Smart Home Systems Design Approach with the Thermal Management Problem Example

Andrey Tsaplin[1[0000−0002−5119−8323]], Alexey Platunov[1[0000−0003−3003−3949]], and Vasiliy Pinkevich[1[0000−0002−8635−5026]]

ITMO University, Kronverksky prospekt 49, Saint Petersburg, 197101, Russian Federation
tsaptsaplin@gmail.com aeplatunov@itmo.ru vupinkevich@itmo.ru

Abstract. The aim of the research is to develop a new approach to shaping and implementation of functionality of middle price range smart home systems. The approach being developed is based on the ideas of a cyber-physical systems design paradigm and deep insights of distributed embedded systems architecture. The current state of the smart home automation systems market and issues of available products are discussed. The classification of smart home automation systems is given. The promising way to solve applied issues of smart home systems is demonstrated with a simple example of the thermal identification of an object. A brief description of the distributed LMT4Home platform used in the experiments is given.

Keywords: smart home · cyber-physical systems · energy efficiency · object identification · embedded systems design.

1 Introduction

Cyber-physical systems are a modern stage of automation and embedded systems development, which is characterized by a new level of sensors, actuators, and computing components integration with the object under control and with each other, as well as their high computational performance. This stage enables a quantum leap to a significant increase in the complexity of the solved task using relatively low amounts of resources and to significantly improve the properties of the created systems.

Within the area of smart home systems, the application of the cyber-physical approach and its elements allows us to solve problems that previously required expensive specific equipment and were present only in mission-critical industrial systems. At the same time, during the design process it is necessary to consider the specific features of low-cost off-the-shelf systems for the wide market and to find a balance between the complexity of the applied tasks, the computing resources required, and the cost of the necessary hardware.

Thus, some of the key stages in the development of modern smart home systems are to reveal meaningful applied problems and to find their solutions that fit the composition of embedded controllers with limited resources connected to cloud devices (servers and terminals) via unreliable communication channels.

The paper provides a brief overview of the smart home products market, provides an example of thermal management problem solving using the limited computing resources of home automation controllers.

2 Home and building automation systems

The topic of home automation has been developing since the mid-'70s of the last century. Over the past time, a huge number of solutions have been proposed and implemented. Standards, protocols, families of hardware modules, embedded software, SCADA, management, and service software have been developed.

Today, a large number of diverse products related to the smart home segment are presented on the market. Here are some examples: Wiren Board [1], Ksytal [2], nooLite from Nootekhnika [3]. There are systems from "big companies" such as Google, Apple (Apple Home Kit), Amazon, Xiaomi (Xiaomi Smart Home Kit) and several others. Russian IT and telecommunication companies such as Yandex, Rostelecom, Megafon, MTS actively develop smart home products. House and building automation systems based on standard industrial automation solutions (e.g. ABB i-bus® KNX and ABB-free@home®) are still present on the market. Technologies based on a number of standards for industrial wired and wireless networks dominate at this market segment. For example, KNX is the open international building automation standard (ISO/IEC 14543-3). Wi-Fi, ZigBee, LoRaWAN and other network standards are widely used. A lot of various Internet services with different specialization and functionality are presented for PCs, tablets, and smartphones. These products range from the simplest hardware consoles ("Logika doma" – "Home logic" application, Bluetooth Terminal HC-05), integration applications (IFTTT [4]) to energy analysis services (Bidgely [5]), monitoring systems ("Nardony Monitoring" project [6]) and full-fledged SCADA (ISaGRAF , SAYMON, iRidium).

From this brief overview we can conclude that the "smart home systems" class can be divided into a number of categories:

1. The simplest devices of local automation ("smart socket").
2. Devices with remote control ("GSM socket").
3. Centralized and distributed automation devices with limited functionality (simplest applied algorithms, no user programming).
4. Distributed systems with "deep" programmability (are often based on industrial automation solutions).
5. Scalable intelligent systems with flexible functionality, which should be based on the principles of cyber-physical systems design [7, 8].

Let us briefly note the main issues of today smart home systems. In the segment of simple solutions, there is essentially no integration of functions, only the simplest scenarios and algorithms are available. In fact, there are no programming capabilities for the consumer. In the segment of expensive systems, the user almost completely depends on third-party integration companies if it is necessary to change or expand the system.

Thus, the possible goal for the designers of smart home platforms today can be the creation of flexible, intelligent and end-user-customizable home automation tools in the class of mid-range off-the-shelf solutions.

3 LMT4Home platform

The LMT4Home system [9] is designed for the intelligent control of various devices in a cottage (country house), office or enterprise area with remote control and monitoring of the object. Due to the unique LMT4HomeFusion technology, the system provides a high level of various sensors and actuators integration in automated control tasks, as well as flexibility in operation algorithms tuning and good scalability. A variant of the appearance of the controller is shown in Fig. 1.

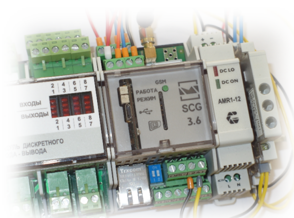

Fig. 1. A variant of LMT4Home controller hardware

LMT4Home is a cyber-physical system, ready for integration into the Internet of Things (IoT) and it already actively uses the principles of distributed architecture, supports a variety of communication channels and cloud services. Reliable autonomous intelligent control is provided by LMT4Home built-in algorithms, while cloud-based monitoring, analysis, and prognosis allow expanding the capabilities and make the person's communication with smart home automation as comfortable and efficient as possible. LMT4HomeFusion technology is aimed at providing functional integration of smart home services.

The system allows you to combine a wide range of devices from smart sockets and electricity meters to smartphones and tablets. The LMT4Home hardware platform is built with highly reliable components, allowing operation in a wide temperature range (–40...55 °C). The application of industrial design and implementation standards guarantees reliable operation of the system over a long period of time (more than 10 years).

LMT4Home is permanently evolving. This primarily refers to the expanding base of applied algorithms. The main topics here are a set of thermal management tasks, electrical energy management, improving the flexibility and convenience of a human-machine interface (HMI).

4 Smart home systems implementation principles

The most important principles that should be implemented in a system designed using the proposed approach can be stated:

1. Implementation of adaptive algorithms that correct their behavior with respect to the system working history.
2. The smallest possible amount of required initial setup and configuration, the optimal "average" mode of operation must be preset.
3. At least two sets of parameters: a simple set for the novice user, and an advanced set for fine-tuning.
4. High level of fault tolerance and survivability, adaptation to failures and graceful degradation of applied functions.
5. Self-diagnosis, issuing warnings about the present and potential problems, recommendations for improving the system and the controlled object.

Formal approaches and methods that can be used to analyze data about the object and the control system: analytical models, spline interpolation, neural networks, fuzzy logic, statistical processing, ontologies, and others. Today, they are more often united under the title of "Big Data Analysis". The designer's goals are to look for a solution with minimal algorithmic complexity for a resident implementation (in the controller) for time-critical functions and to provide extensive cloud support for advanced analysis.

5 Thermal management problems

As an example, let us consider a set of thermal management problems relevant to a country house (a cottage) with a full-time or partial-time year-round inhabitation. This is the segment of cottage settlements and summer cottage cooperatives.

The following typical subtasks can be defined:

1. Object identification.
2. Object monitoring:
   - short-term monitoring for real-time control;
   - long-term monitoring for identification of degradation processes, evaluation of the effectiveness of cottage repairs, etc.;
   - emergency or failure detection.
3. Energy-efficient transfer of the object to a given thermal regime by a given time (heating, cooling).
4. The thermal regime maintenance (stabilization).
5. Energy-efficient "safe mode" of the object (standby and conservation regimes).

6. Prediction of the state of the object in the future (short-term, long-term prognosis).
7. Management in an emergency (failure) situation (minimization of the damage, estimation of risks).

Some of these subtasks overlap with other areas such as electrical energy management, security, etc., but this article deals with their thermal aspect.

While requesting a minimum amount of information from the user, it is necessary to obtain the characteristics of the object for the subsequent use of this model in energy-efficient heaters management.

The developed approach is aimed at obtaining the necessary data about the object without detailed room blueprints and thermal models provided by the user. This will allow implementing a user application interface that has reasonable complexity and solves thermal problems with limited controller resources, in offline mode, if necessary.

6 Example of thermal identification of an object for a cottage

Let us show an example of applying the proposed approach to the problems of thermal management in a cottage using the LMT4Home controller. Thermal sensors are connected to the controller to monitor the temperature inside and outside the building. Also controller drive heater control relays.

We use a simple thermal model of the room based on the electrothermal analogy. We simulate the room as an RC circuit that can receive, accumulate and give away heat (thermal energy). We need to calculate the thermal resistance of the walls in the room and the rate of cooling/heating using the real monitoring data. For this experiment, we have chosen a room with dimensions of 2.8x1.4x2.5 m, with an electric heater with a power of 0.35 kW. The area of the walls, ceiling, and floor of the room is 28 m^2.

The coefficient of thermal resistance that shows the resistance of a wall with an area of 1 m^2 can be calculated as follows:

$$R = \frac{(t_1 - t_2) \cdot S}{Q_{avg}}, \tag{1}$$

where S is the area of all the surfaces of the room, t_1 and t_2 are the temperatures on the outer and inner surfaces of the wall, Q_{avg} is the average power of the heater.

The controller maintains a constant temperature in the room, turning the heater on and off in thermostat mode. As a result, the required average heater power is determined by the temperature difference inside and outside the room.

Table 1 shows the monitoring data and calculated R values for three time periods during October 2019. Fig. 2. shows the experimental data used for the second case. The calculated R values are quite close to each other. As the value

Experiment	Time, hours	Heater power Q_{avg}, W	The average temperature on the external surface $t_1, ^\circ C$	The average temperature on the internal surface $t_2, ^\circ C$	Coefficient of thermal resistance R, $\frac{m^2 \cdot ^\circ C}{W}$
1	20	140	7	23	3.2
2	20	113.5	9	23	3.45
3	11	190	0	23	3.39

Table 1: Diagrams of temperature obtained from sensors and heater status

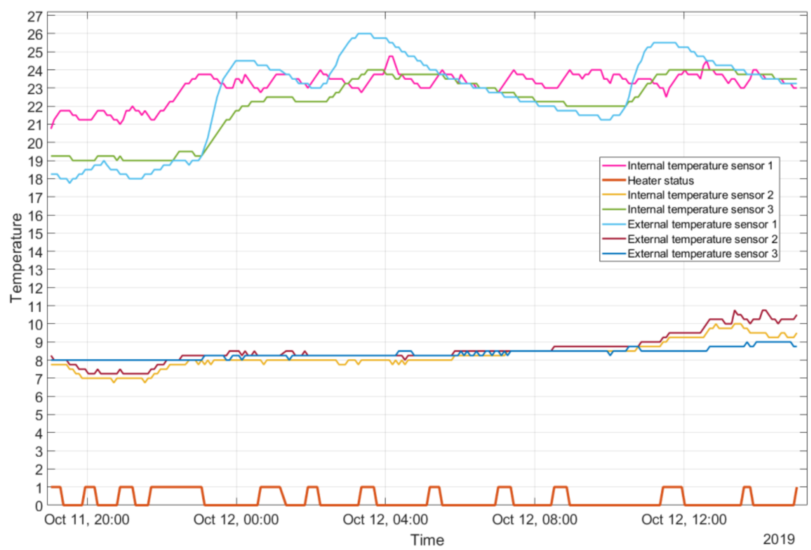

Fig. 2. Diagrams of temperature obtained from sensors and heater status

of the coefficient of thermal resistance for further use, we take the average value of the results obtained: $R_{exp} = 3.346 \frac{m^2 \cdot ^\circ C}{W}$.

Let us also calculate thermal resistance for this wall according to the reference data using the formula $R = h/\lambda$ as we know the composition and properties of the materials. h is the thickness of the layer of wall materials and λ is the coefficient of their thermal conductivity.

The wall consists of a layer of wood with a thickness of $h = 0.05\ m$ ($\lambda = 0.05\ \frac{W}{m \cdot ^\circ C}$) and mineral wool with a thickness of $h = 0.15\ m$ ($\lambda = 0.045\ \frac{W}{m \cdot ^\circ C}$). The resistances of the individual layers of the material should be summed up. As a result, we get $R_{theor} = 3.666\ \frac{m^2 \cdot ^\circ C}{W}$.

A comparison of the theoretical and experimental values of thermal resistance shows a good correlation and demonstrate the applicability of this method for processing real monitoring data.

As a next step, we determine the rate of temperature change in the room. Thermal engineering used in the construction of buildings utilize a variant of the classical Newton's law of cooling to determine the time needed to change the temperature of an object in a medium with a constant temperature:

$$R = \beta \cdot \ln \frac{t_{env} - t_1}{t_{env} - t_2}, \quad (2)$$

where t_{env} – environment temperature, $^\circ C$; t_1 – the initial temperature of an object, $^\circ C$; t_2 – the temperature of an object after z hours, $^\circ C$; β – coefficient of heat accumulation of a building, hours; z – time, hours.

The most reliable, sufficiently accurate and simple way to determine the coefficient of heat accumulation β is the practical measurement of the air temperature change in the room with the heating turned off and with stable outdoor temperature in cloudy, calm, windless weather without precipitations. Table 2 shows the calculation data for two time periods during October 2019. The formula for calculating β is derived from (2).

Experiment	Time, hours	Average external temperature $t_{env}, ^\circ C$	Initial temperature $t_1, ^\circ C$	The temperature at the end of experiment $t_2, ^\circ C$	Coefficient of heat accumulation β, hours
1	16	5	24	18	42.2
2	16	-1	24	16	41.5

Table 2: The coefficient of heat accumulation calculation

The average value of $\beta_{exp} = 41.85$ hours. Now, the calculated data can be used to predict the temperature in the room, as well as the time necessary for heating and cooling, amount of energy to warm up the room at the required time, energy consumption optimization.

Let us verify this by calculating the time required to warm up the room, and following comparison with the experimental data. From the perspective of the above calculation formulas, turning on the heater in the room is equivalent to increasing the outdoor temperature by the amount of temperature difference between the room and environment that the heater can maintain. This difference can be calculated as derived from (1): $\Delta t = (R \cdot Q)/S$, and in this case (with $Q = 350\ W$) it equals to 41.8 $^\circ C$. Then the formula (2) can be used as:

$$R = \beta \cdot \ln \frac{t_{env} + \Delta\ t - t_1}{t_{env} + \Delta\ t - t_2}, \quad (3)$$

Let us provide the real conditions for warming up the room for the formula (3): $t_{env} = 6\ ^\circ C$, $t_1 = 11\ ^\circ C$, $t_2 = 23\ ^\circ C$. The calculated time is 16.5 hours. However, according to real data, 10 hours have passed.

As can be seen from this test, the results differ by more than 1.5 times, but for the simplest model used this is already a pretty good result. To improve the quality of calculations, more complex models can be used. For example, it should be taken into account that when a room cools down, the walls give heat away first, and the air cools later. But when a room is warmed up with a heater, things are vice versa: the air warms up first. Using the current model, the results can be significantly improved by using the separate value of β calculated during the heating of the room. As another option, an average value calculated for cooling and heating can be used.

The presented example shows that simple models with a minimum of data about the object are acceptable and meet the requirements of practical applications. The user only needs to set the location of the temperature sensors and assign a relay to control the heater. The heater power and room area are not required in this model, because it is enough to calculate the complex parameter $(R \cdot Q)/S$ using the formula (1) with information about the fraction of the heater active time in thermostat mode.

Permanent monitoring of the object during the system operation allows the system to refine the parameters of the models and adapt to changes of the object (sensor relocation, heater change or room redevelopment), as well as give recommendations to the user on the power of the heater, improving the thermal insulation of the room, etc.

7 Conclusion

While the problems of country house automation may seem to be solved, the practice shows an extensive range of open problems. The real needs (expectations) of the user from the low-cost smart home system greatly differ from what the market offers. Research and development activities, some examples of which are presented in this work, certainly are promising.

Application of the proposed principles for implementing the smart home automation features demonstrates the ability to achieve a sufficiently high level of user service with limited resources. The LMT4Home platform selected for experiments met expectations as an effective solution for real automation of objects and as a rather powerful and convenient tool.

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