Chapter 1

Network of Sensor and Actuator Agents for Building Automation Systems

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Due to at least two reasons, energy consumption for heating, ventilation, air conditioning (HVAC) and domestic hot water (DHW) systems should be reduced. First, the total energy consumption is high since nearly 20% of total energy in USA is accounted for HVAC systems. Sencond reason is exploitation of renewable energy sources, which depend on current time and weather situation. Thus, the energy management should improve to effective by managing currently available energy. For this purpose, the sensor actor agent network is proposed with an example on domestic hot water heating, taking into account several aspects including the occupant presence. The simulation model was used, where the water consumption affected system dynamics. The agent-based schema combined with the simulator enables an occupant to choose the most subjectively desirable policy of the DHW control mechanism.

1.1. Introduction

Due to depletion of resources and increasing population, reducing energy consumption for heating, ventilation and air conditioning systems (HVAC), domestic hot water (DHW) and lighting is important research field. For example, in USA, HVAC systems consume 50% of an energy in building and 20% of total energy [1]. On the other hand, renevable energy sources are becoming available at home: residental buildings are able to extract energy from sun, wind or ground. The amount of energy produced using renevable energy sources at home is limited and depends on location and time of the year what is closely related to current weather situation. By improving the algorithms for energy management, energy production and consumption can be regulated more efficiently.

Multi-agent system (MAS) approach to building automation and energy management enables system decentralization. Modern buildings contain efficient systems for HVAC, DHW, lighting, safety, entertainment, renewable energy extraction and others. However, these systems are often being managed through one central system. Small entities, such as mobile phones or sensors have enough working power to perform tasks such as usable data processing, data storage and communication. By distribution of tasks among such entities, one can benefit in several ways, for example: distributed responsibility, relaxation of processing power, adding or removing new systems and entities during system runtime.

This paper presents a way to decentralize building automation system (BAS) to a network of sensors and actuators, which are able to communicate when and if needed for control purposes. In Section 2 related work is surveyed. In Section 3, simulation environment and simulation model used in our work are presented. Methods for evaluation of comfort, price and energy consumption are also presented. In Section 4 the proposed network of sensor and actuator agents used for control is presented on an example DHW system. Section 5 includes data used for simulation, and results. Final remarks, conclusion and future work are in Section 6.

1.2. Related Work

There are many research projects, where MAS was applied to control systems in building. Comparison between traditional and agent approach for control systems in building was performed by Wagner [2], who argues, that agent approach results in transparent software structure and dynamic and adaptive application software.

Common wireless technologies, such as ZigBee, Bluetooth, X10 for establishing network of control entities were revised critically and new Tag4M devices with processing and storage capabilities using Paxos communication protocol were introduced for reliable BAS [3]. Wireless sensor - actuator network was implemented for system decentralization for mobile control appliances also by [4], while agent platform for personalized control of buildings and appliances was analysed by Qiao et al. [5]. Authors of [6, 7] considered appliance commitment for load scheduling, since exploitation of limited resources depends on behavioural parameters of individual appliances. Weather forecasting and energy price were applied into the control system by Escriv-Escriv et al. [8] what shows the potential in further research activities for control strategies.

Finally, there are complete smart home projects, starting with Neural Network House in the nineties using neural networks for intelligent control [9]. IHome [10] and MavHome [11] were following with intelligent multi agent approach, using several techniques for user behaviour modelling and predicting their actions. Gator Tech Smart House [12] is a project for researching pervasive computing methods in smart building. Research systems often use real data about weather and occupant preferences for management of simulated objects, such as ThinkHome [13].

1.3. System Simulation

Simulation of objects is crucial for implementation and testing of control algorithms on large dynamic system representing HVAC, lighting or DHW operation in building. It gives an opportunity for cheap and quick evaluation of control system behaviour over a daily, monthly or yearly level. We implemented the model, representing DHW system used in building, where occupant activities such as water consumption for shower, cooking, washing hands and occupancy affected system dynamics.

1.3.1. *Simulation Environment and Simulation Model*

For simulation purposes, EnergyPlus [14] simulator, integrated with BCVTB [15] into Ptolemy simulation environment, was used. Simulation of dynamic system were obtained using EnergyPlus model of physical system, weather data history file and user activities history file. Simulation environment is represented on Fig. 1.1. For preliminary results we used an example model representing stand-alone electric water heater. It consists of:

- Static construction parameters such as tank volume or maximum heating power, which are fixed during simulation runtime
- Transfer functions expressing system dynamics, e.g. how water temperature is changing when heater is on or off
- Input variables, representing thermostat set points, which are being enforced by control system
- Output variables, representing system states, such as water temperature or water consumption in each simulation time step

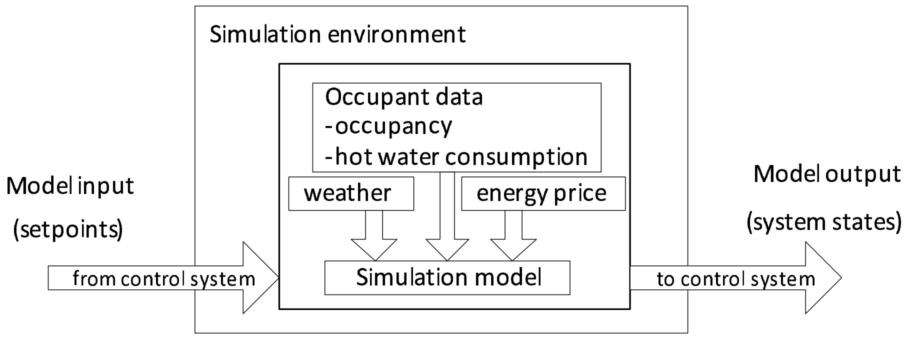

Fig. 1.1. Simulation environment

During simulation time step, simulation environment accepts thermostat set point simulation environment outputs tank water temperature, hot water consumption flow, energy consumption, electric energy costs and occupancy.

1.3.2. *(Dis)comfort, Energy Consumption and Price*

The three measures are used for evaluation of system performance. Firstly, the discomfort t_{missed} is measured by summation of time steps, the occupant uses hot water for taking shower, preparing breakfast, preparing dinner and preparing drink and the water temperature T_w is below the temperature comfort threshold T_c. Similar notation is commonly used to evaluate HVAC operation for comfort [16].

$$t_{missed} = \sum_{t=0}^{n} sign(T_c - T_w(t)) * sign(Q_w(t)), \tag{1.1}$$

where $Q_w(t)$ is the hot water consumption volume flow out of the water heater during consumption. Function $sign(x)$ returns 1 for $x > 0$ and 0 for $x \leq 0$. Secondly, energy consumption is aggregated energy consumption rate during simulation time. Each simulation time step, $E_{consumed}$ increases according to the following equation:

$$E_{consumed} = \sum_{t=0}^{n} P(t) * \Delta t, \tag{1.2}$$

where $P(t)$ is power consuming during simulation time step t and Δt is a time step duration. Finally, electric energy price is calculated using the schedule for High Rate and Low Rate tariff. Each simulation time step, EnergyCosts increases according to the following equation:

$$EnergyCosts = \sum_{t=0}^{n} P(t) * \Delta t * R(t), \tag{1.3}$$

Where $R(t)$ is a Rate tariff, mentioned above.

1.4. Control System

Control system was implemented using agents deployed in Java Agent Development Environment - JADE [17]. We used two type of agents: sensor agents and actor agents to achieve the simulation of grid of sensors and actuators as autonomous entities. The control system including simulation environment and communication is shown in Fig. 1.2.

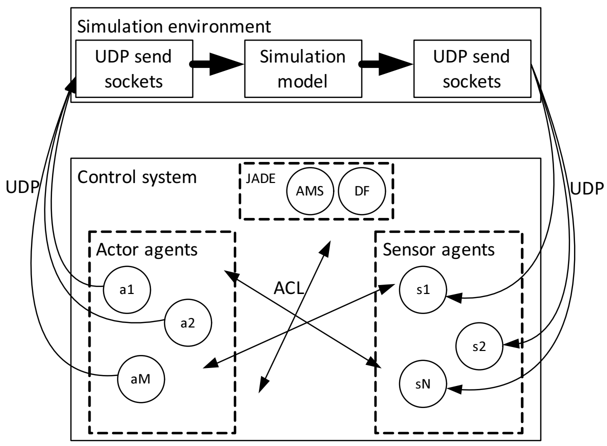

Fig. 1.2. Control system

1.4.1. *Sensor Agents*

Sensor agents perform two tasks: the first task is to continuously receive system states from simulation environment and store current value. The second task is to wait for messages, sent by other agents - actor agents in our example. Such messages include requests for sensor readings: e.g. actor agent asks sensor agent to provide sensor values each time, the sensor value will change. Sensor agents, used in our model, were:

- Water temperature agent, providing data about tank water temperature
- Occupancy agent, providing data about occupancy in building
- Hot water consumption agent, providing data about hot water consumption flow
- Energy price agent, providing data about price of electricity
- Energy consumption rate agent, providing data about energy consumption

To summarize, each of these agents were used to memorize state information from simulation environment and provide these information to agents, which requested for the data.

1.4.2. *Actor Agents*

Actor agents are used for changing (setting) set point values using model input port (see Fig. 1.2) and here algorithms for control of dynamic system are implemented. Agent behaviour represents control algorithm. Four different behaviours were implemented for different types of control:

- On behaviour, where set point temperature is set once, and is not changing during simulation
- Schedule behaviour, where set point temperature is changing according to a predefined schedule
- Schedule and price behaviour, where set point temperature is changing according to a predefined schedule and electric rate tariff
- Occupancy events behaviour, where set point temperature is changing according to occupancy in building

When actor agent starts or changes a behaviour, it firstly asks appropriate sensor agents to provide requested data by sending a request message to that sensors. If the sensor answers by a confirmation message, then actor start performing control operation. During control operation, actor waits for inform messages from sensor about sensor states and change set point value according to control algorithm.

1.5. Results

Simulation was performed using electric water heater for DHW in an apartment, inhabited by one person for a period between the dates 25.2.2008 and 23.3.2008. We choose the electric energy tariff rates from electric energy provider Elektro Gorenjska[a], where the High Rate tariff is between 6.00am and 22.00pm during working days and Low Rate tariff between 22.00pm and 6.00am during working days and on Saturdays, Sundays and feast days.The High Rate and Low Rate tariffs were 0.07315 EUR/kWh and 0.03911 EUR/kWh respectively.

Kastreen dataset [18] was used in the model for hot water consumption and for building occupancy. Activities *leave house*, *take shower*, *go to bed*, *prepare breakfast*, *prepare dinner* and *get drink* were converted to hot water consumption flow as listed in Table 1.1. Peak Use is the maximum possible hot water consumption flow.

Table 1.1. Water consumption flow by activity.

	Peak Use	Shower	Breakfast	Toilet	Dinner	Drink
Q_w $[l/s]$	0.345	0.104	0.01725	0.00345	0.01725	0.00345

There were two predefined set point temperatures, $high = 62°C$ and $low = 40°C$, used for schedule and sensing event behaviour. Simulation results for four different types of control algorithms are shown in Table 1.2. Values, marked by (*) represent best values.

Under given parameters, our system computed four characteristic control behaviour or control policies, presented in Table 1.2. One can see that behaviour 4 presents best results according to user comfort, but the price for energy consumed and electric costs are higher, compared to behaviour 3. Behaviour 3 is better when energy consumption is important. If we overlook six minutes in a month that the temperature fall below $50°C$, than behaviour almost dominate the others. Behaviour 1 is the worst option. The reason for poor performance in case of energy costs and comfort is in bad schedule setting, which was created manually, without energy costs and user occupancy taking into account. Behaviour 2 is an improvement of behaviour 1 in case of energy costs, but the comfort here almost has not improved, while energy consumption has raised.

However it is on a specific user to decide for any of the four characteristic control behaviours. The task of the system was to compute and present results to the occupant and he/she has the privilege of the informed choice. Later, when occupant consumption

[a]Web page: http://www.elektro-gorenjska.si/Za-gospodinjstva/Tarifni-casi;
Last accessed: 19.6.2012

Table 1.2. Simulation results.

	$Schedule$	$Scheduleandprice$	$Occupancyevents$	On
t_{missed} [min], $T_c = 45°C$	8	8	0	0*
t_{missed} [min], $T_c = 50°C$	22	21	6	0*
t_{missed} [min], $T_c = 55°C$	112	88	112	85*
$E_{consumed}$ [kWh]	211,789	215,818	208,674*	212,427
$EnergyCosts$ [EUR]	14,13	12,59*	13,12	13,46

changes, he/she can repeat the simulation when desired.

1.6. Discussion, Conclusion and Future Work

The paper presents a system architecture based on distributed control of building automation systems. The architecture is general and flexible and uses standardized agent communication between developed sensor and actor agents. For actor agents, several control behaviours were implemented and the results show the potential in multi agent approach control. Further research guidelines are to apply developed control system on a complex simulation model with occupant data about activities for longer period of time. The proposed control system enables the usage of user behaviour model for energy management systems in buildings.

The main advantages of the system are:

- A flexible agent-based ambient intelligence simulation
- Enabling occupants to make informed decision based on characteristic behaviours of the local DHW system, adopted to each particular user consumption

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