A Holistic IoT-based Management Platform for Smart Environments

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***Abstract*—Internet of Things (IoT) is a vision towards Future Internet where "things" are provided with enough intelligence to communicate with each other without the human intervention. In the near future, the number of IoT-enabled nodes is expected to grow substantially, therefore the heterogeneous nature of implementations demands effective IoT deployments that ensure proper interoperability and reliability of network infrastructures. In this line, we present a holistic IoT-based platform to gather and analyze information, and propose concrete actions according to different goals in smart environments. This platform bases on the optimal integration and use of data collected from a plethora of different sources. It has been deployed in a real IoT context framed in the smart buildings field. For its validation and evaluation, a reference scenario for indoor energy efficiency and comfort has been considered, where a set of tests have been carried out to validate the building management techniques implemented to maintain user comfort while assuring a good energy balance.**

Keywords*—IoT; Smart Buildings; Energy Efficiency; Context Awareness.

I. Introduction

The widely used term of *Smart Environments* has finally become reality thanks, mainly, to recent advances in new Information and Communication Technologies (ICT). Nowadays, we are living in a world where everyday ordinary objects are potentially connected to the Internet thanks to the development of new sensing, wireless communication and Internet technologies. This emergent field where "smart things" are interconnected into a full ecosystem is called Internet of Things (IoT) [1]. Over 50 billion devices are expected to be connected following this paradigm by 2015. It represents the most promising trend towards transparent and seamless access to millions of smart devices and resources.

IoT has raised interest in many fields, both from the industrial sector, for which it is seen as a new market opportunity, and from researchers and public stakeholders, where IoT is seen as a tremendous experimentation field able to deal with major technological challenges worldwide. Energy efficiency, social exclusion or urbanization processes are some fundamental challenges gaining attention in this area. In this sense, different IoT application domains have been already proposed. But the heterogeneity of resources and service attributes, and the dynamicity of mobile environments, require efficient solutions that can discover services matching them to the data and capability requirements from users and different application contexts. To date, implementations of IoT architectures are confined to particular application areas and tailored to meet only limited requirements of specific applications, which do not interact with each other in a global and standardized way, as considered by the European Research Cluster on the Internet of Things (IERC) definition[1]. Hence, the complexity involved in data acquisition, quality control, context interpretation, decision support and action control, hinders the uptake and penetration of specific tailored services for IoT applications.

In order to overcome the technology and application domain boundaries, and to dynamically design and integrate new types of services, it is required to create a holistic platform that is able to gather and exploit data from sensors and actuators across domain boundaries that integrate different communication technologies and data formats. In this way, it would be possible to create and provide services and environments based on reliable IoT ecosystems both for enabling business processes and for creating socially aware user-centric domains. In this line, we present an IoT architecture for intelligent systems able to collect and analyze information from a vast number of sensors (considering individuals in this group), to carry out concrete actions according to different application domains. For that, this system provides an intelligent processing layer able to make decisions according to target goals identified in different smart environments, such as buildings, transportation, security, health assistance, etc. Besides, with the goal of offering in this paper a more detailed vision of the IoT architecture proposed, we describe a real deployment of this architecture in a specific smart scenario (smart buildings), and we show the evaluation tests carried out considering the particular indoor problem of providing energy efficiency and comfort in a reference automated building.

The rest of the paper is organized as follows: Section II presents an overview of current IoT deployments, both in the private and the public sectors. In Section III our holistic IoT-based platform is presented, which is able to provide intelligent management capabilities in different smart environments. In this way, in addition to describe its main capabilities, we

[1] http://www.internet-of-things-research.eu

describe the architecture of a case of study in a smart building. In Section IV we focus on this particular IoT scenario to validate the platform through a set of tests. Finally, Section V concludes the paper with a set of final remarks and presenting future lines.

II. Overview of current IoT deployments

As has been already said, for a lot of different aspects of modern live, the IoT enables a broad range of applications in the context of smart environments. For each of these applications it is necessary to understand the requirements to design an optimal interaction with humans, machines, context, etc., in order to understand the dependencies between the implemented systems and thus being able to optimize their interoperability. Looking at what is already available nowadays, the fact is that current IoT initiatives are in different stages of development. A lot of application scenarios have been already developed, as can be checked in the IoT-i project[2], nevertheless, there are still very few real solutions on the market. The reason could be the difficulty to deploy IoT solutions on a grand scale, since one has to face important challenges regarding communication issues, protocols, platforms, and data exchanges and processing. Thus, the IoT developments identified until now are mainly claimed by the private sector (industrial), on specific applications focused on solving some concrete and particular goals through little interoperable solutions. In this line, for instance, HP is leading an important IoT project based on a platform called CeNSE[3] (Central Nervous System for the Earth), whose goal is to create a worldwide network of sensors.

Therefore, to make platforms flexible, but also realistic and sustainable in time, IoT management frameworks have to be designed taking into account the specifics of different IoT devices, the contexts in which they are running, as well as the stakeholders' policies and requirements. New efforts are required to integrate and fine-tune technologies coming from different ambits, such as IETF or IEEE, for instance. Moreover, IoT systems are able to collect and organise live data from the real world to support sustainable developments and to transform the way people live and work, for example, accelerating the mission of cities, improving their mobility, through smart environments and governance, etc. It is clear that, while a large part of an IoT infrastructure will be formed by (wireless) sensors and actuators networks embedded in the environment (buildings, factories, etc.), the role of user nomadic terminals is crucial in this vision. Recent research on this field encompasses both the user opportunistic and participatory sensing techniques applicable in smart environments.

Bearing all these aspects in mind, it is evidenced the need of developing some control and monitoring schemes and decision-making systems based on intelligent information processing techniques. In addition, these systems must be extensible to services involved in different IoT application domains, like transport, water management, buildings, environmental monitoring, energy efficiency or social requirements. Apart from the current situation of real IoT deployments, a large number of proposals for IoT scenarios are available in the literature. The IERC proposes a categorizing scheme to get an overview of the huge amount of these scenarios. Another categorizing scheme was created by the IoT-i project, as part of its survey about IoT application scenarios. Both schemes are very similar, in which the main goal is to have a common structure for collecting and discussing these scenarios. Taking the IoT-i's proposal as reference, for instance, a set of IoT application scenarios are considered based on the expectation to have the highest business and societal impact. Main resulted scenarios after this analysis are: smart cities, smart homes, smart factories, culture and tourism, transportation, emergency, environment, user interaction, supply chain, retail, healthcare, agriculture and energy.

Currently there are proposed different efforts to support early IoT-based designs. From Europe, for instance, the IERC cluster was created a few years ago by the European Commission to provide a light-weight management approach for overcoming isolated, redundant research and knowledge barriers in IoT. Additionally, there are several ongoing IoT projects which require special mention. The IoT6 project[4] aims at exploiting the potential of IPv6 and related standards (6LoWPAN, CORE, COAP, etc.) to overcome current shortcomings and fragmentation of the Internet of Things. The IoT-A project[5] reckons a strong and exhaustive analysis of the state of the art for envisaging the superset of all possible functionalities, mechanisms and protocols that can be used for building IoT architectures able to show how interconnections could take place between different IoT applications. In the line of these two projects, we aim to fill the gap in current platforms to collect and analyze information, and then propose concrete actions to apply in different smart environments based on the IoT paradigm and current available technologies.

Our proposal integrates in an optimal way the data available in the environment, mainly offered by infrastructure sensors, users and the Internet, to provide smart services. A large part of our IoT infrastructure is composed of wired and wireless sensors, and actuator networks embedded in the environment, but users, through their interaction with the system, as well as the data provided by their wearable devices (e.g. mobile phones), also play a key role. All these aspects provide our proposal of platform with huge flexibility and scalability to be applied to different environments and to achieve different goals.

III. A holistic management system for smart environments

The IoT architecture proposed in this work is depicted in Figure 1. For the design of this architecture, as it has been already mentioned, we have especially taken into account the vision proposed by the IoT-A project. Following this approach, our IoT-based architecture promotes a high-level interoperability at the communication, information and service layers. Our approach is generic enough to be applicable in different smart environments such as intelligent transport systems, security, health assistance or smart buildings, among others.

The next parts of the section give more details about this architecture. At the same time, a reference case of study is

[2] http://www.iot-i.eu
[3] http://www.readwriteweb.com/archives/the_coming_data_explosion.php
[4] http://www.iot6.eu
[5] http://www.iot-a.eu

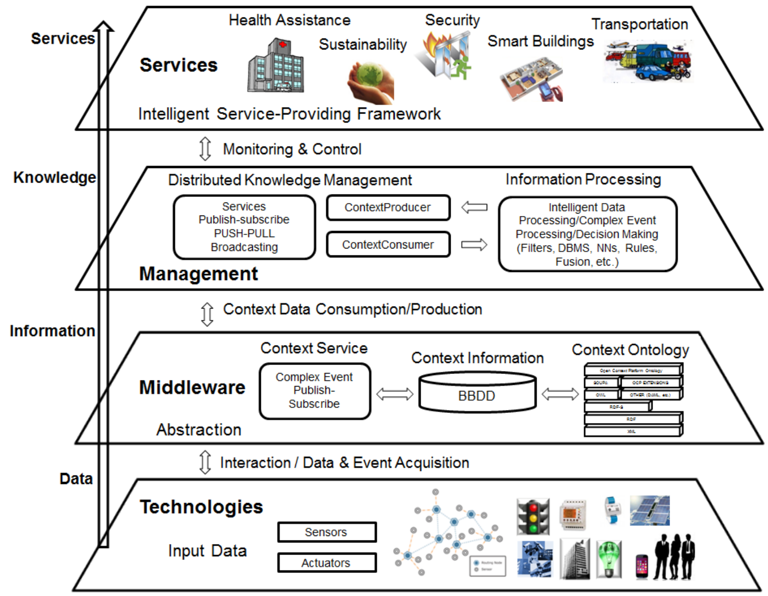

Figure 1. IoT Architecture for smart systems

presented, which consists in the practical application of this architecture in the smart buildings field.

A. Technologies layer

Looking at the lower part of Figure 1, input data are acquired from a plethora of sensor and network technologies such as Web, local and remote databases, wireless sensor networks or user tracking, all of them forming an IoT framework. Sensors and actuators can be self-configured and controlled remotely through the Internet, enabling a variety of monitoring and control applications.

Among previous works related with automation systems for smart buildings presented in literature, we take as reference the proposal given in [2], where the authors describe an automation system for smart homes on top of a sensor network. Although the goal pretended in this work is similar to the one aimed by our reference use case here presented, the system lacks on automation flexibility, since each node of the network only offers limited I/O capabilities through digital lines, there is not a local friendly interface for users in the house, and, what is most important, the integration of energy efficiency capabilities is in fact weak. The work presented in [3] is also based on a sensor network to cope with the building automation problem, but this time the messages of the routing protocol include monitoring information of the building. We present here a real and interoperable experience on a general purpose platform for building automation, which is able to address the problem of energy efficiency and comfort, monitoring and security issues, among others, by means of a flexible sensor architecture which allows the collection of data, and is able to control a wide range of automated parts of the building.

Our automation system, which is used to gather information from sensors and actuators allocated in the building, has been developed as a particular study case of our system in the University of Murcia in a testbed building[6]. The base system is known as *Domosec*, and its main components were presented in detail in [4]. Domosec has been used as the basis for an automation system able to monitor environmental parameters, gather data for tracking occupants, detect anomalies (such as fire and flooding in buildings), and take actions to deal with key efficiency requirements, such as saving power or water consumption. The main components of this architecture are the network of Home Automation Modules (HAM) and the SCADA (supervisory control and data acquisition). The HAM module comprises an embedded system connected to all the appliances, sensors and actuators of the various spaces of the building. These devices centralize the intelligence of each space, controlling the configuration of the installed devices. Additionally, the SCADA offers management and monitoring facilities through a connection with HAMs. Thus, all the environmental and location data measured by the deployed sensors are first available in HAMs and then reported to the SCADA, which maintains a global view of the whole infrastructure.

B. Middleware layer

This layer is responsible for the management of the information flows provided by different sources. The different information sources could be: sensors, data bases, web pages, etc., whose data and behavior can be controlled. These data sources can be enquired through several coordination mechanisms, for instance through publisher/subscriber methods. In our IoT-based architecture, we use the OCP platform (Open Context Platform), developed by the University of Murcia and further described in [5]. OCP is a middleware to develop context-aware applications, which is based on the paradigm of producer-consumer. Hence, the producer, in our case the Domosec system collecting information from the automated devices, adds information to the OCP. Meanwhile one or more consumers interested in some specific context parameters are notified about the changes performed in this information. The context information is collected in an ontology defined

[6]www.um.es/otri/?opc=cttfuentealamo

according to the model that represents the knowledge of the application domain, while a service to manage this information using OCP is used by consumers and producers of the context.

C. Management layer

This layer is responsible for processing the information extracted from the middleware and for making decisions according to the final application context. Then, a set of information processing techniques are applied to fuse, extract, contextualize and represent information for the transformation of massive data into useful knowledge that is also distributed. In this layer two phases can be distinguished. The first one acts as context consumer of the middleware, and intelligent data processing techniques are implemented over the data provided by the middleware layer. The second phase acts as context producer. In this stage, complex event and decision making processes are applied to support the service layer with useful knowledge. During this stage new context information can be generated, which is provided to the middleware for its registration in the ontology context (acting then as context producer). Therefore, different algorithms must be applied for the intelligent processing of data, events and decisions, depending on the final desired operation of the system (i.e. the addressed services).

Considering the specific application in the smart buildings context, in this layer it should be implemented the data processing techniques for covering, among others, security, tele-assistance, energy efficiency, comfort and remote control. In this context, intelligent decisions are made through behavior-based techniques to determine appropriate control actions, such as appliance and lights control, power energy management, air conditioning adjustment, etc.

D. Services layer

Finally, the specific features for service provisioning, which are abstracted from the final service implementations, can be found in the upper layer in Figure 1. This way our approach is to offer a framework with transparent access to the underlying functionalities to facilitate the development of different types of final applications. In order to provide a local human-machine interface (HMI) in our system, several control panels have been spread in the building to manage automated spaces. These comprise an embedded solution with an HMI adapted to the controlled devices.

Taking into account the services cited so far in the smart buildings context, it is important to remark the importance of achieving energy efficiency, since buildings represent one of the fields where sustainability must be taken into account, mainly due to the increasing amount of time that people spend indoors. Besides, buildings are an important energy consumption area worldwide, with a pronounced tendency in recent years. As a reference, in developed countries the electric consumption of buildings covers between 20% and 40% of the total. Nevertheless, in addition to the energy efficiency requirements of smart buildings, the quality of life of occupants should be also ensured through three basic factors: thermal comfort, indoor air quality and visual comfort [6]. Therefore, it is necessary to provide users with increased awareness (mainly concerning the energy they consume) and to permit them to control the underlying processes, empowering them to take active part in this IoT-based system.

Considering all these aspects, the reference case of study presented in this paper tackles with both energy efficiency and comfort in smart buildings. Thus, in the next section, the implementations carried out in the management layer of the proposed architecture for achieving these goals are detailed, together with the most important results obtained from the tests performed.

IV. System validation through a real use case deployment

A. Energy efficiency and comfort in smart buildings

Based on most advanced sensing technologies, smart buildings must be able to monitor status parameters, analyze these data and, finally, actuate to reach some objectives, but considering at the same time transversal and essential goals such as cost and, more recently, energy efficiency [7]. The latter is obviously interrelated to cost, but, in the last years, its influence in environment preservation has gained terrain. The main goal of the scenario here presented is to reduce the energy consumption of a smart building through efficient management of resources, while occupants comfort needs are satisfied at acceptable levels, being necessary to rely on multiple network accessible devices and services. Below we formulate the problem associated to the provision of these services in the smart buildings context.

1) Problem statement: a fundamental objective of smart buildings is to improve the inhabitant experience meanwhile it is ensured the building productivity. For example, incorporating mechanisms to make the most of the used energy, such as integrating its own energy sources and thus providing auto-sustainability in terms of energy consumption. The reduction of energy consumption is usually achieved by constantly sensing the relevant parameters of the environment (inside and outside the building), and by controlling the operation of automated devices that could save energy. This is done by matching the user needs with environmental conditions, and then aggregating different services so their combination fulfills the user needs while reducing energy consumption.

Buildings are far from being low power consuming infrastructures, even when the majority of their equipment are relatively low power devices. The number of desktops, monitors, laptops, phones, lights, etc. in buildings is really high, and the electricity bill must be inevitably expensive in large corporations or public institutions. A proposal for reducing power consumption while maintaining the comfort in buildings is through the proper management of consuming devices in accordance to natural resources and low-power measures. For example, we can easily consider issues such as the use of natural lighting or ventilation instead of artificial light and A/C, respectively. These issues are presented with more details in the next section.

2) Integrated solution in the IoT-based platform: as mentioned in Section III, the management layer of our system architecture is the responsible for carrying out the information processing required to make decisions that satisfy the final goals associated to the services implemented. Attending to our reference case of study, such decisions address the problem of saving energy in smart buildings while user comfort is maintained. For this management process, an important issue to be solved is the indoor localization problem, since having real-time information about user location is essential for deploying customized services according to user preferences or needs. For this reason, we have implemented a mechanism which provides localization of occupants by using RFID (Radio-Frequency Identification) and IR (Infra-Red) sensors deployed in the building [8]. In this way, it is possible to carry out control decisions that satisfy comfort requirements depending on the occupant location and the distribution of comfort appliances.

For the energy and comfort control in the building, we apply a combination of techniques based on behavior (*Behavior-based Mechanisms*) and computational intelligence [9]. For both modeling processes it is necessary to consider the data provided directly by users (through their interaction and/or their mobile phones), since in this way they can collaborate with the system by providing information about their comfort preferences or about the comfort conditions associated with a group. Finally, users can change the comfort conditions provided automatically by the system and, consequently, the system learns and auto-adjusts according to the changes.

The total variables controlled in our system are: user identifier, user interaction, user negotiation, environmental parameters, lighting level, generated energy value, energy consumption and electrical devices switched on. On the other hand, the outputs of our system are forwarded to the actuators deployed in the building, such as the regulation of heating/cooling systems and electric lighting. For that, we base our solution on the CEN standard EN 15251 [10], which specifies the design criteria to be used for dimensioning the energy system in buildings, establishing and defining the main input parameters for estimating building energy requirements, and evaluating the indoor environment (thermal and visual comfort, and indoor air quality).

The data processing mechanism implemented for the comfort and energy control system is able to learn and adapt itself on line and in real-time according to the users behavior and the environment. For that it is taken into account, mainly, comfort conditions of occupants provided through their interactions with the system, forecast of environmental parameters, and data about the real-time energy consumed and generated in the building.

B. System validation

The reference building where the proposed system is currently being evaluated it the Technology Transfer Centre at University of Murcia. It provides smart services such as lighting and HVAC control. The roof of the building is covered with solar panels, and all the rooms of the building have been automated (through an HAM unit) to optimize energy consumption using the intelligent management system presented above. Using this building as reference, an indoor characterization of different scenarios has been carried out, taking into account aspects related to comfort, energy-efficiency and occupants' behavior. Therefore, different representative environments similar to a home context are analyzed: a dining room, a corridor and an office. Each of these locations has different comfort requirements and a different distribution of HVAC and lighting appliances according to features such as natural light level, interior space activities and number of occupants. Our management system is in charge of changing the setting of the actuators (HVAC and lighting appliances) of each locations with the aim of saving energy while indoor comfort is insured according to the users preferences.

It is important to remark that, in order to assess a system characterised by the features described in this work, it is necessary to identify representative scenarios that capture the behavior of a large number of possible sensor network applications, user behaviors and environmental conditions. Furthermore, each simplification or adjustment in the system (different input data, rules, locations, comfort conditions, etc.) requires extensive testing and validation with respect to the environment chosen to carry out the evaluation. In addition, the system validation must be extended to cover different seasons in order to analyze its behavior according to different weather conditions during the year. The evaluation process of our system covers several months, although the aim is to provide data for several years.

Although time limitations have hindered the overall assessment of the system in terms of the above issues, we have evaluated the predictive models involved in the comfort and energy control system in order to identify notable aspects observed until now. Thus, we present here the main findings of the evaluation performed of the fuzzy model responsible for estimating the energy consumed during eight weeks of continuous operation of the system. For that, we use the information gathered about the energy consumption of the electrical devices involved in the tests performed, which is available through the Domosec platform. Then, by using (a) the different input data sets monitored in our system, (b) the estimated values of the energy consumption involved, and (c) the values of the real energy consumption measured a posteriori and stored in Domosec, we can analyze the fuzzy model performance in terms of errors involved in the energy consumption estimation process.

Figure 2 shows the computed error of this fuzzy model considering three representative environments in our reference building: the dining room, one of the offices and one of the corridors. As we can see, the error values obtained in these locations must be considered acceptable. Considering our results, the maximum error value predicting the energy consumption of the corridor during the 40 days of testing is about $47Wh/m^2$, which can be considered as insignificant against the average value of $718Wh/m^2$ of total energy consumed per day in this same location (i.e. in the corridor) measured during the previous year (2012). Besides, it is important to note that, as the knowledge generated in the system grows, our system is able to learn and adapt by itself, adjusting the models in real-time and on line. For this, both user interaction and environmental measurements are used to tune up the system, improving its performance at its operation time.

Moreover, during the tests we noticed a remarkable aspect related to the impact of user involvement in the system operation. As mentioned, occupants can interact with the system to change their comfort preferences or to communicate their degree of discomfort associated to some comfort conditions.

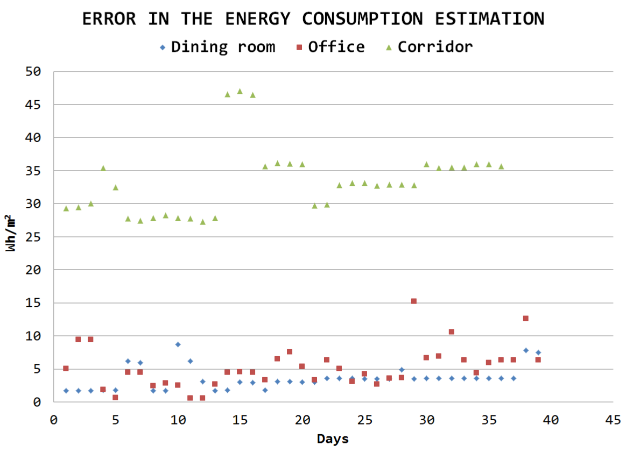

Figure 2. Error in the energy consumption estimation in the reference smart building

Most people usually ignore the energy implications associated with the selected comfort conditions, and some others are not sure about the proper comfort conditions applicable to their needs (for instance, depending on their activity type or activity level). Nevertheless, we observed that, when users receive feedback concerning the energy consumption as regards to their particular comfort conditions, they become more responsible, adjusting comfort parameters in a collaborative way to achieve higher energy efficiency levels. This was the case, for instance, when our system recommended that users should not switch on the lights when the natural lighting covers the necessities in one of the three spaces subject to study in the building.

V. CONCLUSIONS AND FUTURE WORK

With the proliferation of ICT solutions connected to the cloud in smart environments, proper data management platforms and interconnection strategies are needed to cope with the high data volumes expected and perform the necessary intelligent actions. IoT capabilities aims to bridge the gap between business services and the heterogeneity of networked sensors, actuators and objects, providing trust, user control and transparency when computerized nodes are accessed.

The platform proposed in this work is powered by IoT capabilities and provides a novel user-centric framework that deals with the issues of data collection, intelligent processing and representation of information, and proper service access to generated knowledge. The proposal, through a set of horizontal layers, supports a wide range of services envisaged in future ICT-enabled environments such as smart cities, intelligent transportation systems and building automation, among others.

Apart from the concept design, the applicability of the proposal has been demonstrated through a real instantiation in a concrete use case within the smart buildings domain. A real automated building has been set-up to gather sensor data for both monitoring the power consumption and tracing occupants following an IoT approach to access information sources. This data has been used to act on appliances in charge of maintaining the comfort conditions (lighting, temperature and air quality) with the goal of saving energy. Through the evaluation tests performed and the preliminary results obtained so far, we can state that our IoT-based proposal is able to cope with the heterogeneity of situations, thanks to the interoperability and flexibility of our layered system architecture, which count with a data management layer able to provide adjustment through its learning and adaptation engine. In the study case, different comfort profiles (such as those required for a dining room, an office and a corridor) have been covered successfully by our reference implementation. This feature is essential for being able to extrapolate its performance to other smart building contexts.

At the moment we are working towards large-scale experiments on mobile crowd-based sensing techniques for gathering data from occupants' devices. This information will complement the current data measured by our current building infrastructure. In addition, an ongoing study focuses on testing stressful scenarios that require the most of the algorithms and hardware considered in our deployment.

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