of objects is proposed. A profile-aware approach when making semantic descriptions goes beyond simply annotating sensor data. Profiles can empower semantic meaning, allowing for intelligent knowledge extraction schemes due to increased context sensitivity.

Semantic profiles have been scarcely explored, and the existing ones focus mainly on sub-ontology extraction methodologies, based on user profiles. These, however, do not mitigate the interoperability problem between IoT vertical silos since users end up using different tools. For this reason, we believe that in the case of IoT, the answer for interoperability should come from the inside of constrained networks and objects. Since the CoRE work group is developing standards for constrained networks and objects, an interoperability solution with a greater chance of broad acceptance would be one integrated with CoRE standards. That is, the CoRE framework can be the key semantic driver for data integration, by providing the mechanisms that allow the semantic profiling of objects.

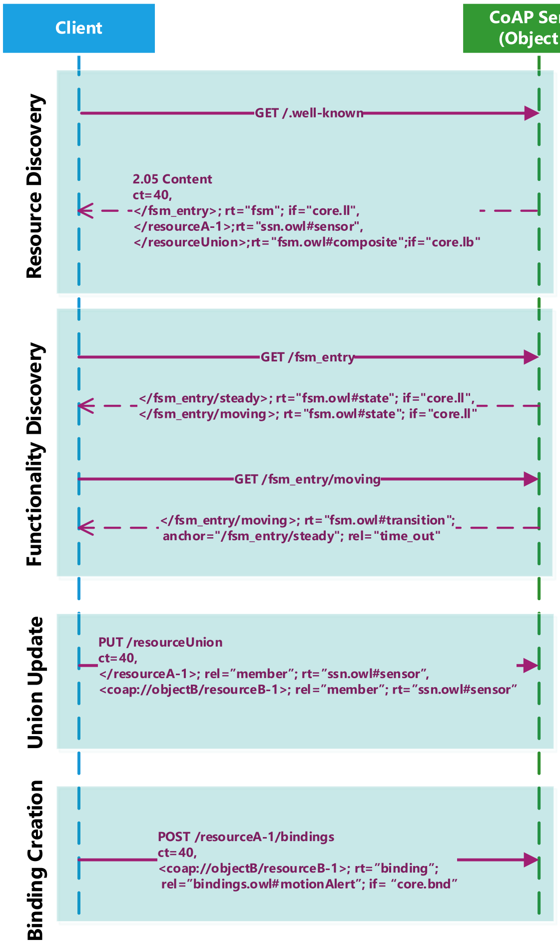
A. FRAMEWORK DESCRIPTION

As shown in Figure 4, the proposed framework includes two layers: a lower layer for object functionality description, and an upper layer for semantic profiling. These are discussed below.

1) OBJECT FUNCTIONALITY LAYER

Each object has an embedded state graph, that describes the object's functionality. A *finite-state machine* (FSM) ontology can be used. CoRE is used to discover such functionality, where a resource ends up being a possible object state. The graph elements can be a:

1) Resource – A state that may be affected by events;



```
GET /.well-known

2.05 Content
ct=40,
</fsm_entry>; rt="fsm"; if="core.ll",
</resourceA-1>;rt="ssn.owl#sensor",
</resourceUnion>;rt="fsm.owl#composite";if="core.lb"

GET /fsm_entry

</fsm_entry/steady>; rt="fsm.owl#state"; if="core.ll",
</fsm_entry/moving>; rt="fsm.owl#state"; if="core.ll"

GET /fsm_entry/moving

</fsm_entry/moving>; rt="fsm.owl#transition";
anchor="/fsm_entry/steady"; rel="time_out"

PUT /resourceUnion
ct=40,
</resourceA-1>; rel="member"; rt="ssn.owl#sensor",
<coap://objectB/resourceB-1>; rel="member"; rt="ssn.owl#sensor"

POST /resourceA-1/bindings
ct=40,
<coap://objectB/resourceB-1>; rt="binding";
rel="bindings.owl#motionAlert"; if= "core.bnd"
```

FIGURE 5. Discovery of functionality and dynamically built resources.

2) Link – A transition including the event triggering the transition and any performed actions.

Figure 5 shows how a client may discover the functionality of an object using CoRE. A first GET to "*/.well-known*" gets a reply showing resource "*/fsm_entry*" of semantic type "*fsm*", meaning that it is the entry point for the state graph. Then a GET for resource "*/fsm_entry*" returns all possible states, which may also be queried for further information on transitions associated with it. The CoRE Interface Link List (*if*="*core.ll*") is used allowing query operations only. Multiple entries may exist in a state (e.g., "*/fsm_entry/moving*"), each referring to a transition leading to that state. The "*rt*" can be used to semantically describe the transition, "*anchor*" may refer to the previous state, and "*rel*" may include the event and any actions associated with the transition.

2) SEMANTIC PROFILING LAYER

At the upper layer, a graph reflecting the current relationship between objects is dynamically built over time. CoRE can be used to build, change or discover such relationships. The elements in this graph can be a:

1) Resource – Which includes a single or multiple objects; each resource has a current state property that can be in one of the multiple mutually exclusive states available;
2) Link Binding – To connect/bind resource states together such that updates to one of the states are sent over the link to the other.

The resource discovery shown in Figure 5 also returns “*/resourceUnion*” and “*/resourceA-1*” resources. The first defines a union between two resources that ends up creating a new resource at the semantic profiling layer. That is, objects can be joined together to offer new resources that would be impossible to be offered individually. Its content can change dynamically, according to the environment and/or behaviour of objects, and the Link Batch interface (*if=“core.lb”*) is used to manipulate such Collection. Figure 5 shows an update of resource “*/resourceUnion*” in order to include the local resource “*/resourceA-1*” and the external resource “*coap://objectB/resourceB-1*” as members.

Resources can have Binding entries. As shown in Figure 5, resource “*/resourceA-1*” includes a Binding (*if=“core.bnd”*) to resource “*coap://objectB/resourceB-1*”, and “*rel*” is used to semantically describe the relation type (e.g., “*/resourceA-1*” in a moving state forces resource “*coap://objectB/resourceB-1*” to be in an alert state). Bindings can change dynamically, according to the environment or behaviour of other objects.

Figure 4 illustrates the described resources. The Binding appears as an arrow from ResourceA-1 to ResourceB-1, while the Collection appears as Resource ∪ (union). The behavioral characteristics of objects, together with a knowledge of their intrinsic features, end up semantically profiling objects.

3) USE CASE EXAMPLE

Let us assume a PIR device with a Motion Movement functionality described by *rt=“http://www.objectPIR.org/ontology.owl#motionDetection”*, and a camera device with a Recording functionality that is described by *rt=“http://www.objectCamera.org/ontology.owl #Recording”*. The “*rt*” links point to an ontology where functionalities are described and explained in an explicit and machine-readable way. This way, devices capable of processing “*rt*” will have an additional knowledge about what these functionalities are, and how to interact with them. Legacy clients, not capable of processing “*rt*”, may still consume the data with the help of a gateway (see Figure 4) that would act as a mediator.

Although devices can be consumed separately, richer applications can be built if these devices are able to discover the functionalities of each other, and work together. This way, and without having any previous knowledge of the other, dynamically-produced resources can emerge.

Figure 6 shows the case of Binding the functionalities of the PIR and the camera, in a way that when the PIR detects movement a notification is sent to the camera, so that it starts recording. The PIR and camera resources, available at separate objects (that might include other resources too), can be joined to offer a virtual device/resource. This abstraction hides unnecessary details from a user interested in consuming the virtual resource. The knowledge provided by an ontology describing a *security system*, together with the semantic description in the PIR and camera devices, allows functionalities to be combined so that a virtual security system becomes available. Fundamentally, the base description of functionalities and features associated with a security system, can be enhanced with knowledge retrieved from the semantics embedded in the PIR and camera devices.

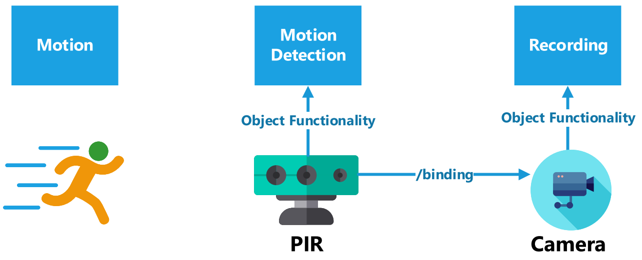


FIGURE 6. Use case example: PIR plus camera.

B. VALIDATION AND REASONING

The object functionality and semantic layers end up semantically profiling the objects through existing resources, which may relate to states influencing each other (Binding) or to Collections. Such knowledge becomes a basis for data validation and reasoning engines once data is received. Therefore, the following operations can be performed:

- Trustworthy and Consistency Validation – Data can be validated using semantic profile knowledge.
- Data Annotation – Context-aware annotation of data can be performed. That is, data can be semantically annotated according to the knowledge of object functionality and semantic profiles.
- Reasoning – Semantic reasoners can infer logical consequences from a set of facts, can anticipate behaviours, detect similarities between objects for collaborative tasks, and change Binding and Collection resources accordingly.
- Application Dependent Engine – Integration with other domain-specific ontologies and rules, for further knowledge to be inferred, can be done according to each application.

It should be highlighted again that the RESTful nature of CoRE allows for profiles to be discovered and dynamically created, updated or deleted. Such open and dynamic architecture provides, therefore, the basis for smart applications to emerge.

VI. CONCLUSIONS

This article presents a vision of how interoperability at the data and knowledge levels can be achieved for smart applications to emerge in IoT. The CoRE framework is proposed as the key driver for data integration, providing the mechanisms for the semantic profiling of objects that will facilitate data annotation, validation and reasoning. This allows for people-oriented applications to be developed in an open, dynamic and smart way. Tools for both providers and users should be developed to assist in the interaction with objects and resources, as well as validation and reasoning, and to ensure the consistency of information at different objects.

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