An Internet of Things based approach for Smart Home Management

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Abstract

The advent of the Internet of Things (IoT) paradigm has led to the construction of technological environments based on device communication. In this scenario, solutions have been developed for the intelligent management of various services, such as those related to Smart Cities. In such a scenario, widespread use is that of Smart Homes, environments that can provide management help and intelligent and tailored services to users. This paper aims to present an Internet of Things-based approach to Smart Home management. The proposed approach, which leverages graph approaches, enables the extraction and processing of contextual data, collected from sensors, and probabilistic approaches able to provide valuable information and autonomous actions. The system training phase is performed using graph approaches, which could represent an increase in Context and Situation Awareness. In the experimental phase, a prototype is used to test the proposed method's energy-saving and ventilation management capabilities, which shows encouraging findings.

Keywords: Internet of Things, Smart Home, Situation Awareness

1 Introduction

In recent decades, the Internet of Things (IoT) paradigm has led to the daily use of interconnected smart devices for different purposes and in different domains. Such devices, connected to the Internet, are able to exchange information with each other and humans by competing for specific goals [1]. Many application fields benefit from the Internet of Things, such as, for example, Smart City-based environments [2]. In this context, we find countless applications, such as in health care [1, 3], home monitoring [3], smart environment monitoring [3, 4], water consumption [3, 5].

In this scenario, Smart applications for home environment management are becoming more and more widespread in the world. These systems allow the implementation of some remote control functions of alarm systems, totally automated [6]. For example, it is possible to manage home appliances remotely through innovative mobile applications [7]. Smart homes have several features, and among them is that they can automate various functions, such as opening and closing doors, windows, and shutters, but not only. In fact, one of the most exciting applications is to monitor and control electrical or heating systems in an intelligent way. Such application could lead to reduced consumption. Such systems can be connected to self-regulating temperature systems, which automatically turn heaters on or off depending on

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the temperature reached in a given room. Other features in this area lie in the ability to adjust the lights and the intensity according to the use of the space. All of this can be functional, in addition to saving energy, to achieve maximum comfort [8]. Several paradigms may be helpful for the purpose of enabling the effective management of such environments. In particular, approaches aimed at understanding and managing environmental parameters such as Context and Situation Awareness [9, 10, 11] can be used in managing the available data for this purpose. With these applications and data from sensors, it is possible to represent home environments effectively by generating predictions helpful to users in managing such scenarios. The ability to describe environments is able to lead to the design of a Domestic Digital Twin [12]. The digital twin enables home management of the physical environment through the cyber environment. It is based on processing and translating data into reliable predictions based on the user's habits and preferences. Indeed, the creation of the Digital Twin requires smart devices that can communicate and collect data.
This paper presents an Internet of Things-based approach to Smart Home management, focusing on supporting users to effectively manage their available resources while achieving high levels of comfort. The proposed approach leverages three graph approaches, such as Ontologies [13], Context Dimension Tree [3, 14], and Bayesian Networks [15]. Specifically, Ontology manages data-related knowledge and collaborates with the CDT to determine constraints that improve the construction of the Bayesian Network. Such a system has been tested in a real home environment using a developed prototype, obtaining promising results.

2 Background and Related Works

To allow an adequate description of the context and situation and subsequent prediction of actions to be performed to support users, the proposed approach aims to exploit three graph approaches: Ontology, Context Dimension Tree, and Bayesian Network.

The purpose of an ontology is to manage knowledge through the facts and description of a particular area [16]. C is the collection of ontology concepts, A represents the attributes associated to concepts, H includes the hierarchical relationship among concepts, R_T is the set of preset semantic connections, and A_x contains the ontology's axioms.

$$O = \{C, A, H, R_T, A_x\} \tag{1}$$

There are two different typologies of ontology:

- Lightweight, in which there are no semantic relations among concepts and the equation (2) represents the representative graph;

$$O = \{C, A, H\} \tag{2}$$

- Heavyweight, in which there are semantic relations and axioms in addition to Lightweight ontologies.

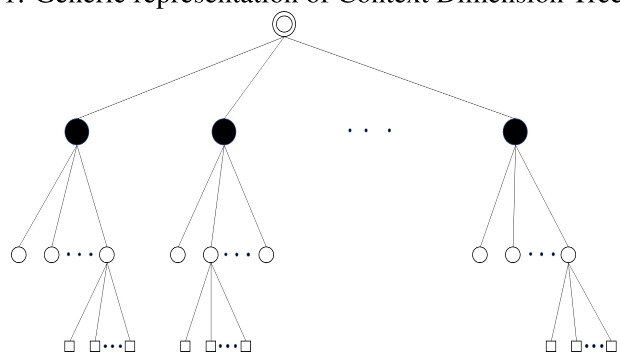
In the suggested method, ontology knowledge management refines data by analyzing context. Context refers to any information relevant to characterizing the condition of an object that might influence how users interact with systems [17]. The context analysis enables the system to identify dependency and independence links and enhance the Bayesian Network graph design. Specifically, the Context Dimension Tree depicts all potential contexts visually. The CDT is a non-oriented, acyclic, and linked graph denoted by the equation (3) and the illustration 1.

$$CDT = \{r, N_{CDT}, E_{CDT}\} \tag{3}$$

The components of the CDT graph are [14]:

- the root r;
- the nodes set N_{CDT} that can be divided in:
  - Dimension Nodes N_d, that represent the contextual dimensions and graphically consists in the black nodes of Figure 1;
  - Concepts nodes N_c, that consist of the value that a specific context assumes. They graphically are represented by white nodes in Figure 1;
  - Parameters, represented by white rectangles, consist in the children of the concepts nodes and specify information related to them;
- the edges set E_{CDT}.

Figure 1: Generic representation of Context Dimension Tree (CDT).



With these graph approaches, it is possible to support the construction of Bayesian Networks, which consists of a direct acyclic graph described by equation (4), in which N_B is the nodes set and E_B is the edges set.

$$BN = \{N_B, E_B\} \tag{4}$$

Bayesian Networks work both as probabilistic and graphical approaches [18] and are based on the Bayes Theorem. Let A and B two events, the Bayes Theorem allows to calculate the probability $P(A|B)$ through the probabilities $P(B|A)$, $P(A)$, and $P(B)$.

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)} \tag{5}$$

Probabilistic techniques will enable the employment of a methodology that can adequately characterize the context and scenario of a home environment and assist users in making decisions based on the outlined approaches. Several techniques in this regard have been presented in the scientific literature. Gu et al. use Web Ontology Language, and knowledge of context [19]. Specifically, their suggested methodology uses Ontology to capture contextual information. Based on ontology and semantic reasoning, Chen et al. provide a knowledge-driven technique. Both simulated and real situations are used to assess the approach [20]. Verma et al. manage patient care in smart homes using a Bayesian Network. The Internet of Things paradigm enables data collection for training Bayesian Networks useful for decision-making process. Seventy-five users were involved in the experimental phase, which relies on a training set based on thirty days of data collection. Colace et al. present a novel approach for the administration of cultural buildings. Specifically, they use a Bayesian method to predict building deterioration and give a damage prevention that identifies the most efficient preventative measures. In addition, Smart Homes may represent a specific Internet of Things application, based on Situation Awareness concept, using graph approaches extensively [21]. Kolbe et al. achieve Situation Awareness via the use of Contextual information and Ontology [22]. In their study, the Context Space Theory enhances the framework's reasoning skills. In addition, Li et al. provide a new approach for collecting knowledge using a Web Ontology Language to govern traffic in smart cities. The approach divides the Ontology into three parts: the Manager Ontology; the Monitoring Ontology, which controls the tunnel status; the Traffic Ontology, which manages the entrance of cars into the tunnel; [23]. Clarizia et al. present a method for predicting urban precipitation. This method utilizes a Bayesian Network, a Hydrologic Ontology, and Context Awareness that has been customized for six context dimensions. During the training phase, human behavior, meteorological condition, and traffic accident data are collected [24]. These approaches highlight the combination of Context Awareness methodologies, and probabilistic approach in the Internet of Things applications for achieving the Situation Awareness. The following section will describe the proposed approach, which is based on three graph approaches. Using Context Dimension Trees, Ontologies and Bayesian Networks the proposed system could be able to predict and perform actions.

3 The Proposed Methodology

The suggested methodology is capable of processing sensor data and using them to give users valuable recommendations. For instance, depending on the acquired data, the system may identify the need to switch on/off the house's heating, lighting, or ventilation systems. These actions are specifically dictated by the dependency or the independence of Bayesian Network variables. The identification of the relations between variables, also depends on the semantic relations set R_T of the Ontology's equation (1). In fact, it is feasible to join Ontology concepts C thanks to the semantic relations of ontology. In addition, the Context Dimension Tree filters semantic relationships using contextual data. Due to the fact that experts construct the Context Dimension Tree and Ontology prior to the input of data into the system, the interaction between these two graph approaches enable the incorporation of context analysis into the constraints-related decision-making process. The first list imposes the dependent relations between two variables of the Bayesian Network, whereas the second list prohibits the construction of the dependence relation between two variables. The second list offers information about independent variables based on an investigation of the Context Dimension Tree and Ontology. The relationship (1) describes the Ontology associated with the suggested method, where the dependency relations set R_D and the independence relation set R_I are two separate sets that make up the semantic relations set R_T.

$$R_T = R_D \cup R_I \qquad R_D \cap R_I = \emptyset \tag{6}$$

These sets allow connecting Ontology concepts without hierarchical relationships. Indeed, the formulas (7) and (8) describes the edges of the Ontology.

$$(c_1, \alpha, c_2) \quad c_1, c_2 \in C \quad \alpha \in H \tag{7}$$

$$(c_1, \alpha, c_2) \quad c_1, c_2 \in C \quad \alpha \in R_T \tag{8}$$

The formula (7) has the label $\alpha \in H$, and represents the hierarchical connection between the nodes c_1 and c_2 of the ontology concepts set C.

The Context Dimension Tree CDT= $\{r, N_{CDT}, E_{CDT}\}$ has as dimension nodes N_d and concept nodes N_c the concepts nodes of the Ontology.

$$N_d \cup N_c \subseteq C \tag{9}$$

In addition, the random variable, represented by the set of nodes N_B of the Bayesian Network, is chosen from the common components of the Context Dimension Tree and the Ontology.

$$N_B \subseteq N_d \cup N_c \subseteq C \tag{10}$$

The presence of common between the Ontology and the Context Dimension Tree allows the proposed approach to analyze each case from the data. The principal aim is the creation of two constraints sets:

- The dependence relations set $R^{(D)} = \{d_1, d_2, \ldots, d_n\}$. The constraint $d_i = (c_1, c_2)$ connects the two nodes $c_1, c_2 \in N_B$ of the Bayesian Network and imposes that the edge (c_1, c_2) belongs to the edges set E_B.
$$R^{(D)} = \{d_1, d_2, \ldots, d_n\} \subseteq E_B \tag{11}$$
- The independence relations set $R^{(I)} = \{r_1, r_2, \ldots, r_m\}$. The constraint $r_i = (c_1, c_2)$ is related to the nodes $c_1, c_2 \in N_B$ of the Bayesian Network and imposes that the edge (c_1, c_2) does not belong to the edges set E_B.
$$R^{(I)} \cap E_B = \emptyset \tag{12}$$

The suggested technique then enables the creation of the Bayesian Network through the Ontology and the Context Dimension Tree. To enhance the creation of the Bayesian Network structure, the constraints sets $R^{(D)}$ and $R^{(I)}$ are incorporated into the ”K2” method [25].

3.1 An IoT-based Architecture

Figure 2 depicts the numerous functionalities of the proposed architecture, which utilizes the proposed methodology.

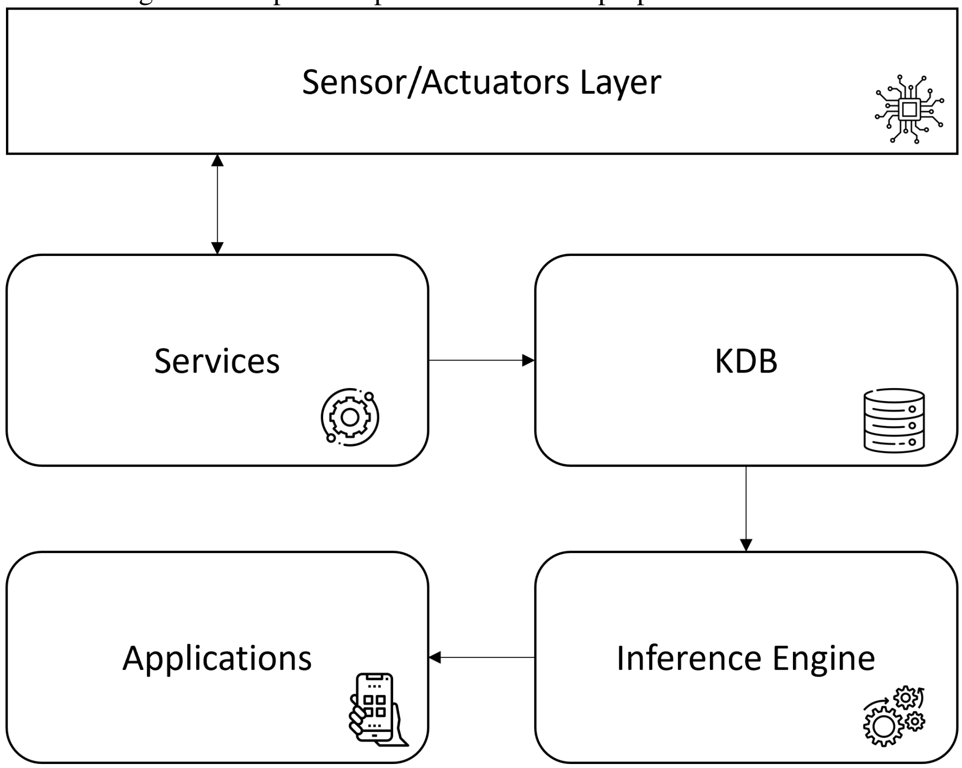
The top layer consists of implanted sensors meant to gather meteorological and indoor/outdoor environmental information. The collected information is saved in a database and serves as the basis for the development process. In addition, the collected data must undergo a process of pre-elaboration in which the data is formatted according to a selected representation standard, and noise is removed. Following the pre-elaboration phase, the proposed technique elaborates on data in order to provide useful suggestions. Specifically, the Ontology and Context Dimension Tree govern the Perception and Comprehension stages of Endsley’s Situation Awareness [26]. The establishment and training of the Bayesian Network based on data allow the network to enter the Prediction phase. The inference engine uses the knowledge database to provide suggestions for users and enhance the management of energy and ventilation cost reductions. In particular, the inference engine allows the goals to be achieved by refining the conditional probabilities determined during the training phase of the Bayesian Network.

The application layer engages the user with enhanced information. Specifically, the application layer differentiates between two sorts of users: experts, who can get specialized information from the system, and regular users, who cannot interact with the system but may provide input.

4 Smart Home case of Study

This Case of Study, based on a Smart Home prototype, is used to validate the suggested methodology. This case study attempts to combine information from ontologies, context information, and Bayesian inference in order to assist users in controlling the domestic environment and validate the trustworthiness of the offered ideas. Sensors collect data that are contextualized based on the selected contextual domains. The Bayesian Network constructed from the Ontology and CDT graphs gives roles for monitoring the domestic environment. The test of specified roles’ dependability requires the development of a prototype with web- and application-accessible server and client components.

Figure 2: Graphical representation of the proposed architecture.



In order to develop the proposed prototype are used Python language, and Web API Django REST framework, which represents a robust and versatile toolset for developing Web APIs. The prototype associated with the case study utilizes the Dart-based Flutter framework. In addition, the Raspberry Pi 4 e Pi 0 enables the establishment of an intelligent environment and is compatible with various indoor sensor types. The Raspberry Pi 4 is linked to a Weather Station, which collects meteorological weather data. The installed sensors are listed in Table 1. They enable monitoring of the inside and outside surroundings, including the presence of users, humidity, temperature, and air quality.

Table 1: Prototype: Sensors and parameters

Parameters	**Sensor**
Air indoor/outdoor Temperature	BME680
Air indoor/outdoor Humidity	BME680
VOC indoor/outdoor	BME680
Luminosity	SI1145 Digital UV Index IR Visible Light Sensor
Voltage	Voltage Sensor
Weather Presence	Pi Camera
Wind Speed	Anemometer
Wind Direction	Wind Vane
Rainfall	Rain Gauge

Table 2: Prototype: Actuator and Actions

Action	**Actuator**
Light Control	Dimmer
Ventilation	Fun Motor

In this study, sensors enable the capture of data that is then refined using the Multilevel Graph technique, enabling the determination of the responsibilities for managing energy conservation and ventilation. In particular, energy-saving management focuses on switching off artificial lights when solar light is sufficient or when a room is unoccupied. Aspirators are used to ventilate and disinfect a particular space.

4.1 Experimental phase

The experimental phase focuses on the evaluation of the proposed methodology and seeks to evaluate two distinct aspects:

- Verify the system's effectiveness in managing the domestic field and the degree of automatic actions;
- tests the dependability of the user recommendations.

The experimental portion of these verifications employs two distinct measures. Initial exploits Accuracy, accuracy, and recall [27] to validate the system's effectiveness in managing energy savings and ventilation. Let TP represent the number of true positives, FP represent the number of false positives, FN represent the number of false negatives, and FN represent the number of false negatives ((13), (14), and (15)).

$$\text{Precision} = \frac{TP}{TP+FP} \tag{13}$$

$$\text{Recall} = \frac{TP}{TP+FN} \tag{14}$$

$$\text{Accuracy} = \frac{TP+TN}{TP+FP+TN+FN} \tag{15}$$

The second step of validation is performed through a questionnaire divided into the following sections:

A Interaction

1 The system interaction is easy.

2 The prototype provides clear suggestions.

B Recommendation

1 The services and contents offered have met the user's needs based on personal preferences and the current context.

2 The system has managed to adapt to changes in the context.

C Presentation

1 The information has been presented appropriately.

2 The information provided was comprehensive.

D Usability

1 The application interface is easy to use.

2 Response times are adequate.

Each section of the questionnaire, based on the Likert scale, presented two assertions to which five possible answers were associated: I totally disagree - TD, I disagree - D, Undecided - U, I agree - A, I totally agree - TA. The data has been collected for seven months, and about 5000 instances. These instances are divided into a Training set (80%) and a Testing set (20%).

In Table 3, the gathered data's precision and recall in relation to Saving Energy are detailed. The stated accuracy is 96.28 percent.

Table 3: Saving Energy Performance

	Yes	**No**
Precision	89,13 %	98,22 %
Recall	87,11 %	98,41 %

The Ventilation-related precision and recall of the gathered data are shown in Table 4. The stated accuracy is 97.27 percent.

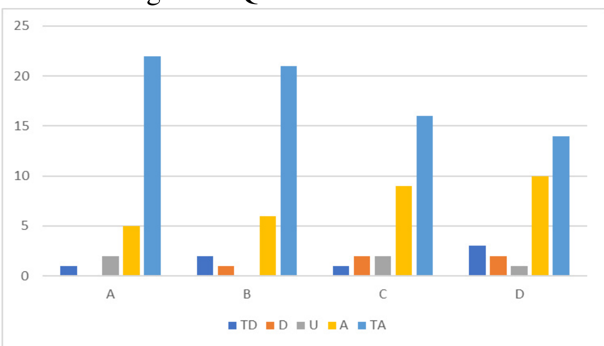
Table 4: Ventilation performance

	Yes	**No**
Precision	95,48 %	98,01 %
Recall	91,27 %	99,22 %

The suggested method yields good results since the acquired precision surpasses the criterion of 96%. Particularly, the accuracy of ventilation outcomes is greater than those of energy conservation.

A further validation step is tested on a sample of twenty mobile device users. Users range in age from 24 and 61 years old. Displayed in the Figure 3 are the results of the survey. The questionnaire findings

Figure 3: Questionnaire Results



are encouraging. Particularly, Section B pertaining to System recommendation capability, is one of the highest rated, while the others are scored adequately.

These results illustrate that the proposed design assists users in executing the required task with precise results. The efficiency of the proposed design is shown by the fact that both energy savings and ventilation control are achieved with higher than 95% accuracy.

In addition, the feedback reveals the users' pleasure with the prototype's interaction.

5 Conclusion

The present Article presents a Smart Home field case study. A combination of three different graph approaches (Context Dimension Tree, Ontology, and Bayesian Networks) enables the control of the domestic environment with the aid of data acquired. The suggested method is to advise users on ventilation and saving energy. The experimental phase establishes two guidelines: verifying the suggested approach's effectiveness and the prototype's dependability. Future work will focus on verifying the effectiveness of the suggested strategy in other industries and expanding the number of people who test the prototype. In addition, the application might include a Recommendation application to suggest the incorporation of additional sensors to users to enhance the home environment's management.

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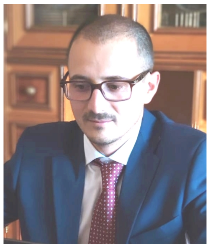

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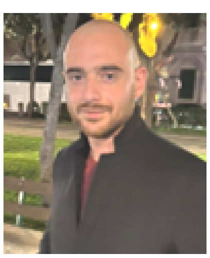

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