A Unified Semantic Knowledge Base for IoT

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***Abstract*—In the Internet of Things (IoT), interoperability among heterogeneous entities is an important issue. Semantic modeling is a key catalyst to support interoperability. In this work, we present a unified semantic *knowledge base* for IoT that uses ontologies as the building blocks. Most of the current ontologies for IoT mainly focus on resources, services and location information. We build upon the current state-of-the-art ontologies to provide contextual information and set of policies to execute services. Our knowledge base consists of several ontologies *viz,* resource, location, context & domain, policy and service ontologies. This helps in building a unified knowledge representation for IoT entities. In our knowledge base, we specifically model dynamic environments in which IoT entities operate. Our knowledge base also facilitates service- composition, discovery and modeling for IoT in dynamic environments.**

I. INTRODUCTION

The Internet of Things (IoT) as defined in [10], refers to the general idea of things – especially everyday objects – that are readable, recognizable, locatable, addressable, and/or controllable via the Internet. Everyday objects include not only the electronic devices but also physical objects, which we encounter in everyday life. That is, the things that we do not ordinarily think of as an Information Communication Technology (ICT) entity at all – such as food, clothing, and shelter; materials, parts, and sub-assemblies; commodities and luxury items; landmarks, boundaries, and monuments, etc. With the advent of ultra-low power electronic devices and advancements in wireless sensor networks many of the ICT entities can accomplish a range of smart functions. Services are now available to interact with these smart entities over the Internet and actuate them [11], [12]. In IoT, another notable aspect is abstraction of resources as services. This has laid the foundations for a plethora of applications such as smart home, smart office, smart transportation, smart cities, etc., where users can search, query and actuate entities in real-time. These services are provided by a huge number of heterogeneous objects that are directly related to the physical world. With large number of devices in the real world, many physical parameters and real world entities can be reached via Internet. Thus, there is a need for seamless integration of the physical world with the digital world in IoT [4]. The data and/or services provided by these objects need to be defined in a homogeneous way to allow interoperability and thus supporting autonomous decision making mechanisms. In traditional web-oriented systems, services are mere static entities deployed in resource-rich systems with scope for configuration, maintenance, etc., [30]. On the contrary, services in IoT are provided by the resource-constrained devices, which have limited computing power, network bandwidth, storage, and energy. Thus the traditional service discovery mechanisms cannot be directly used, due to substantial communication and system resource requirements. Moreover, service discovery mechanisms for IoT have to consider the dynamic environment, where the resource-constrained devices may be unreachable due to intermittent connectivity, mobility and/or energy constraints. Therefore, IoT entities need to be formally represented and managed to achieve interoperability.

Semantic modeling captures the capability of entities to express information and its relationship among other entities to enable efficient information exchange. Semantic modeling coupled with service oriented computing [21] and ontology provides a homologous and scalable means of accessing IoT entities. An ontology is defined as “a formal, explicit specification of a shared conceptualization” [18], and it is used to represent knowledge as a set of concepts related to each other. Ontology consists of four main components namely: *classes*, *relations*, *attributes* and *individuals*. Classes describe the concepts of the system, and individuals are instances of the classes. Attributes represent the features and characteristics of the classes, and relations describe how the classes and individuals are related.

In this work, we propose a unified semantic knowledge base for IoT capturing the complete dynamics of the entities. We use semantic modeling, specifically ontologies [18] for developing a unified knowledge base to support: a) semantic definition and representation of IoT entities; b) dynamic service discovery and matching based on user request; and c) service composition [22] and orchestration in dynamic environments [24]. In this paper, we consider ontologies as the key component for automatic service- representation, composition, discovery, and orchestration for IoT in dynamic environments. Our proposed knowledge base hides the heterogeneity of entities and consequently enables semantic searching and querying capabilities. Our knowledge base integrates several existing ontologies that were mainly related to sensor resources [29], web services [20] and extends them for IoT. The main goal of this paper is to extend the existing efforts on ontologies for IoT to support interoperability among heterogeneous entities. Specifically, in this work we model contextual information and the dynamic environment where IoT entities are deployed.

The rest of the paper is organized as follows: In Section II, we provide a detailed state of the art studies and highlight key contributions of this paper. In Section III, we describe IoT system architecture and its functionalities. In Section IV, we describe our knowledge base for IoT. Finally, we conclude this article in Section V.

II. RELATED WORK

In this section, we first discuss the state of the art recent works on IoT architecture and applications, and then review

TABLE I. REVIEW OF EXISTING WORK AND OUR CONTRIBUTIONS.

Ontology	Existing efforts	Our contributions
Resource	SSN Ontology with high level schema describing only sensor devices	Extension of SSN ontology to include all IoT entities. Our knowledge base includes sensors, actuators, physical objects and composite objects as entities
Location	GeoNames Ontology with features mainly describing outdoor locations	Fine-grained indoor location information, neighbor, nearBy features for geospatial contextual information
Context & Domain	NA	*Aspect - Scale - Context* model is used to define context information with quality constraints for IoT entities
Policy	NA	Provides macro level specifications for service orchestration, uses *Belief - Desire - Intention - Policy* to model dynamic environments
Service	OWL-S Ontology contains schema mostly for web services and follows profile-process-grounding pattern	Extension of OWL-S for IoT, addressing dynamic nature of service creation, discovery and adaptation

existing works on semantic modeling for IoT. IoT is emerging as one of the major trends shaping the ICTs at large [3], [14]. The ability of a physical entity to sense, collect, transmit data and communicate with other entities, leads to a variety of applications like smarter environment [28], social sensing to track objects [1], smart devices [5], health-care applications [26], [8], etc. Several research efforts like Atzori et al. [3], Miorandi et al. [9], Serbanati et al. [2] and projects like iCore [13], IoT.est [15] and IoT-A [16] try to address issues such as semantic interoperability, heterogeneity, scalability, inaccurate or incomplete metadata, unknown topology to envisage above mentioned applications.

In this work, we address these issues holistically by developing a unified semantic knowledge base for automatic service- representation, discovery, modeling and composition in dynamic environments. Several recent works try to address the above-mentioned issues with the help of ontologies [18]. For instance, Semantic Sensor Networks (SSN) ontology [29], represents a high level schema model to describe sensor devices, their capabilities, deployment details and other features. The SSN ontology does not include other entities that exist in IoT such as physical objects, actuators and complex systems. In this work, we build upon SSN ontology to include more specific features particular to IoT. Henson et al. [7], describes a semantically enabled sensor observation service called SemSOS, providing the ability to query both high-level knowledge and raw low-level sensor readings. However, the authors in [7], do not consider context and domain related information for retrieving high level knowledge and thus knowledge retrieved may not be accurate. Chirstophe et al. [6], presents an ontological framework for the representation and retrieval of connected objects in Web of Things. Ontology based model for service oriented sensor data is proposed in [17]. It consists of three main components – *ServiceProperty, LocationProperty and PhysicalProperty*. The systems in [6], [17], however lacks modeling contextual information, resource description and service discovery for IoT. Some works like [31], [32], [22], [23] also try to build semantic model for IoT, but lacks modeling contextual information and dynamic environments with resource-constrained entities. In our work, we model dynamic environments with the help of the policy ontology that is exposed by other ontologies to assist dynamic service modeling. Our Knowledge base also models contextual information to enable service adaptation. This work tries to merge several concurrent efforts in semantic modeling and builds on top of existing well known ontologies such as SSN, GeoNames, OWL-S, etc., to provide a comprehensive unified knowledge base for IoT as shown in Table I.

III. IOT SYSTEM ARCHITECTURE

In this work, we follow the design guidelines described in the EU FP7 iCore project [13]. One of the goals, of the project is to define an architecture for IoT that can be applied to various applications like smart home, smart office, smart transportation, etc. The design principle in iCore is that any physical/real world object in this world can have a virtual representation through a Virtual Object (VO). A VO includes a semantic description of the functionality, and hides the heterogeneity of the real world object. Several VOs can be aggregated to form a Composite Virtual Object (CVO), which can provide more comprehensive and resilient services. In general, CVOs are composed to accomplish a specific service request. Thus, the iCore architecture has three layers namely, VO layer, CVO layer and Service layer as described in Fig. 1. The functionalities of the three layers are described below:

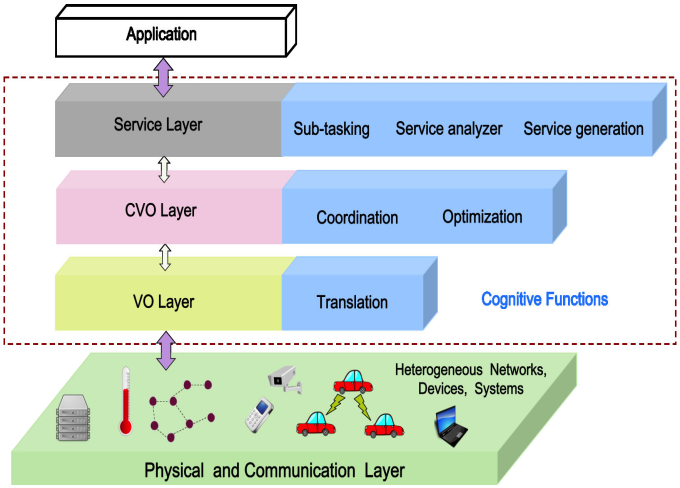

Fig. 1. iCore system architecture describing functionalities of various layers.

- *VO layer*: In this layer, any real world object is represented in the digital domain as Virtual Object (VO). Users can semantically search and retrieve information from any existing VO. Further, actuation could be executed through the VO.

- *CVO layer*: VOs are mashed together to address a specific service request generated by the user or by the system. This layer provides functionality to semantically search and query specific types of CVOs for service accomplishment.

- *Service layer*: This layer accepts the request from the users and analyzes the service requests to determine the types of CVOs required for service accomplishment. This layer also handles service composition and orchestration in dynamic environments.

The iCore system also contains a few systemic components namely:
a) *Registry:* Each layer has a registry holding references to the available VOs, CVOs and services. These registries provide methods to semantically search and query existing VOs, CVOs and services.
b) *Authentication and authorization functions:* This component authenticates actors of the iCore system. Actors can be users or applications. Each actor is associated with an access profile, if not, system creates one.
c) *Usage control functions:* This component regulates access to the VOs, CVOs and services based on the level of the actors.

In the next section, we describe our knowledge base addressing various IoT entities and their features.

IV. UNIFIED SEMANTIC KNOWLEDGE BASE

Ontology is a key component in our knowledge base for IoT. In this work, we propose ontologies that models all the layers of the architecture described in Section III. The knowledge base comprises of ontologies, *viz,* **Resource Ontology**, **Location Ontology**, **Context & Domain Ontology**, **Policy Ontology** and **Service Ontology**. Our proposed knowledge base is generic and can be applied to any IoT application. Fig. 2 shows the mapping between various ontologies and layers of the architecture. We consider standard design principles such as lightweight, completeness, compatibility and modularity for ontology creation in developing our knowledge base.

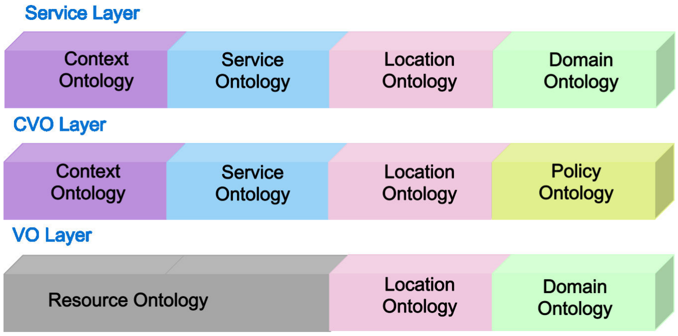

Fig. 2. Mapping between various ontologies and layers of the architecture.

In the next subsections, we discuss in detail on each of the ontology and its applicability for IoT.

A. Resource Ontology

Resource Ontology represents an entity in IoT. An entity can be a sensor, actuator, physical object and composite objects. Fig. 3 shows how an entity is described in resource ontology.

- *Sensors* are devices that have the capability of measuring a physical parameter of the real world. e.g., humidity, weight, light intensity.

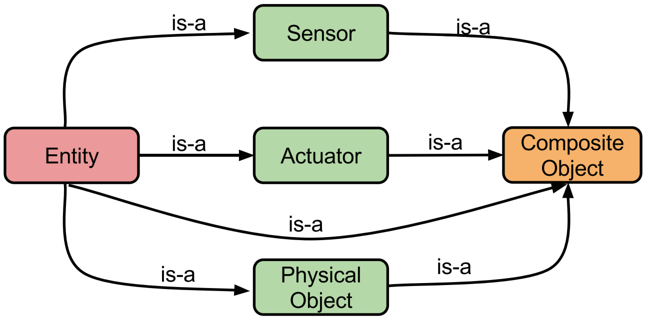

Fig. 3. IoT entity description in resource ontology.

- *Actuators* are devices that can perform an action or control a physical entity in real world.
- *Physical objects* are entities that represent a real world object.
- *Composite objects* are devices that are combinations of one or more devices described above.

Due to paucity of space, in this paper we focus only on modeling a sensor resource by extending the SSN ontology [29]. Some of the properties exposed are *role, events, haspartof (subsytem), deployment, operating range, measurement capacity, observations, implements, detects*, etc. Fig. 4 describes part of the ontology for IoT sensor resource with five major subclass *viz, observed, deployment, feature_of_interest, operating_range and implements*. Note that actuator resources can also expose the properties similar to the one identified for the sensor resource. The deployment subclass exposes the location ontology which is described next.

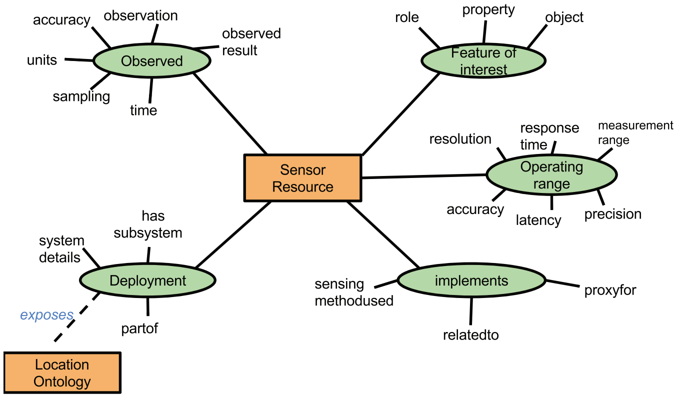

Fig. 4. Resource ontology for sensor entity with important properties.

B. Location Ontology

Location ontology adds geospatial semantic information for IoT. We extend the GeoNames ontology [27] to link IoT resources and services. The existing GeoNames database contains over 8 million geographical names consisting of 7 million unique features. Features in the GeoNames Semantic Web are interlinked with each other using linked data principles [19]. Location class can be administrative divisions, populated places, structures, mountains, water bodies, etc. Some of the properties of location class are name, latitude, longitude, country code, area code, type, wikidocs, sameAs, etc. Location class has three major components:

- *Children* that define subclasses associated with the location class like countries for continents, rooms for buildings etc.
- *Neighbors* that define neighbors of the location class. For instance, neighboring countries or neighboring buildings, etc.
- *Nearby* that defines nearby places to the location class like nearby popular places around a particular location.

Our location ontology includes indoor location information to provide additional contextual information. Location ontology is exposed by context ontology described later to include geospatial semantic contextual information about IoT entities. Location ontology can be used to perform reverse geocoding, to identify a place using latitude, longitude and vice versa. Our location ontology is generic enough to represent any particular location (indoor or outdoor). It also provides fine-grained location information for IoT. Fig. 5 describes a part of the location ontology consisting of place, buildings, area and rooms for IoT.

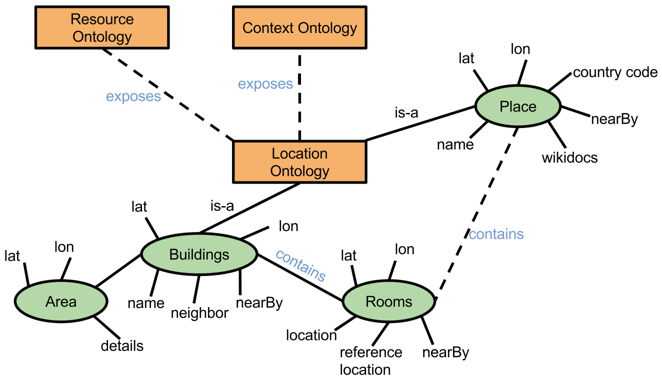

Fig. 5. Location ontology with important properties.

C. Context & Domain Ontology

Context and Domain Ontologies represent contextual information and specific knowledge about domains like smart home, smart office, smart transportation, etc. In our knowledge base, high level contextual information is provided by the context ontology and low level domain specific information is provided by domain ontology. Context ontology enables context-awareness and contextual interoperability during service discovery and composition. Contextual information can assist smart and intelligent service discovery and matching. Thus, it is very crucial to describe contextual facts and inter-relationships in a well designed model. The contextual information can be obtained via *direct* methods and *indirect* methods. Direct methods use sensed information and user defined knowledge to determine contextual information. On the contrary, indirect methods use reasoning and inference mechanisms to obtain contextual information. In our context modeling, context reasoner is used to infer contextual information using machine learning mechanisms. Context interpreter is used to derive contextual information from the sensor data obtained.

In this work, we adapt *__A__spect-__S__cale-__C__ontext* (ASC) pattern to model contextual information for IoT entities. *Context information*, as described in [25], is any information that can be used to characterize the state of an entity concerning a specific aspect. An *aspect* is a value-range that contains subset of all reachable states, grouped in one or more related dimensions called *scales*. Each aspect aggregates one or more scales, and each scale aggregates one or more context information and are interrelated via *hasAspect, hasScale and construtedBy* relations. One-to-one mapping between scales is represented by *IntraOperation* and mapping between one scale to multiple scales is represented by *InterOperation*, subsequently allowing inter-relationships among the scales. IoT resources are mostly resource-constrained and thus contextual information derived from these sensed data may not be accurate due to the limitations and/or faultiness of the sensor. Hence, we introduce *quality constraints* like *accuracy, resolution, certainty, lifetime of sensed data* to derive contextual information. Fig. 6 shows part of context ontology used to represent contextual information for IoT entities.

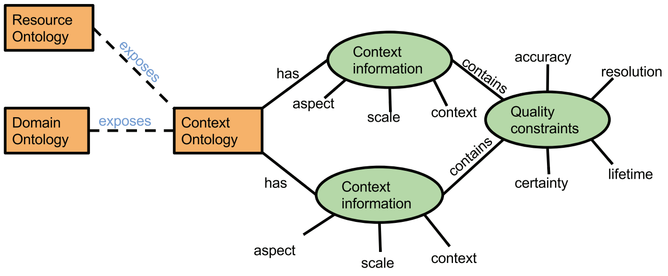

Fig. 6. Context ontology and its relation with other ontologies.

The Domain Ontology models a specific domain like smart home, smart office, smart transportation, etc. where particular entities applied to other domains may have unique significance. The domain ontology has two parts namely *generic part*, which describes common objects that are applicable across various domain, and a *view-specific part*, which describes unique features of a particular domain. We have currently modeled few domains like smart home and smart office for IoT entities. Due to paucity of space, we omit the details of domain ontology. In general, domain ontology will be developed with the help of domain experts that are later exposed by context and resource ontology.

D. Policy Ontology

Policies provide macro level specifications and are in general, an effective way to adapt dynamic systems. Policy ontology is used to provide information on how to accomplish a service requested by an actor in dynamic environments. Policy ontology provides a semantic description of generic policies, comprising of *high level policies* containing abstract service definitions, *concrete policies* with specific goals to be achieved based on the service request, and *low level policies* describing the execution plan of the service. Policy ontology is *exposedBy* service ontology to model services in dynamic environment.

Some of the properties in the policy class are *policy id, modality, trigger, subject, target, behavior, constraint, role, desires, intentions, assignment,* etc. The policy ontology is driven by ***B**elief-**D**esire-**I**ntention-**P**olicy* model, where *Beliefs* are generated based on service requests; *Desires* are sub goals that are to be achieved based on the beliefs; *Intentions* represents execution plan to accomplish a service requested. Policy ontology defines the roles of each entity associated with the service and its authorization and obligations respectively. Fig. 7 shows a part of policy ontology for IoT. In iCore architecture, policy ontology is used in the CVO layer to determine which IoT entities are required to accomplish a service. Thus, as mentioned before, policy ontology is *exposedBy* the service, context and domain ontologies.

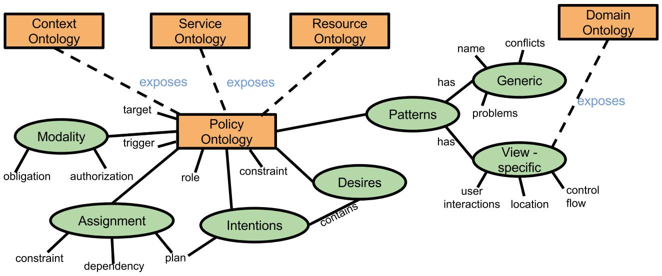

Fig. 7. Policy ontology with important properties.

E. Service Ontology

Service ontology describes how services can be defined, represented and modeled in a machine interpretable manner. Our service ontology is built upon the concepts identified by OWL-S [20]. The traditional OWL-S is a semantic model for SOAP/WSDL services and is based on "Profile-Process-Grounding" pattern. The traditional OWL-S cannot be used directly for IoT because of the dynamic environments in which IoT entities operate. We extend the OWL-S "Profile-Process-Grounding" pattern to "Profile-Process-**Policy**-Grounding" pattern to facilitate service adaptation, modeling and composition in dynamic environments. An IoT service is more a real-world service and hence its association with IoT Resource, Context, Location and Policy needs to be modeled. The relationship "exposes" is defined between Service class and other classes to model the association among them. The structure of service ontology is described in Fig 8.

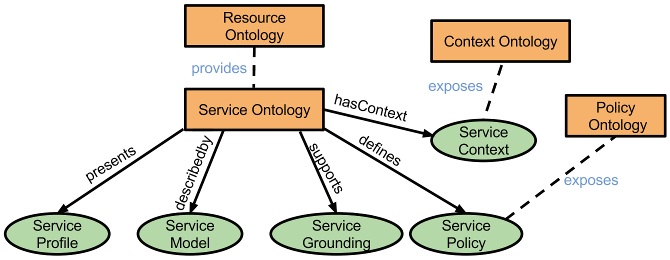

Fig. 8. Service ontology with important properties.

As described already, our service ontology is based on Profile-Process-Policy-Grounding pattern. The functionality of these components are:

- *Service Profile* provides description of what is accomplished by the service and its limitation. It also describes the Quality of Service (QoS) and specific requirements based on service requests. Service profile provides the generic features offered by a service in a semantic manner.
- *Service Process/Model* provides semantic details on how to interact/use a service. Service model defines functional contents of a service used for service descriptions, querying and service composition. A process can be atomic, simple or composite. An atomic process requires a single server action, composite process requires multiple server actions and, finally, simple processes provide an abstraction mechanism to provide multiple views of the same process.
- *Service Policy* describes when to use a particular service based on historical information and real-world information. Service policies are exposed by policy ontology, to provide details on when a particular service can be used in dynamic environments.
- *Service Grounding* specifies how to access a service. Grounding provides details such as communication protocols, message formats, and other service-specific details that are required to access the service.

V. CONCLUSIONS

In this paper, we have presented a unified semantic *knowledge base* for Internet of Things. Semantic modeling is an important component to address issues related to interoperability among different entities to realize the grand vision of IoT. Our knowledge base comprises of ontologies to model *viz,* IoT resources, location information, contextual information, domain knowledge, policies for dynamic environments and IoT services. Most of the current work focuses on IoT resources and services, however modeling contextual information in dynamic environment assists in more accurate knowledge representation for IoT entities. We build upon, and extend the existing ontologies for IoT to support heterogeneity and seamless interoperability among entities. The knowledge base supports, among others: (a) service representation and definition for IoT entities; (b) dynamic service discovery and matching service requests; and (c) service composition and adaptation in dynamic environments. This unified knowledge base can be used by researchers for semantic service- composition, discovery and modeling for IoT in dynamic environments. We plan to exploit this unified knowledge base for developing an approximate service matching algorithm in real world environment.

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