Extending DataTweet IoT Architecture for Virtual IoT Devices

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***Abstract*—Virtual sensors promise numerous benefits to the Internet of Things (IoT) in terms of enhanced computing on sensor data, sensor fusion and overall cost reduction. But a wide deployment of this concept in the IoT system is not witnessed due to a lack of uniform approach to create and maintain them. Also, virtual actuators are not fully explored yet. This paper proposes a uniform mechanism to create and operate a virtual IoT device (VID) that can represent either a virtual sensor or a virtual actuator. VID integration into an IoT architecture is presented and operational phases are explained. Utilization of the virtual IoT devices in an horizon IoT application involving connected vehicles and Smart City is outlined. The main novel aspects of the work are - (i) remote creation of VID by a system administrator and/or a consumer, (ii) standard web technology based implementation of VID promoting interoperability in IoT architecture, (iii) generic and flexible deployment, (iv) support of discovery and management of VIDs through the IoT architecture and (v) ability to communicate to both smart and legacy IoT devices.**

***Index Terms*—Discovery; Internet of Things; IoT architecture; Virtual Sensor; Virtual Actuator; Web of Things.**

I. Introduction

The Internet of Things is widely recognized as the next evolution of the Internet which will interconnect Billions of things [1]. Smart City initiatives (e.g. SmartSantander[2], Barcelona[3] etc.) around the world have already started deploying sensors and other resources in city environment to offer consumer IoT services. Market research companies estimate that the current cities will spend almost $41 Trillion USD over next 10-20 years to upgrade themselves to Smart Cities. A significant share of the cost will be spent to (i) deploy IoT devices (sensors, actuators), new communication infrastructure & in their maintenance and (ii) make IoT systems interoperable among themselves. Moreover, the capabilities, properties and actions supported by the devices are largely limited to their manufacturing. Additionally, with the advancement in IoT technologies, sensors and communication modules of connected vehicles can be used to collect data about their environment. This may reduce the need of physical deployment of massive quantity of resources to the Smart City environment. In this context, the researchers are investigating novel mechanisms to offer better consumer IoT services through virtual sensor concept.

A virtual sensor (VS) has been defined as an entity or a functional module capable to detect events produced by a physical entity [1]. Most common deployment of VS in the current literature is on a Cloud System which provides Sensor as a Service [2]. It offers many advantages - (i) better utilization of available Cloud Computing and sensor resources, (ii) a collection of such sensors can be provisioned as a single entity to improve availability, (iii) portability of physical things does not affect VS and (iv) enhanced performance of (constrained) physical sensors as computing can be done in the Cloud platform.

Despite a lot of research efforts and known benefits, a wide spread deployment of virtual sensors in ongoing IoT platforms and consumer IoT services is not witnessed. One of the main reasons for that is a lack of unified approach towards creating, operating and managing such sensors. Also, most of the current literature concentrated on virtualization of sensors and virtual actuator concept is not fully explored. There is no uniform framework that achieves interoperability and easy integration of such VS into an existing IoT system.

This paper recognizes the benefits that virtual sensors bring to the IoT systems and extends the virtualization concept to actuators as well. In our previous work, we explored DataTweet IoT architecture [3] and its application development framework [4]. It decouples the IoT services from underlying infrastructure dependencies and shifts the focus on data centric services. The architecture is generic in nature and is applicable to a multitude of verticals including Smart City crowd sensing [5] and connected vehicles [6]. The application framework allows developing horizontal IoT applications by using semantic web technologies to reason on sensor data originating at different vertical domains. Our main contribution in this paper is in presenting an extension of DataTweet framework that allows creating and operating virtual IoT devices (e.g. both sensors and actuators). The enhanced DataTweet IoT architecture consolidates VIDs with common service functions of IoT. Since DataTweet framework and its extensions follow oneM2M IoT and W3C Web of Things specifications, interoperability is maintained. Other key contributions of our work are enabling following functionalities.

- The virtual IoT devices (VID) can be created and configured remotely by a consumer and/or an IoT system administrator. Each virtualization corresponds to a device

[1] http://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf
[2] http://www.smartsantander.eu/index.php/testbeds
[3] http://datasmart.ash.harvard.edu/news/article/how-smart-city-barcelona-brought-the-internet-of-things-to-life-789

description that consists of capabilities, properties and actions supported by the virtual IoT device.
- The implementation of the VIDs is based on standard web technologies that assist in maintaining interoperability among similar devices and IoT platforms.
- The proposed implementation supports flexible deployment at a Cloud platform as well as edge device (e.g. IoT gateway, Road Side Unit). This widens the applicability of developed virtual sensors and actuators.
- The extended DataTweet IoT architecture supports discovery and management of virtual devices from consumer subsystems.
- The virtual IoT devices can communicate to smart physical devices (i.e. capable of communicating over IP) as well as legacy devices (communicating over non-IP technologies like Modbus). This features widens the applicability of VIDs to more physical devices.

Rest of the paper is organized as follows. Section II surveys the state-of-the-art and points out the merits and demerits of the available research works. Section III focuses on the internal components of the VID, proposed extension of DataTweet IoT architecture and novel aspects of our work. Section IV summarizes the paper and concludes with future directions.

II. State-of-the-art

This section studies the current state of research works on virtual sensors and their applications to identify their benefits and limitations.

A. Virtual Sensors

The authors of [1] have examined the rationale behind the virtual sensors and their conceptual form. Based on sensor capabilities and deployment in an IoT architecture, a taxonomy is proposed and it includes singular, accumulator, aggregator, selector, qualifier, context-qualifier and predictor & compute. The authors implemented the virtual sensors and demonstrated various metrics & results.

Englert et al [7] has applied the virtual energy sensor concept to estimate electricity consumption of IoT appliances. The main contribution of the paper lies in developing a software solution of electricity metering instead of relying on dedicated measurements from each appliance. A device specific energy model is prepared for energy consumption approximation. The model also takes care of the energy consumption by the virtual sensors. With a prototype the authors demonstrate that the solution approximates the energy consumption of common appliances with an error between 2.19% to 10.8%.

The authors of [8] introduced the concept of composite virtual objects (CVO) to provide services and collaboration among smart physical things in an IoT environment. The authors have argued in favor of using the web technologies to implement the CVOs. The main goal of these virtual objects is to deliver a service infrastructure that simplifies IoT application management. Another important benefit is in achieving interoperability among physical device communication and IoT services through semantics. For this purpose, the physical entities are virtualized along with their semantic ontologies. To ease the creation of CVO in any IoT platform, the authors have presented a CVO ontology. The CVO creation and execution for a purpose is explained through an architecture.

Contrary to that, the authors of [9] use the virtual sensor concept in relation to Cloud of Things to enable remote sensing. The paper describes a distributed sensing resource directory and virtualization algorithms to deploy a virtual sensor network on top on physical IoT devices. Through mathematical analysis and simulation, the authors prove that such a deployment can be done with minimal resources and communication overhead.

Ravindran, Rabby and Iannelli have detailed a publish-subscribe based IoT system [10]. It allows virtual sensors to post events from an external source. Such sensors constitute of two key aspects (i) physical sensing elements to collect environmental (raw) data and (ii) computing power to infer useful information. A computational and communication structure of a virtual sensor is proposed where an object-oriented model for sensors is shown. Re-usability and reconfigurability of the virtual sensor are identified as two major contributions in the work. A prototype of such a system for video surveillance is also presented.

The author of [11] proposed a smart mechanism to automatically select the best set of sensors to form a high level and reusable virtual sensor. A tool named sensor composer is developed to consider each sensor as a sharable and reusable entity. The tool has been applied to different applications including smart home and locating remote sensors.

Self-configuration of sensor virtualization concept is investigated in [12]. The core idea of the paper is a middleware architecture that creating virtual sensors. External IoT applications and services can discover such sensor capabilities through "Zeroconf". The self-configuration is assisted through a gateway.The middleware architecture, protocol adapter and implementation are explained in details.

Social media data streams are considered as virtual sensors in [13]. Such data streams are major source of information in ongoing smart city initiatives and on processing can reveal important events about a city. But such processing must take care of trust and reliability of the source of such data.

Other use of VS includes rapid prototyping of interaction between a mobile phone and Microsoft Kinect [14]. This paper lists several virtual sensors (including proximity sensor, accelerometer, pose sensor, motion sensor and light sensor) that are using Kinect data to function. VS building over sensor networks is presented in [15] while VS utilization for tourism and map is studied in [16].

B. Virtual Service and Platform

Authors Alam and Noll presented a framework where sensors can provide virtual services [17]. The framework exposes physical sensor capabilities, data and relevant functionalities as virtual services. These are hosted in a virtualization layer of the framework. When a consumer device sends a query for a sensor data or to discover sensor capabilities, the virtual services are used in the process. The capabilities and functionalities are represented using lightweight ontologies developed by the authors. They have validated their work an electric vehicle use case. The main benefit of the research is in establishing virtual services offered by resource constrained sensors.

Application of web technologies are extended to create a virtual platform as well. As portrayed in [18], the platform interfaces between the consumers and the IoT ecosystem. The authors have looked at Virtual Reality (VR) based applications for the virtual platform to create (i) improved awareness among sensors and the data being collection and (ii) improved engagement of users in urban and smart city contexts.

C. *Abstracting IoT Devices and Sensors*

Authors Suyama, Kishino, Naya have described the importance of providing abstraction of IoT devices [19]. A virtual machine (VM) is prepared based on the Common Language Infrastructure (CLI) of .NET framework. It allows software developers to create abstraction using Visual Studio tool. The system has been applied to an environment monitoring system.

The paper [20] describes virtual sensors as a programming abstraction that simplifies the development of wireless sensor network applications. The data collected from a set of sensors can be aggregated and processed to perceive as measurement coming from a single virtual sensor. Similarly, the paper introduces a virtual actuator that allows interfaces to distribute commands to physical actuators. The physical sensor and actuator devices are abstracted into their virtual counterpart through logical neighborhoods [21]. The main application of this approach is that the software developers can focus on the IoT application logic rather than working on low-level development.

D. *Traffic and Computation Offloading*

Virtual sensor concept also benefits traffic and computation offloading scenarios. Wang et. al. [22] have argued that the cellular networks are being overloaded in vehicular cyber physical systems (CPS). They proposed mobile data offloading techniques through Wi-Fi and VANETs. The computation on vehicular sensor data can then be aided by a virtual sensor.

Vertical Handoffs (VHOs) in an Internet of Vehicle (IoV) context is described in [23]. The authors described a self-selection decision tree which is similar to virtual sensor mechanisms.

E. *Limitations*

Several limitations are identified while studying the state-of-the-art.

- Although virtual sensor concept is widely used in existing systems, virtual actuator concept is not really explored.
- There is a lack of open, standard architecture allowing creation, configuration and operation of virtual sensors.
- Performance and scalability aspects of virtual sensor deployment are not well studied.

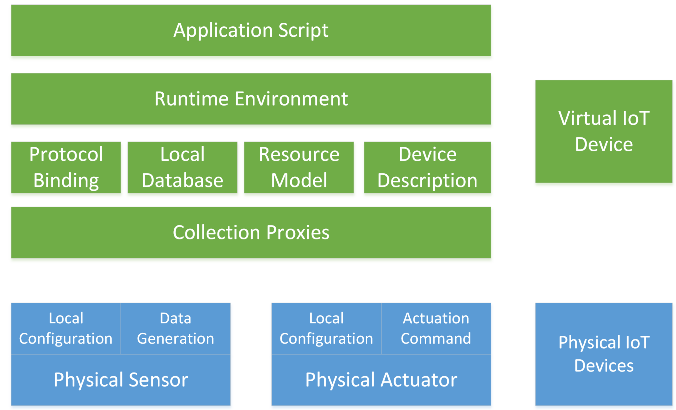

Fig. 1. Virtual IoT device and its internal components

- In many cases, virtual sensors provided an interface for end user interaction. But the architecture and middleware building blocks do not include access control which is paramount in current and future IoT systems.
- Web technology based virtual sensor development and deployment is not yet fully studied.
- Semantic web technology based interoperability in current virtual sensors is not at all observed.
- The deployment of virtual sensors are completely cloud based. Edge device based deployment for specific IoT use case are not investigated.

III. DataTweet Framework Extension for Virtual IoT Devices

This work introduces the notion of virtual IoT devices (VID) that can be associate with a physical sensor or actuator. In simple terms, VID includes both virtual sensor and actuator. We define a VID as - (i) a virtualized instance of one or more physical device, (ii) hosted in a Cloud or Edge Computing platform and (iii) provides device description including a list of capabilities in terms of events, properties and action.

This section initially describes an internal structure (shown in Fig. 1) of the proposed virtual IoT device. To provide a uniform approach for VID development, we propose to utilize the standard web technologies. This in turn sets the stepping stone for interoperability among VID access and operation. Then we explain extensions for DataTweet IoT architecture that allow creation, operation and management of such devices. Finally, we present all phases of VID creation, operation and actuation. Applicability of the proposed concept to a horizontal IoT application involving connected vehicle and Smart City is also described.

A. *Virtual IoT Device*

As shown in Fig. 1, our proposed VID caters to both sensor and actuator devices used in IoT systems. The internal architecture of VID includes several components and we described them using a bottom-up approach below.

Collection Proxies. Smart and legacy IoT devices use many different communication technologies (e.g. LoRa, BLE, Wi-Fi, 3G/4G, Modbus, QNX etc.) and protocols (e.g. CoAP, MQTT, HTTP) for connecting to an IoT system. In order to develop a generic mechanism to create the VIDs, it is necessary to connect any IoT device regardless of the communication technologies. The "collection proxies" include all necessary software libraries to achieve this task. Furthermore, the communications with physical sensor & actuator are handled by a "proxy-in" and "proxy-out" respectively [24]. This is an important component that is missing in most of the current literature.

Protocol Binding. While the above component houses the software libraries, this one converts interactions with physical devices using information in device description according to the protocols (CoAP, MQTT, HTTP) used.

Device Description. Each VID must have its own description allowing it to be discovered and managed from the consumer and administration subsystems of the DataTweet IoT architecture. This component effectively allows a physical entity to be associated with a virtual entity. The device description represents physical IoT device's name, unique ID, URI and the capabilities in terms of events, properties and actions. The VID description can be represented using CoRE Link Format [4] as well as semantic web technologies (SWT). Utilization of later also leads to semantic interoperability and JSON-LD[5] can be used to serialize events, properties and actions [25]. When a device description is created and VID is instantiated, it must be associated with one or more physical devices of similar type.

Resource Model. It mainly provides a common abstraction across different protocols. Similar to the web, the resource model allows to identify and address interaction points using URIs defined in the device description. However, this feature is optional for VID.

Runtime Environment. This building block provides a scripting API for creating functions which utilizes resource model, protocol binding and device description. It also allows discovery of device descriptions to create a VID.

Application Script. This implements the application logic for VID operation in a modular and portable manner. For example, if a virtual IoT device is used to aggregate or average multiple sensors' data, that logic is implemented here. The taxonomy proposed in [1] are available as pre-configured scripts at this level. The application script (AS) also interfaces directly with the runtime environment to utilize necessary APIs for discovery, protocol binding etc. Thus, the AS allows consumers to create an instance of a specific VID and associate it one or multiple sensors or actuators. The consumer and administrator subsystems of the DataTweet IoT architecture can also modify VID description if they have proper access control. This helps in VID management and maintenance.

Local Database. This is for local storage of VID descriptions and pre-configured scripts of virtual sensors and actuators.

[4]https://tools.ietf.org/html/rfc6690
[5]http://json-ld.org/

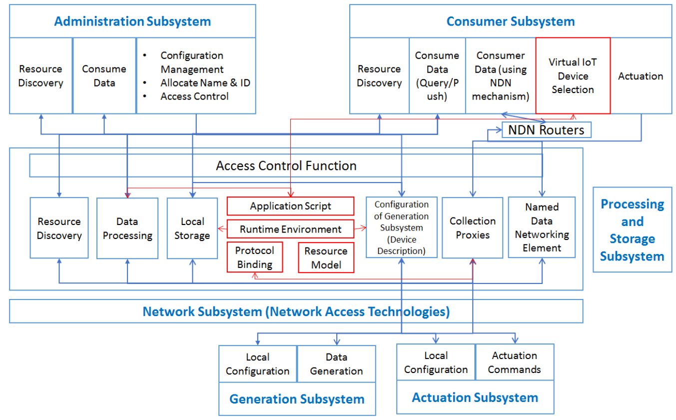

Fig. 2. Enhanced DataTweet IoT architecture with VID components

B. DataTweet IoT Architecture Extension for Virtual IoT Devices

The previous DataTweet IoT Architecture is presented in [3]. It consists of five main subsystems - (i) generation and actuation, (ii) network, (iii) processing and storage, (iv) consumer and (v) administration. The existing building blocks are designed and developed using oneM2M IoT and W3C WoT specifications. Our proposed VID components are can be easily integrated to the architecture. The enhanced architecture is shown in Fig. 2 and added building blocks are outlined using red.

The processing and storage subsystem (PSS) includes several oneM2M IoT common service functions [5]. The device description, local storage and collection proxies elements already exist and their software modules are upgraded to accommodate VID functionalities as well. VID specific components (e.g. AS, runtime environment, protocol binding and resource model) are added to the PSS. The runtime environment interworks with the existing resource discovery element for consumer VID search requests. When AS needs to perform sensor data processing as a part of its application logic, the AS interworks with the existing data processing elements of the PSS. Thus integration of VID components with a current IoT architecture becomes simpler.

The consumer subsystem (CS) adds a dedicated module that triggers the VID specific tasks. For example, for an application where average of several sensor data are needed, the CS would initiate creation of a VID that can accomplish this task. This request is forwarded to the AS which triggers appropriate runtime environment functions.

C. Steps for VID Creation and Operation

There are four main steps for the virtual IoT device creation and operation.

Device Description Discovery and VID Creation. The first step is to initiate a Virtual IoT Device description search (from the consumer subsystem) based on target application logic. This request is forwarded to the Application Script which invokes the discovery function of Runtime Environment. If

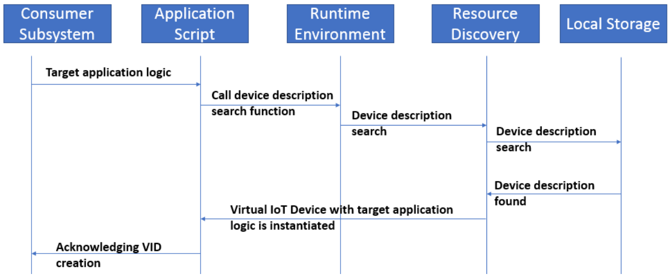

Fig. 3. Virtual IoT device creation

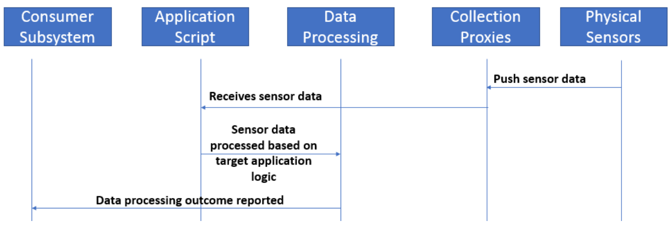

Fig. 4. Virtual IoT device data processing

a similar description is found in the IoT architecture, then an instance of a VID is created. This is shown in Fig. 3. Otherwise, the consumer subsystem is redirected to a web interface to create the device description after validating access control rights.

Association with Physical IoT Devices. The second step involves associating the created VID with one or more physical IoT devices. This involves the operation stage of the VID. The association must handle both static (e.g. smart home) and mobile (e.g. connected vehicle) IoT devices. For the static or fixed IoT devices, the VID can use RESTful interactions to collect data or send commands. For the mobile IoT devices, they push the relevant data to the VID. To establish the association, protocol binding component is used.

Computation. The third step is about computation on the data collected from sensor(s). For this purpose, the AS utilizes the data processing element of the PSS. The outcome of computation is then reported to the consumer subsystem as shown in Fig. 4.

Actuation. The final phase deals with virtual actuators. The consumer subsystem sends actuation instruction(s) after processing the outcome of the third step. Once such commands are received, the IoT system internally searches for relevant actuators and then makes association with them. Then the commands are forwarded through collection proxies. If no physical actuator is available, then a null is returned to the CS. Fig. 5 portrays this phase.

D. Horizontal IoT Application Use Case

The data centric nature of the IoT architecture allows developing horizontal IoT applications using DataTweet software framework [4]. We describe an use case that combines connected vehicle and Smart City domains for a mobile crowd sensing application.

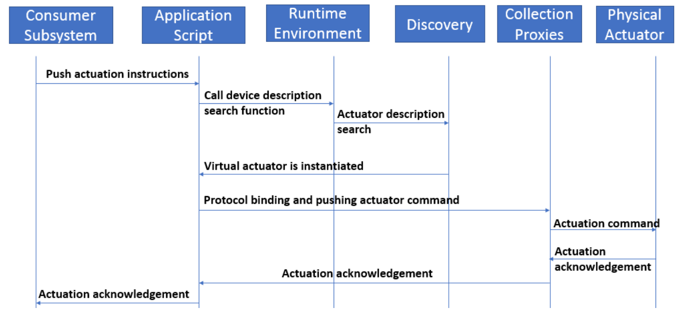

Fig. 5. Virtual actuation

Imagine, at certain intervals of any road or at intersections, there is a communication hot-spot through which connected vehicles can report data about the road and environment. Such data will be routed to a cloud that hosts the virtual sensors. When a local municipality wants to examine the road conditions, a virtual sensor will be created into the cloud that filters relevant sensor data from the vehicular data stream. This is an effective mobile crowd sensing scenario that exploits virtual sensor concept on connected vehicle sensors.

The same virtual sensor can be used to compute if there is any fog in the driving environment. In case, fog is detected by the PSS, the consumer subsystem can send two actuation commands - (i) reduce vehicle speed and (ii) turn on fog lamp to avoid accident. These commands are first sent to a virtual actuator in the PSS which forwards it to the vehicle actuators in the foggy environment.

For this type of horizontal IoT application, instead of deploying several sensors to create a connected road infrastructure, we benefit from the connected vehicle resources and VID concept. The W3C Automotive Working Group[6] is providing specifications about vehicle data access protocols. Using that, vehicular sensor data can be exposed to an external PSS (a Cloud platform in this case).

E. Solving Identified Challenges

Our work advances the state-of-the-art in virtual sensors by solving the identified challenges in Section II. Following highlights our advancements.

Virtual actuator. The proposed VID can act as a virtual actuator as well. In such a case, the actuator is responsible for sending instruction to a group of physical actuators.

Standardized architecture. Our proposed VID builds on standard and loosely coupled web based components. Adoption of web technology to build the VID components is described well in the paper and this allows rapid creation, configuration and operation of VIDs through open and standard APIs. The overall approach is aligned with ongoing standardization of the Web of Things in W3C. The extended DataTweet architecture is also following oneM2M IoT architecture recommendations.

[6]https://www.w3.org/auto/wg/

Access control. For interfacing with end users, the VID building blocks benefit from strong access control and authentication mechanisms installed by the DataTweet IoT architecture.

Distributed deployment. Due to the generic nature of DataTweet architecture, its processing and storage subsystem can be deployed at any cloud as well as edge system. This allows the deployment of the VIDs to be versatile. Also adoption of web technologies allows the VIDs to be operated from IoT gateways and mobile devices as well.

IV. Conclusion

This paper introduces the concept of virtual IoT devices that extends to both the virtual sensors and actuators. We developed a uniform approach based on standard web technologies to create and operate VIDs. The components of the VIDs are integrated well into DataTweet IoT architecture. As a result, the enhanced framework can provide additional computation on the sensor data. The applicability of the VID is mentioned using a horizontal IoT application involving connected vehicles and Smart City. As for future work, we aim to (i) study semantic interoperability applicable to VIDs and (ii) evaluate their performance and scalability aspects.

V. Acknowledgments

This work has been partially funded through the French ANR Project DataTweet[7]. EURECOM acknowledges the support of its industrial members - BMW Group, IABG, Monaco Telecom, Orange, SAP, ST Microelectronics and Symantec.

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