An Open Source Software Architecture for Smart Buildings

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***Abstract*— Open-source software has helped opening the software market to different players, usually cut off by licenses of expensive software packages. We claim that in the Built Environment a similar open source disruption can happen by putting together different projects in a software architecture based on open data standards. This paper describes the main open-source components of such software architecture, the Smart Building Controller (SBC) that we are developing, and possible future applications.**

Keywords—Cyber-Physical System, BIM, BPMN, openHAB

I. Introduction and Motivation

Better public services, more energy-efficient buildings and improved citizens' well-being are the driving motivations for the development of smart cities [1]. Smart building is any built environment that uses automated processes to automatically control the building's operations including heating, ventilation, air conditioning, lighting, security and other systems. A smart building uses networked sensors and actuators to collect data and manage it according to configurable services. This infrastructure helps owners, operators and facility managers improving asset reliability and performance, such as reducing energy use, optimizing how space is used, and minimizing the environmental impact of buildings.

New buildings, or older structures that have been converted to smart buildings, are constantly changing: they are connected to a network with intelligent and adaptable software, and they are often called Cyber physical systems (CPSs), which combine computing and networking power with physical components and networks of sensors and actuators, often called Internet of Things (IoT) [21].

Such CPSs have strict requirements for mobility, security, safety, privacy, and the processing of massive amounts of information [2]. Such complex and heterogeneous systems are usually composed of different proprietary technologies, which can often lead to different technical problems: the lack of open standards in terms of data format and communication protocols can cause delays due to software adaptation and integration costs; closed-source proprietary code can delay progress as expensive software licenses can lock customers to products not compatible with one another or with ones relying on open standards; closed-source code is also more difficult to verify in terms of reliability and security.

In the Built Environment domain, Building Information Modeling (BIM) is a digital representation of physical and functional features of a building, to be used as shared knowledge resource for information to provide a reliable basis for decisions during its lifecycle, from earliest design to demolition. BIM (Building Information Modeling) is a 3D model-based process that gives architecture, engineering, and construction professionals the tools to more efficiently plan, design, construct, and manage buildings and infrastructure. For each asset in building the intention is that two versions will exist, the real one and the digital one: the digital model will be relevant throughout the lifecycle and the legacy data will not become outdated and unusable. With the help of BIM, both time and resources can be saved. In fact, it has been estimated that in the construction industry the same data may be entered up to seven times [1]: this could be avoided by using BIM models as an information source. BIM is disrupting the construction world, with government contracts increasingly requiring its implementation. But for Small-Medium Enterprises (SMEs), BIM seems like out of reach: it is expensive, it requires training, and it might not increase profits or decrease costs, so why even consider using it?

In the software world, open-source software has provided a good answer for SMEs, and our research aims at creating a CPS architecture for smart-building fully based on open-source software and standard data formats and communications protocols; this paper describes the main components of the software architecture, discussing its various open-source components, and future extensions.

II. OPENHAB FOR SMART HOMES

Different open-source software projects can be used to build a free software framework for various smart-home applications (Fig.1). Heating, ventilation, and air conditioning (HVAC) systems are the typical example of building's assets that are controllable and configurable, and can be easily enhanced with sensors and actuators to achieve more automation and to program intelligent behavior (for example to minimize energy consumption). Moreover, temperature, occupancy and motion sensors can be used to detect human presence in different rooms; such live information can be used for safety purposes, to guide firefighters towards people trapped in a build on fire, or for energy-saving purposes, to save energy in rooms that have not been occupied and utilized for a certain period.

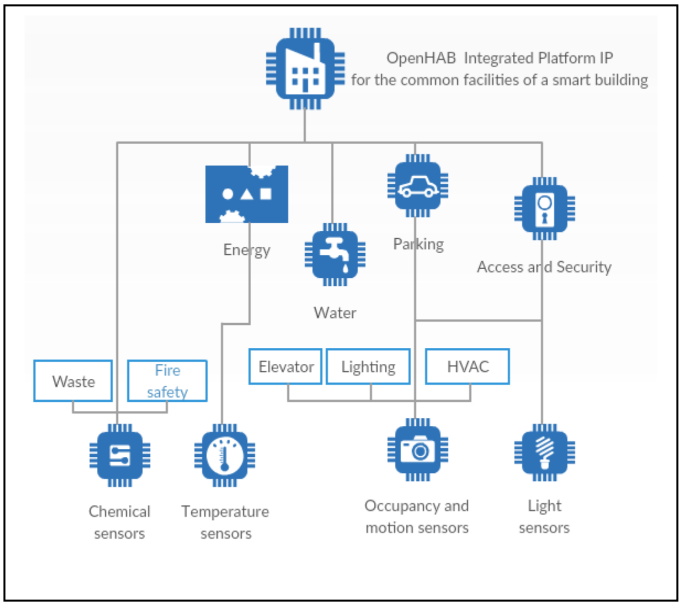

Fig. 1. Open Source Software Architecture for Smart Homes

OpenHAB [4] is a fully open source software for integrating different home automation systems and technologies into one single solution that allows automation rules and that provides uniform user interfaces. OpenHAB is designed to be vendor-neutral as well as hardware/protocol-agnostic, and can run on any device that can run a JVM (Linux, Mac, Windows).

OpenHAB comes with different web-based GUIs as well as native GUIs for iOS and Android; and it is easily extensible to integrate with new systems and devices, providing APIs for being integrated in other systems: many home automation technologies and devices are already integrated and compatible with OpenHAB [15] as shown in Table 1.

OpenHAB has been designed to provide a uniform interface to users to connect and manage different heterogenous smart home devices. Further steps need to be done to extend it for managing a whole smart-building, where along with single homes/units there are common areas (e.g. lifts, roof, basement, stairs) that can be enhanced with sensors.

Table 1 Compatible devices with OpenHAB

Sector	Compatible devices with OpenHAB
Control	Push Button / Switches / Input devices
	Remote Control
	I/O Relay Board / Output Devices
	Blinds
	Motor / Drives (Control Windows / Blinds)
DMX	DMX / Network
HVAC	HVAC Controls
	Humidity Sensor
	Temp Sensor
	HVAC Controls
Lighting	Light Switches
	Dimmer Switches
	RGB Wireless Controllers
Metering	Electrical Usage
Safety	Smoke Detectors
	Weather Stations
Security	Motion Sensors
	Contact Switches
	Tilt Sensors (Mercury Switch)
Tablets / Touch Screens	LED Displays

III. SOFTWARE ARCHITECTURE FOR SMART BUILDINGS

OpenHAB was designed for smart home applications but to address the needs of smart buildings we propose an extended software architecture where different openHAB units can be coordinated by a Smart Building Controller (SBC) which is responsible for the overall building (see Figure 2). In this architecture the common areas like garden, parking, roof or elevators can be considered as different special openHAB units managed by the SBC.

The architecture consists of three layers: sensors/actuators, openHAB middleware acting as smart home controllers, and the application layer where SBC also controls the Data Store and the Business Process Manager (BPM). The sensors are responsible for collecting raw data from the physical environment and send it to the respective openHAB controller; based on the received data the control center generates feedback and send it to the actuators which modify the physical state [39].

The Data Store can be any cloud computing platform collecting data from the sensors and from other third-party services or feeds from the internet, that can be integrated in the architecture. OpenStack [10] is used as Data Store as it is a cloud operating system that controls large pools of computing, storage, and networking resources throughout a private datacenter.

In smart home systems, intelligent services, represented with rule-sets, are realized by analyzing sensors data and executing rules. OpenHAB has a powerful rule engine for automation needs, that can be utilized to program the intelligent behavior of the smart home system with a set of Event-Condition-Action (ECA) rules.

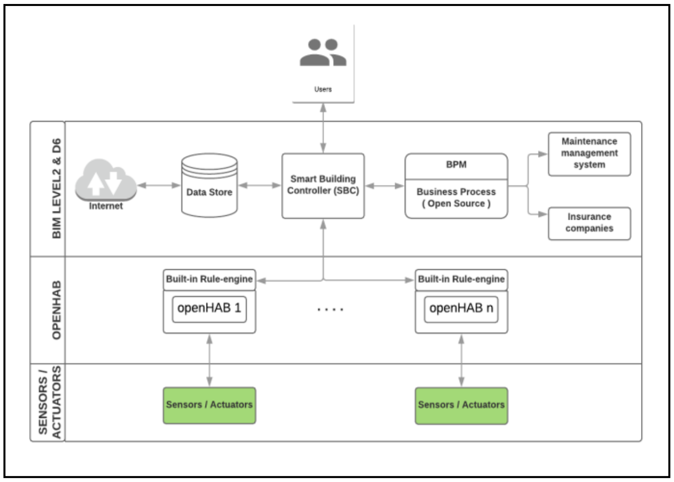

Fig. 2. Open Source Software Architecture for Smart Buildings

Similarly, the SBC contains a higher-level smart building rule engine able to correlate events from the different sensors in the smart homes via their respective openHAB units: for example, if a light sensor detects a failure in a particular part of the building it can trigger the lights maintenance process by sending a message to Business Process Management (BPM) engine: this will create a new business process instance to monitor and track the different tasks involved in the corresponding maintenance process defined by the Maintenance Management System. Moreover, another type of business process can be triggered for example when water faults are detected, to start a process with insurance companies to claim refunds in case a device failure causes damages and such device is still under warranty or it has been insured.

Bonita [5] is one of the many open source Business Process Management (BPM) tools, that can be used to design, connect, execute, monitor business processes defined using the BPMN2 [6] standard notation. A business process execution engine has integration capabilities to connect applications with third party services, business data modeling tool, advanced monitoring and reporting solutions.

Enacting rules and business processes on such heterogenous datasets requires a common standard data representation: a solution can be based on OpenBIM [7], a universal approach for collaborative design, realization and operation of buildings based on open standards and workflows. Industry Foundation Classes (IFC) is a common data schema proposed by buildingSMART [8] as a standardization effort for sharing of machine-readable information throughout the lifecycle of any built environment asset, throughout the design, procurement, construction, maintenance and operation phases. The IFC is one of the most utilized XML-based data standards proposed by the buildingSMART consortium, providing more data than the BIM model [9]. Each buildingSMART standard will be translated into an ISO and CEN standard, and it exists to perform different functions in the delivery and support of assets in the built environment.

All these building's data must be safely stored in a cloud computing platform, such as an OpenStack data center, that could host several OpenBIM databases for multiple units in the building, automatically updated with data collected from sensors. Such data can be used, for example, to support Facilities Management (FM) operations, which includes but not limited to maintenance and lifespans of different components of the building. The part of BIM which is responsible for collecting such kind of data is BIM 6D (6th dimension) [14]. Such aggregated data will also serve the purpose of creating an energy performance profile to the building, which could be used for further sustainability and energy efficiency analysis and could be used to estimate the annual energy needs [15]. Big Data analytics applications, for example based on Hadoop [11], could be run to correlate data among different units and to calculate overall metrics such as energy and water consumption of the building.

Different types of users (smart home users, owners, maintenance team, safety officials) can have a different type of access interfaces to the system (tailored to their technical skills) and something can be done to enable end user service creation with visual editors and user-friendly GUIs, following existing model-driven architecture approaches [50], able to generate platform-specific languages (such as openHAB rule sets) from visual diagrams specifications.

Smart buildings have several sub-systems: fire, air conditioning, door controls; each of them has its own safety regulation and standardization and an open problem is how to extend such safety compliance regulations to consider such new attack scenarios on smart buildings [46][47]. We aim at detecting some known attack scenarios with the rule engines in our software architecture. The following subsection describe an attack from literature that can be performed with misconfiguration of a boiler [45].

A. Preventing misconfigurations from destroying a Boiler

A boiler is a closed pressure vessel in which water is used to heat a building, while a furnace uses warm air. Once in the CPS, a hacker can send blocking error codes to the boiler to shut it down or stopping the feed water while it is permitted to boil dry; in this case, the feed water is then sent into that empty boiler, and such a small quantity of incoming water instantly boils on contact with the superheated metal shell and leads to an explosion that cannot be controlled even by steam safety valves. The most dangerous situation is a fuel explosion in a boiler. Conditions can be created for an explosion to occur by a hacker maliciously changing the configuration profile (the operating parameters) so that the CPS "thinks" the boiler is operating properly when in fact it is exceeding manufacturer settings and no alarm would be raised [45].

IV. Related Works

There are many examples of proprietary software products for the internet of things not only in smart building environment but also, for industrial, mobility and healthcare services. One industrial product is MindSphere from Siemens [18], an "open IoT operating system" based on a cloud Platform as a Service (PaaS), with high ability to connect with IoT machines seamlessly, and also with third-party services. Another commercial product is KEPServerEX from Kepware [19], focused on Industrial Internet of things (IIOT) and providing a high connectivity platform for device-to-cloud interoperability.

Cyber Physical Systems have been used for space utilization and optimization tools in smart cities, using automated rule system [30], automated operational management [31], real-time systems monitoring [32], management and temperature prediction were proposed, all to increase comfort while economizing energy [31].

Many approaches were introduced to implement smarter, more efficient and more automated energy management systems by using hybrid power grids controlled by real-time CPS [23][24][25][26][27][28]. For example, according to Germany Trade and Invest [11]. CPS are expected to reduce CO_2 emission levels by more than 41 million tons in Germany by 2020 by implementing intelligent building climate management systems. Furthermore, forecasts show that smart building adaption in Germany will reduce 45% global energy consumption increase by 2025.

Cyber Physical Systems have been used to detect human behavior modeling and activity interpretation systems [33] similarly to context-aware systems based on mobile phone usage [51]. A localization approach was introduced as tracking systems based on CPS [34] to produce location-based services [48]: a database was built and Markov-chain prediction model was used to assist the positioning based on the stored data [26]. CPS is a component of the Building Management Systems (BMS) responsible could function as fault detection and diagnosis tool in the system [35], aiming to enhance maintenance services and reduce its cost [36].

CPS is an active area of research with significant importance for the industry. Although a lot of progress has been done, CPS is not ready yet for critical mission applications or advanced systems management [37]. According to [38], challenges in CPS related to safety, security, privacy and some technical, economic and social barriers are needed to be addressed.

Real-Time Cyber-Physical Systems (R-TCPS) will compromise safety constraints and might have life-threatening consequences in case of missing time deadlines. Time is a critical parameter in the context of the quality of data in real-time CPS [1], and ensuring data quality in Cyber-Physical Systems (CPS) is a challenge that have not been addressed yet. The lifetime of data has not been investigated enough especially in smart cities and smart buildings scenarios, in which data are valid in the sensing time only, and the integrity of such kind of data is so crucial specially in critical mission systems. The data quality should be properly represented by identifying some of its characteristics like: data lifetime, source (a sensor, service, human interaction...etc.), accuracy, sampling frequency ...etc. while currently most of CPS systems assume that all of the received data are correct, more action is needed to meet higher criteria to ensure data quality requirements.

Many scenarios ware suggested to improve the data quality of the real-time CPS. An integrated IoT Big Data Analytic (IBDA) framework proposed for storing and analyzing real time data generated from sensors deployed inside the smart building [27], However, their main research focus was to address the processing of a large volume of real-time data in smart buildings.

Another approach proved with implementation that using a clock synchronization module based on NTP protocol was reliable with suitable error rates for CPS system [41], but the research was more in the context of enhancing the reliability of RFID sensors in smart cities scenarios without referring to the other components of CPS (Control centers, actuators and network) where the issues on data quality may increase.

Machine learning as a solution was proposed to enhance the reliability of management response in real-time power systems [42], the study used machine learning to build a machine learning model, the model successfully predicted the real-time reliability management costs. The goal of such research was to predict outcomes of real-time systems rather than making real-time control decisions.

Fault detection technique based on machine learning [43] could be applied to detect and track fault data injection attacks (for security propose) in real-time vehicular cyber-physical systems, and a decision support system was proposed to reduce the probability of any consequent accident. Although, the principle has been applied to vehicular CPS successfully but, this is not necessarily the case in smart cities, not because of the nature of the vehicular CPS comparing to the nature of facilities in smart cities but because of the adopted approach in the study to achieve the results, which is based on the interactions between the moving vehicles and the distance measurements and deceleration of the leading vehicle.

Regarding end user service creation of smart building services and maintenance processes, different visual languages have been used in different domains such as telecom [48], environment monitoring [49], and web services composition [52].

V. Conclusions and Future works

Intelligent services can be built in OpenHAB with a set of rules running in its rule engine, but badly-designed rules can conflict with the smart-building rules defined by the management in the SBC controller, bringing malfunctions in the system; a solution based on anomaly detection and rule conflict detection has been proposed [14], but more work needs to be done to scale up these types of approaches to a smart building scenario.

BPMs can be federated to coordinate more complex business processes cutting across different domains and systems, by implementing the different interaction models specified by the WfMC standard [13]. Such interoperability standard models can be taken as inspiration to design the interaction between different openHAB smart buildings in the same area, or between different business process engines executing maintenance processes involving different companies, and thus running across different BPM engines.

A future line of research will focus on the creation of a visual editor of smart building processes and services based on ECA rules, their automatic deployment on different units.

There is still a lot of work to improve CPS security [22], and future work will try to implement a rule-based detection of violations of security and safety system based on a formal model of cyber-physical attacks [44].

Finally, ensuring data quality in a smart building environment is a challenge [16], as their accuracy, lifetime, location and reliability are a necessary condition for implementing advanced scenarios such as the automated enactment of insurance claims with smart contracts based on a blockchain system verifying data provenance and integrity.

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