Low Cost Integration of IoT Technologies for Building Automation

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***Abstract*—Internet of Things (IoT) envisages a reality in which people and objects are interconnected in such a way that a series of services, previously unthinkable, become real. The impact of IoT technologies is already tangible in industry, particularly under the Industry 4.0 initiative, but yet far to be fully exploited in other areas, such as building automation. This paper highlights the importance of using IoT and other emergent technologies to develop building automation applications that serves as base in smart cities, particularly supporting the interoperability among home automation solutions provided by different manufacturers. For this purpose, a low cost IoT enabler solution for building automation is presented, based on the use of cyber-physical systems, as backbone to integrate different IoT technologies and building automation technologies. The proposed approach was successfully implemented in an open space laboratory.**

***Index Terms*—Cyber-Physical System, Building Automation, Multi-heterogeneous technology integration**

I. Introduction

Every day we are increasingly surrounded by electronic devices connected to the Internet, with the goal to offer better services and applications. Home and building automation is no exception. What in the past started with the automation of lights and blinds, has evolved to support in an integrated manner the comfort, security and energy efficiency, by controlling, among others, the temperature, humidity and lights according to the users' profiles.

Home appliances are not exempt from these developments, since they are also connected to the Internet and provide services such as information or alarms, taking advantage of the benefits of the use of Internet of Things (IoT). As examples, a refrigerator can send a text message to the owner saying that there are yogurts closed to expire, or the kitchen can warn the residents of the house that they have left the gas open, allowing them to can remotely shut it off.

A Building Automation System (BAS), or a Building Automation Control System (BACS), is a centralized control structure aiming to reach comfort, security and energy efficiency in the building. According to [1], information technology systems are essential for an intelligent BAS, but they are not enough on its own, being required to be properly configured and customized according to the users' needs, fully integrated with the building facilities and with each other, as well as commissioned and maintained to guarantee the expected behavior. A building won't be truly intelligent unless the systems are working properly [1].

As previously mentioned, the use of intelligent BAS allows not only the energy savings but also the increase of the users' comfort, by controlling of the heating, ventilation and air conditioning (HVAC) systems. Although, with the technological advances, BAS has expanded its coverage to more types of building systems, such as lightning and security (intrusion, re, smoke detection, gas leaks, water ooding) [2]. Aiming to simplify the users' lives, BAS also provides a remote-control feature, allowing them to initiate procedures even before they reach the building or start/stop devices remotely.

This scenario may seem perfect, but there are several technological drawbacks to overcome. Particularly, it is necessary to integrate and orchestrate all services, applications and technologies disposed in the building, bearing in mind that they are based on different IoT technology providers. Another problem is the increase of complexity in the control of such heterogeneous building automation environment. In addition, building automation is linked to smart cities, and issues such as sustainability and energy efficiency are attracting attention. Nearly Zero Energy Building (nZEB) [3] is an example, where the efficient use of resources and the overall performance are the forefront. However, there are still efforts for integrating these concepts with the objectives of smart cities [4].

Cyber Physical Systems (CPS) is a concept that is being successfully used in other heterogeneous and complex contexts, such as smart manufacturing [5] or smartgrids [6]. CPS integrate computational applications with physical devices, designed as a network of cyber and physical elements interacting between them [7]. CPS are seem as the backbone to implement such complex and large scale systems, aligned with the digital transformation principles, complemented with several emerging ICT and artificial intelligence (AI) technologies, namely IoT, Multi-Agent Systems (MAS), cloud computing, Big data, machine learning (ML), advanced data analytics and virtual/augmented reality [8].

The use of MAS allows the development of large-scale

978-1-7281-4878-6/19/$31.00 ©2019 IEEE

complex engineering problems, as smart cities and building automation are, by decentralizing the control functions over distributed and intelligent software agents, that cooperate together to achieve the system goals. The versability of MAS is suitable to develop intelligent and distributed solutions that couple with such important requirements, namely modularity, complexity, heterogeneity, scalability and reconfiguration.

Aiming to face these interoperable, smart and complex scenarios in the building automation field, this work proposes a low cost CPS solution that integrates different IoT technologies in a symbiotic manner to develop smart building automation applications. This solution, based on multi-agent systems and IoT, achieves an easy integration of building automation technologies from different vendors (not compatible with each other) with customized IoT sensors and actuators in a heterogeneous multi-technology environment. The proposed approach was implemented in an open space laboratory to automatically control the comfort of the space according to the users' profiles.

The remaining paper is organized as follows. Section II reviews some technologies for building automation and IoT enablers. Section III presents the proposed CPS architecture for building automation and Section IV describes the experimental implementation in a laboratory space and discusses the achieved results. Finally, Section V rounds up the paper with the conclusions and points out some future work.

II. Supporting Technologies for Building Automation

An intelligent building needs sensors and actuators throughout the building to offer a more comfortable and secure ambient for the users. While sensors are devices aimed to measure and monitor variables in the building, being the eyes and ears of the system, the actuators are the ones that have the possibility to modify the environment, i.e. acting as the hands. As brought up before, all these devices have to be interconnected with the control units, creating a network to carry out the home automation.

A. Architectures for Building Automation

Sensors and actuators are at the core of intelligent building automation, however, their collaborative work requires the use of technologies that allow the communication between them. Among the several existing communication technologies for building automation, the following ones can be referred (see Table I for a comparative analysis):

- KNX [9]: standardized decentralized OSI-based network communication protocol, that uses dual wire bus or a wireless to connect the devices [10].
- Insteon [11]: home automation network technology that enables devices to operate through RF or power lines [10]. Administrative devices are not required since each device can control or be controlled by each other [11].
- LonWorks [12]: known as Local Operating Network, it works similarly as the KNX technology, allowing the communication via a wire bus [12].

Table I
Building Automation Technologies

	Infrastructure	Data Rate	Nodes
X10	Power line	20 bps	256 [16]
KNX	Distributed bus	16.4 Kbps [16]	65536
Insteon	Power line and/or Wireless	38.4 Kbps [17]	Unlimited
LonWorks	Distributed bus	79 Kbps	32000
Zigbee	Wireless	250 Kbps	240
Z-Wave	Wireless	100 Kbps	232

- ZigBee [13]: an IEEE 802.15.4 standard for low-power, low data rate and low complexity wireless communication between small devices [10].
- Z-Wave [14]: uses the communication via RF in a sub-gigahertz frequency range [10] and uses the same encryption technologies as the online banking [14].
- X10 [15]: an international and open industry standard that uses power line cables and communicates through radio frequency (RF) digital signal bundles [10].

B. IoT Communication Protocols and Technologies

IoT communication protocols are used to support the connection between devices, being responsible for exchanging data between two endpoints, being them users and servers or users to users [18]. Some technologies are adequate to work within a limited area, but currently, there is a need to cover wide-areas that require the use of technologies that support long distances and low power consumption, such as e.g., LoRa, LTE and SigFox. The use of one technology is dependent of the application, being the following, the most promising ones:

- CoAP (Constrained Application Protocol) [19]: a document transfer protocol as HTTP, but conceived for constrained devices. It supports multi-cast addressing enabling a single request to be issued to multiple CoAP devices concurrently over UDP messages, not TCP.
- MQTT (Message Queuing Telemetry Transport) [20]: an open standard designed for machine to machine (M2M) communication over TCP and using the publish/subscribe schema, where sensors are clients of a server.
- DDS (Data Distribution Service) [21]: peer to peer protocol over TCP or UDP that provides high performance and interoperable data exchange between publishers and subscribers.
- XMPP (Extensible Messaging and Presence Protocol) [18]: designed to seek the online presence and for instant messaging applications, based on the Extensible Markup Language (XML).
- AMQP (Advanced Message Queuing Protocol) [22]: a lightweight M2M protocol designed mostly for security and reliability, which uses TLS/SSL and SASL for security and TCP as the default transport protocol.

C. Low Cost IoT Technology Enablers

The evolution of computational power allows the emergence of low cost microcomputers featured enough to enable the spreading of IoT. Moreover, these microcomputers include

Table II
COMPARATIVE OF IOT PLATFORM ENABLERS

	Raspberry Pi 3	BeagleBone Black	Arduino Uno
Architecture	ARM Cortex-A53	ARM Cortex-A8	RISC
Cores	4	1	1
Frequency	1.4 GHz	1 GHz	16 MHz
RAM	1 GB	512MB	2MB
Connectivity	Ethernet/Wi-Fi	Ethernet	None
Price	50€	65€	20€

general purpose input/output (GPIO) pins that allow to physically interact with their surrounding environments. GPIO pins can be used as digital inputs or outputs in first instance, but also reproduce communication protocols as serial ports, Inter-Integrated Circuit (I2C) or Serial Peripherical Interface (SPI). In this way, they can take advance of existing shields and expand their capabilities with analog inputs/outputs.

Two of these single board computers are the Raspberry Pi and the Beaglebone Black. Both of them are development platforms running embedded Linux distribution with very active communities of developers helping to spread their functionalities. Table II summarizes the specifications of both single-board computers, which constitute low cost IoT enablers, and also includes Arduino Uno, as one of the most extended open-source platforms that by means of dedicated shields expands their features with Ethernet or WiFi communications in addition to a great variety of available sensors.

D. Existing IoT in Building Automation

The use of IoT in building automation has been widely explored in literature. As example, Wang et al. [23] developed a smart control system based on a custom wireless sensor and actuator network connected to the Internet. This solution provided services to the users, but did not use standard technologies or communications. Jung et al. [24] discuss the use of IPv6 as an open protocol allowing the interconection of interoperable devices. Minoli et al. [25] present a study of the opportunities and challenges for the use of IoT in building automation field in terms of energy optimization and building management, concluding that standardization and cybersecurity are the main issues to be solved. Lilis et al. [26] also highlight the interoperability challenges, where even products that follow the same standards but from different vendors are not compatible. They argued the use of Internet devices connected in all levels until reach the Web of Things (WoT). As conclusion, it is noticed that research works reported in the literature sustain the use of IoT in BAS but warns about interoperability issues.

III. CYBER-PHYSICAL SYSTEM ARCHITECTURE FOR BUILDING AUTOMATION

As previously described, there are many technology providers for home automation that are, unfortunately, not compatible with each other. Since a BAC is an installation comprising heterogeneous technologies from different vendors, it is necessary to interconnect all these solutions and manage the complexity of a smart city formed by smart buildings. The proposed approach to this challenge is based on a CPS that uses IoT technologies to interconnect the building automation devices (e.g., sensors and actuators) and a MAS to distribute and decentralize the monitoring and control functionalities, as illustrated in Figure 1.

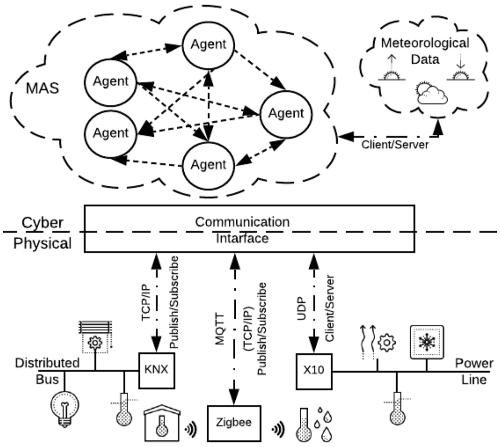

Figure 1. Cyber-physical system architecture for building automation.

A. Physical System Architecture

All the sensors and actuators installed in a building will form the physical elements of the system. One powerful fact is that devices are not fixed in number, neither in location, which means that the architecture can be expanded regarding to the needs or the required performance. The architecture will be formed by devices following one of the technologies conceived for home or building automation enhanced by custom sensors running over open platforms, such as Arduino or Raspberry Pi, and several DB, exploiting the advantages of IoT.

B. Logical System Architecture

As a CPS, the architecture considers a computational node associated to each physical asset of the building system, interconnected through a proper network. For this purpose, MAS are used to implement these distributed, autonomous and cooperative computational control nodes, which act at the same level, without a coordinator or central ruler guiding the performance of the system.

The agent-based model comprises three different types of agents: users, actuators and sensors. These agents interact by offering services between them to achieve a defined set of conditions inside a home or building. The user agent interacts with the user by a human machine interface (HMI), and is responsible to represent the wishes of the user in terms of comfort and security parameters to be used in the building. Actuator agents represent the several actuators disposed in the building and are responsible to influence the physical world, e.g., opening/closing doors or windows and starting/stopping the HVAC system according to the objectives and the current environment status. The information of the surrounding environment, e.g., temperature, light or CO concentration, is sensed by sensors, which are represented by sensor agents.

The number of agents is dependent of the scenario and the needs of the user. As example, in a large room or a long aisle, it may be necessary to include more than one agent sensor to allow the correct operation of the system.

C. Interaction Among Agents

The overall system behaviour emerges from the interaction among the individual distributed agents, each one contributing with its knowledge and skills. Figure 2 shows an example of the interaction among agents, related to the situation when a setpoint operation is changed.

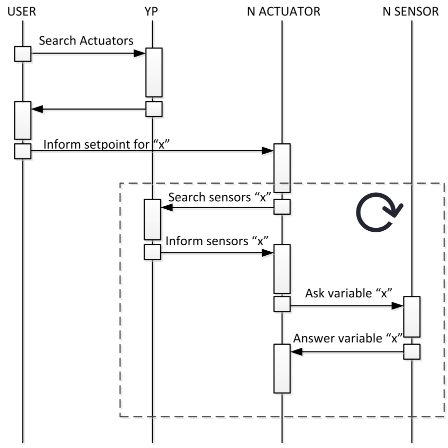

Figure 2. Interactions among agents for a setpoint change.

Briefly, when a person desires to modify some parameters in a room or building, its intention is communicated to the user agent. The user agent looks for the available actuator agents in that room or building through a search in the directory facilitator (i.e. the yellow pages service). Once the user agent knows which actuator agents are in the room, it informs them of its desires, e.g., a temperature of 25°C. When the actuator agents receive the message, they request to sensor agents information about the level of the parameter at hand, process the incoming information, and act accordingly to produce a change in the environment matching the desires of the user agent, and therefore of the room's inhabitants.

IV. Experimental Implementation

An experimental implementation of the CPS architecture has been carried out at the Laboratory of Control, Automation and Robotics at Polytechnic Institute of Braganca, aiming to create a building automation system that integrates several technologies, that at first sight seem incompatible. In this test case, the comfort of the laboratory is controlled in terms of temperature, light and humidity.

A. Implementation

A large number of sensors and actuators were installed in the laboratory, as well as intelligent agents for their control, as illustrated in Figure 3.

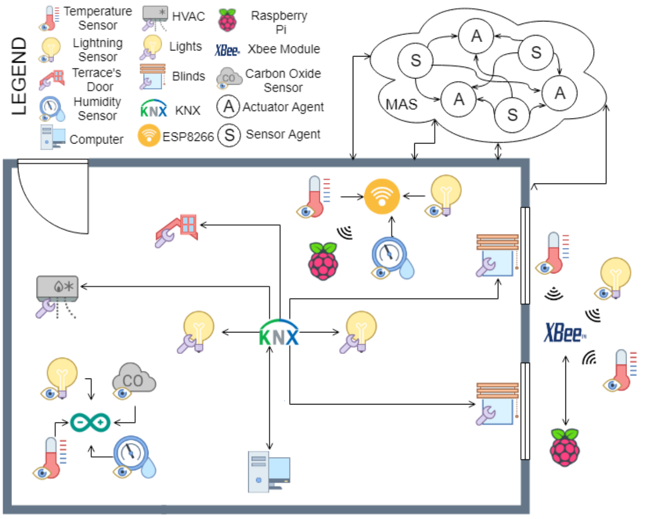

Figure 3. Distribution of sensors, actuators and IoT technologies in the laboratory (icons from [27]).

Besides the user agents, that are as many as the number of users, the agent-based model that controls the laboratory environment comprises the following set of agents:

- 10 sensor agents (2 to sense the temperature inside the laboratory, 2 to sense the humidity inside the laboratory, 2 to measure the light inside the laboratory, 2 to sense the temperature outside the laboratory, 1 to sense the light outside the laboratory, and 1 to sense the carbon monoxide inside the laboratory).
- 6 actuator agents (1 to actuate the HVAC system, 1 to open/close the terrace's window in the laboratory, 2 to actuate the lights in the laboratory, 2 to actuate the blinds in the laboratory).

This agent-based model was implemented using the JADE framework [28] over Java, which is compliant with the Foundation for Intelligent Physical Agents (FIPA) guidelines and provides several important features like the directory facilitator (DF), which acts as the yellow pages, and the FIPA Agent Communication Language (ACL).

The structure of each agent follows the behaviour schema defined by JADE. The setting up behaviour initializes the profile, parses the set of services that the agent offers, registers these services in the DF of the JADE platform and launches a set of behaviours that will be responsible to regulate the operation of the agent. Among others, two main behaviors are present in the agents' structure: a behaviour to handle the negotiation with the other agents and a behaviour to establish the interaction with the physical world (i.e. with sensors and actuators). The agents are running in Raspberry Pi microcomputers connected to a TCP/IP network using wireless or wired connection. The exchange of messages for the negotiation uses the FIPA-ACL and follow the interaction pattern presented in the Figure 2.

The behaviors regarding the interaction with the physical world, are related to the interconnection with sensors to get the sensing data and with the actuators to set the commands. In the test case at hand, the temperature and light levels from the outside were measured from a Xbee wireless network that is attached to a Raspberry Pi. These values are communicated through an UART port and follows the communication protocol defined in the Xbee's API. The behaviour of the agent handles the communication between the main serial port of the Raspberry Pi and the Xbee module using J4PI libraries. Another important point is related to a MySQL database that hosts the information coming from an Arduino Uno, connected to a computer that is running a Node-RED program. This Arduino has attached an one-wire sensor AM2302 that measures humidity, temperature, light and the levels of carbon monoxide in the laboratory.

The wireless module ESP8266 connects another AM2302 sensor, sending the information regarding to humidity, temperature, light and carbon monoxide to a MQTT broker running in a Raspberry Pi. The use of the MQTT protocol allows to execute the publish/subscribe interaction schema. The sensor agent collecting the information from this module implements a behavior that gets the data coming to the subscribed MQTT topics by means of the client Paho by Java.

In the actuators side, a behavior on the agent was implemented to connect a computer to a KNX home automation system controlling lights, blinds, and fan coils (fan speed, heat and cold selection). The Calimero project to Java was used to accomplish the control of the KNX network. A relay module was attached to another actuator agent to control the spare fans in the laboratory. On this case, the behavior of the agent controls the GPIOs connected to the relays using J4PI libraries.

B. Controlling Rules

The automation to achieve the operation and comfort required by the users is performed by the actuator agents that embed some control rules that change according to the nature of them. Since the control system is decentralized, these rules were implemented in the several agents, e.g. embedding Node-Red applications. Figure 4 illustrates the layout of the program for an actuator agent that considers the incoming data from the sensor agents and the temperature setpoint chosen by the user to run the control logic.

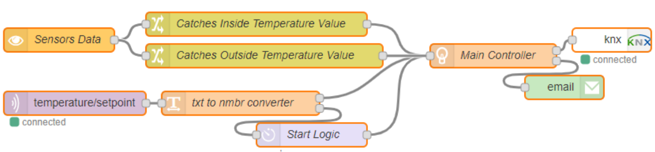

Figure 4. Node-Red application running in actuator agents.

Considering that the goal is to maintain a certain level of temperature, required by the user, with a minimal power consumption, several rules were designed, controlling both blinds and the HVAC system that are interconnected through KNX. The blinds behaviour, illustrated in Figure 5, was designed to attend the following rules:

- **Open** if setpoint is above the current temperature and exterior temperature is High, or setpoint is below the current temperature and exterior temperature is Low;
- **Close** if setpoint is above the current temperature and the exterior temperature is Low, or setpoint is below the current temperature and exterior temperature is High.

```
if (intemp>setpoint)
{
    if(extemp>20){
        msg1={payload:{"dstgad":"2/0/0","value":"0","dpt":"3"}};
        msg2={payload:{"Warn":"Blinds Closing"}};
        return [msg1, msg2];}
    if(extemp<15){
        msg1={payload:{"dstgad":"2/0/0","value":"1","dpt":"3"}};
        msg2={payload:{"Warn":"Blinds Opening"}};
        return [msg1, msg2];}
}
if (intemp<setpoint)
{
    if(extemp>20){
        msg1={payload:{"dstgad":"2/0/0","value":"1","dpt":"3"}};
        msg2={payload:{"Warn":"Blinds Opening"}};
        return [msg1, msg2];}
    if(extemp<15){
        msg1={payload:{"dstgad":"2/0/0","value":"0","dpt":"3"}};
        msg2={payload:{"Warn":"Blinds Closing"}};
        return [msg1, msg2];}
}
```

Figure 5. Two example rules implemented in Node-Red.

More sophisticated control rules can be included, e.g., based on proportional, integrative and derivative (PID) control or fuzzy algorithms, however, the aim of this paper is not in the rules design but instead in the integration of the different heterogeneous technologies existing in the installation.

C. Critical Analysis of Results

The test case allowed to prove the integration and coordination of a heterogeneous multi-technology environment involving Xbee sensors, Wifi sensors, MQTT, MySQL database and KNX network running over a common platform. In fact, the implemented solution was deeply tested under daily operation and allowed to verify its correctness under different condition changes imposed by the users.

In normal operation, the user agents receive orders to set the temperature to a different value than the existing in the laboratory. Then, sensor and actuator agents start to interact to find which actuators are able to control the temperature in the room according to the desired setpoint. After the negotiation between agents takes place, the actuator agent turns on the HVAC until the setpoint is reached. The same procedure is executed in case the user wants to modify the light setpoint. This operation may look simple, and it can be argued that a simple HVAC by itself can perform as the presented proposal, nevertheless it states the foundations to create more complex environments, and more complex distributed control systems, especially when more than one actuator device is present in the system and can control the environment to achieve the modified setpoint.

A first testing scenario was performed to analyze the response time of the system in case of a condition change, namely the time required from the request of a new setpoint to the action performed in the physical world. In the situation presented, in which there are 16 agents interacting, the system responds in 329 ± 55 ms. It is really encouraging the fact that technologies from different vendors can really cooperate to reach a common objective in such a quick manner.

The second testing scenario is related to prove the scalability and pluggability on the fly. In this test, new sensors and actuators were plugged and unplugged at any time during the normal system operation without the need to stop, re-program/reconfigure and restart the system. Therefore, it is possible to include new sensors or actuators at key locations to improve the performance or the precision of the control carried out at any time. Particularly, a maintenance operation that requires the replacement of a sensor/actuator can be done without interfering the normal functioning of the system, and without letting the building or a room without service. As it can be deduced, the responsible for the operation of the system does not have to schedule stops in the system for maintenance purposes, and the impact of disturbances is reduced.

From an economical point of view, a low cost integration of IoT Technologies has been reached, based on the use of open source software solutions and low cost hardware control boards, i.e., Arduino and Raspberry Pi.

V. Conclusions and Future Work

In this paper a low cost solution for the integration of multiple IoT technologies for building automation has been proposed. The proposal solution is a CPS comprising a network of logical entities implemented by using autonomous and cooperative agents, and physical elements interacting with the real world using diverse technologies and standards, such as Xbee, KNX, and MQTT. The agent-based system, implemented using JADE and running in Raspberry Pi microcomputers, acquires the information from the physical environment and modifies it through sensors and actuators agents, respectively. All the sensors and actuators are from different vendors and use diverse communication standards and protocols, being necessary to use an unified infrastructure to achieve interoperability between these devices.

The achieved results show the achievement of a multi-technological building automation system, taking advantage of the MAS inherent characteristics to reach important benefits, namely modularity, scalability, plugability, and reconfiguration. Future work is related to consider a larger scenario with more sensors and agents, to analyze the scalability and response time in such environments, as well as to consider more complex control rules.

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