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Interconnecting smart card system with PLC controller in a local operating network to form a distributed energy management and control system for buildings

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Abstract

Distributed control and energy management for buildings is a viable solution, ensuring both indoor comfort for the occupants and reduction of energy consumption. The aim of this paper is to present the architecture of a distributed building energy management system that can be installed in new as well as in existing buildings, which are more energy inefficient. The system integrates a smart card unit, acting as a user machine interface, sensors, actuators, interfaces, a PLC controller that incorporates the fuzzy control algorithm, local operating network (LON) modules and devices and an optional PC which monitors the performance of the system. The distributed control architecture is based on the properties of the LON. The complete system is installed and tested in the Laboratory of Electronics of the Technical University of Crete. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Control networks; Distributed control; Local network; Smart card system; PLC; Fuzzy control; Buildings energy management

1. Introduction and state of the art

Distributed energy management systems in buildings have gained significant attention due to their high potential in energy savings and reduction of consumed energy expenses. Moreover,

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higher demands are placed on cost minimization of such systems, ease of installation and standardization of various components comprising the system [1,2]. Open distributed control systems feature desirable benefits, such as fault tolerance, expandability and maintainability. Although the installation of distributed control systems in existing buildings was, up to now, cost ineffective, due to the extended wiring required for communication demands, recent developments in the building automation and control sector resulting from the introduction of various transmission media, helped dramatically the feasibility of energy management in existing buildings.

The objective of this paper is to describe the hardware components for an open architecture structure of a building energy management and control system (BEMS). The BEMS incorporates all necessary items to ensure indoor comfort at the zone level, interacting with the zone occupants by using artificial intelligence techniques, while it is supervised by a central PC. The communication network used is the local operating network (LON), which ensures interoperability and expandability.

The main features of the proposed BEMS are:

- Distributed control of the indoor comfort conditions at the zone/room level of the building.
- User interaction, accepting user comfort preferences and displaying energy consumption.
- Monitoring the performance of the overall system and adapting the control strategy accordingly.
- Ability for installation in existing buildings using the capabilities of the LON technology.

The architecture used for two zones is depicted in Fig. 1. The main components of the BEMS are the smart card unit, the sensors and the actuators, the PLC controller, the LON devices and the central PC.

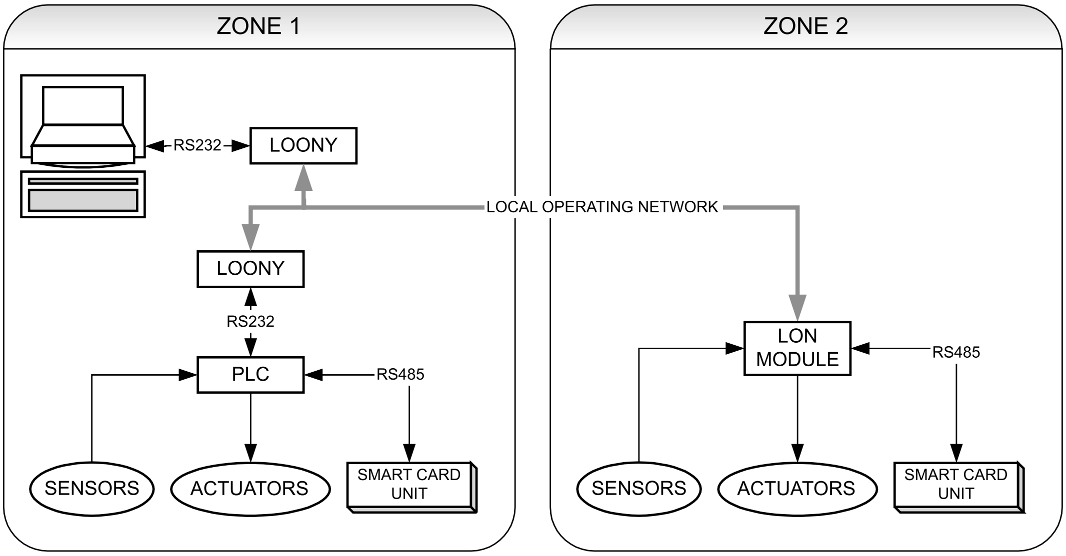


Fig. 1. The architecture of the proposed building energy management system for two building zones.

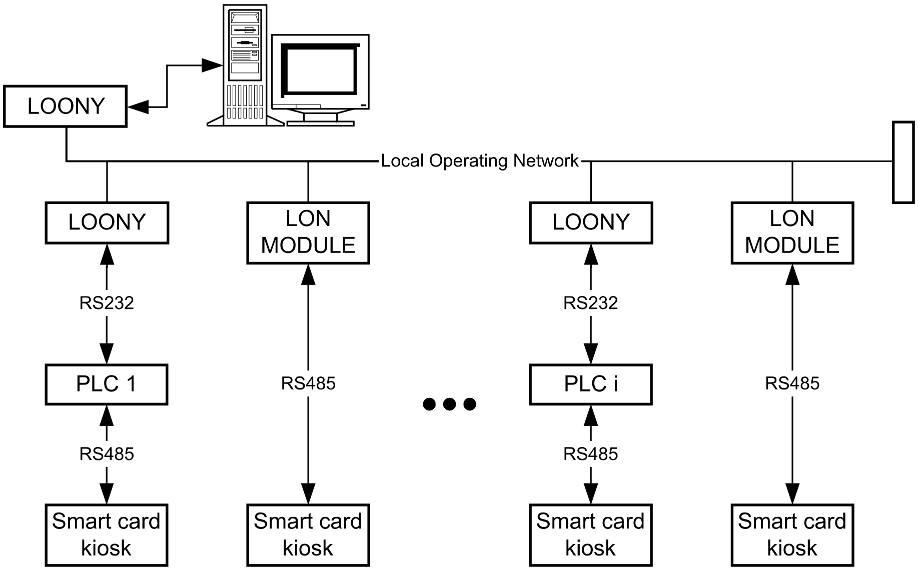


Fig. 2. The communications hierarchy of the BEMS.

The hierarchical structure of the system is illustrated in Fig. 2. The central PC is the master of the overall system. The PLCs and the LON nodes/modules act as slaves of the PC and as masters of the smart card unit. The role of each component and the communication transactions between them is described in the next sections.

2. Description of the functions of each component

2.1. The smart card system

The smart card unit [3], manufactured by the French company INGENICO, forms the interface between the system and the user. The front panel of the smart card unit is illustrated in Fig. 3.

The smart card unit performs the following operations:

(i) The default values of the control variables are stored in the smart card of each user. The Predicted Mean Vote (PMV index) represents the thermal comfort variable [4,5], the indoor illuminance represents the visual comfort variable and the CO_2 concentration represents the indoor air quality variable [6,7]. When the smart card is inserted in the unit, the system detects the presence of the user and starts its operation. The system aims to reach the set points. The set points are either the default values of the control variables stored in the smart card (during the initialization of the BEMS operation) or the short term preferences (STP), which correspond to the users' temporary requirements, or the long term preferences (LTP) that are evaluated by the central PC, taking into account the STP (monitoring the user behaviour for a specific time period,

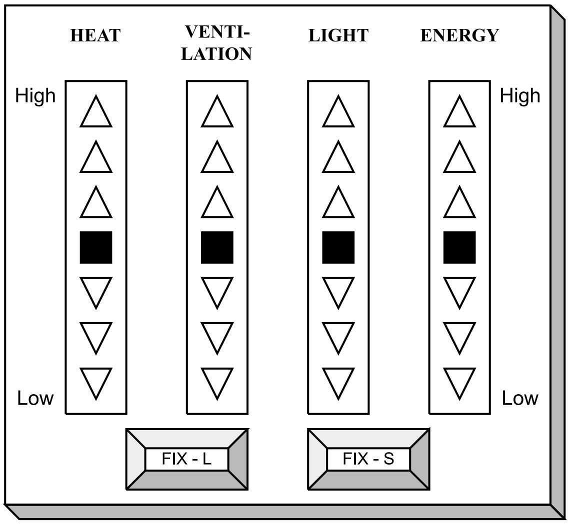


Fig. 3. The front panel of the smart card unit.

e.g. weekly). The LTP replace the defaults on the smart card. The LTP concept minimizes communication between the smart card unit and other components of the system.

(ii) While the system is in operation, the user can change his/her preferences by pressing the up (△) or the down (▽) arrow key on the panel. These changes are called the "delta of preferences". The delta of preferences values varies from -3 to $+3$, corresponding to the user demand deviations compared to the existing values of the control variables for each zone (e.g. $+1$ corresponds to "more", $+2$ corresponds to "much more", -1 corresponds to "less" etc.). Each time a delta of preferences is declared by the user, its value is forwarded to the PC, along with the existing set points and values of the control variables (PMV, CO_2, Illuminance). The PC evaluates the new set points, which are the new STP, and records them on the smart card via the PLC. The "delta of preferences" concept is introduced because users are not usually able to 'understand' the relation between the control variables values and their personal comfort needs.

(iii) The FIX-L and FIX-S buttons permit the user to set the lighting and shading manually to completely ON or OFF for some special cases (e.g. presentations etc.).

2.2. The sensors and the actuators

Each zone is equipped with specific sensors and actuators in order to monitor the control variables and perform the necessary actions.

The sensors installed for measurement of the environmental parameters of each zone are presented in Table 1.

The actuators installed are listed in Table 2.

The damper is directly connected to the analogue output of the PLC or the LON module. The window opening/closing actuators are controlled by a PLC or LON module I/O output, by transforming the linear output variable of the fuzzy controller to a digital signal with time duration corresponding to the variable value. The interconnection of the window actuator with the

Table 1
Sensors

Sensor type	Range	Output type (V)	Function
Mean radiant temperature	−30°C to 50°C	0–5	Linear
Indoor temperature	−10°C to 40°C	0–10	Linear
Relative humidity	0–100%	0–10	Linear
Air flow/hotwire anemometer	0–8 m/s	0–10	Linear
CO_2 sensor	0–2000 ppm	0–10	Linear
Illuminance sensor	0–4000 lux	0–10	Linear
Outdoor temperature	−10°C to 40°C	0–10	Linear
Outdoor humidity	0–100%	0–10	Linear

Table 2
Actuators

Actuator type	Input	Function
Relay for the air conditioning system and the electric lighting	24 V DC	ON/OFF
Window opening/closing motors	24 V DC	Linear
Shading opening/closing motors	220 V AC	Linear
Damper motor	0–10 V	Linear

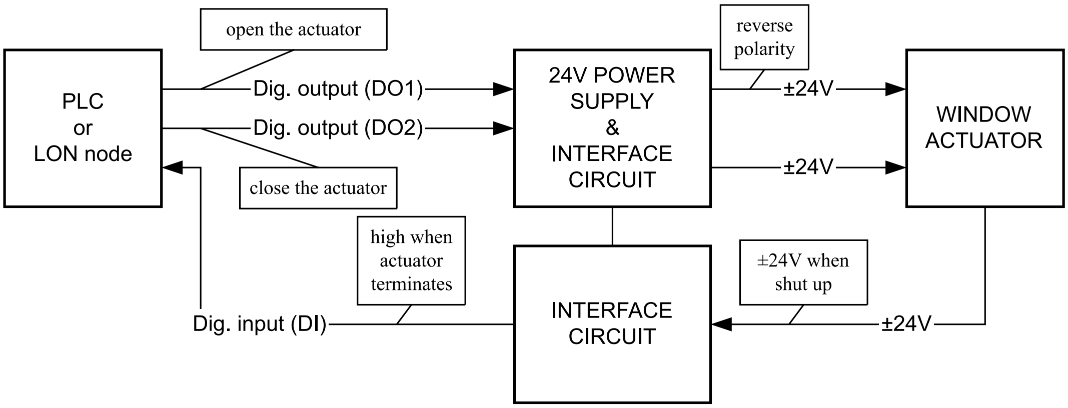


Fig. 4. PLC–window actuator interface.

PLC (or the LON module) is depicted in Fig. 4, while the flow chart of the program supporting the conversion of the fuzzy controller output to the digital signal is depicted in Fig. 5.

The shading actuators are driven by a 220 V input which changes from the open to closed position and vice versa with the use of a switch. The PLC–shading actuator interface is depicted in Fig. 6, while the flow chart of the program that converts the output of the fuzzy controller to the relevant digital signal is shown in Fig. 7.

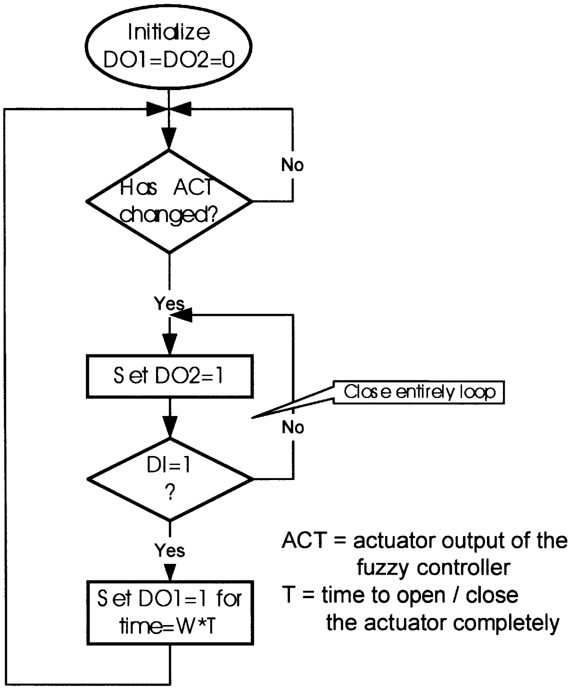


Fig. 5. Window actuator control flow chart.

2.3. The PLC controller

The fuzzy PLC controller, manufactured by the Greek Company AMBER S.A. [8], performs the following operations:

- Reads the sensors data through its analogue input channels.
- Runs the fuzzy decision support algorithm for adjustment of the indoor thermal and visual comfort and air quality levels.
- Drives the actuators through its digital and analogue outputs.
- Communicates with the smart card unit as master, using an RS 485 connection.

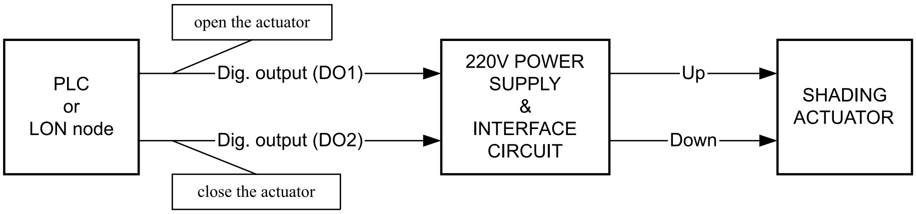
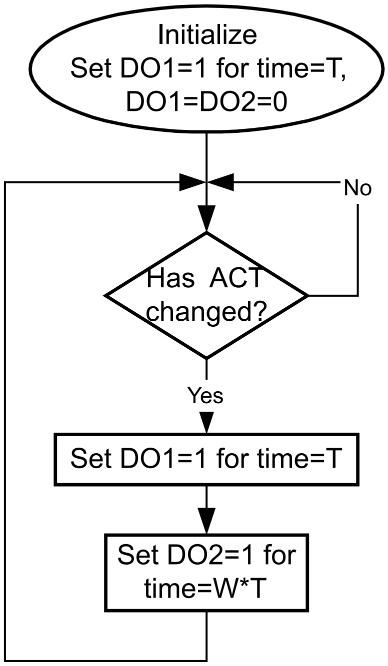


Fig. 6. PLC–shading actuator interface.



ACT = actuator output of the fuzzy controller
T = time to open / close the actuator completely

Fig. 7. Shading actuator control flow chart.

- Communicates with the PC as slave via an RS232 port through the LOONY (a LON device) [9].

2.4. The local operating network (LON)

The LON [10], is formed by a number of nodes, communicating over a variety of media, such as twisted pair, power lines, radio frequency, fiber optics etc., using an event driven protocol named LonTalk protocol. The LON nodes are intelligent devices that can be connected with sensors (temperature, humidity, illuminance etc.), actuators (HVAC, lighting, alarms etc.) and interfaces (displays, terminals, PCs etc.) and can run the relevant application program. The LON network is suitable for distributed control applications and features simple integration of different devices, higher performance due to peer-to-peer communications and low installation and reconfiguration costs. The media supported ensure the applicability of the system in existing buildings.

The LonTalk protocol, which follows the reference model for open systems interconnection (OSI), providing services at all seven layers, addresses its components using domain, subnet and node IDs. This simplifies replacement of nodes in an operating network. Free topology connection (ring, bus or star and all combinations of the above) is allowed.

2.4.1. The local operating network node

The node's hardware incorporates the neuron chip, which is fully programmable using the NEURON-C language. Each node has a number of I/O connectors where the sensors and actuators can be connected by using a suitable interface. The integration of the node with the interfaces forms the LON module. Furthermore, each node supports 62 network variables, which can be bound with other nodes variables to perform a specific task as soon as new information arrives (event driven property) [11]. The layout of the LON node is depicted in Fig. 8. The fuzzy controller application is programmed in the node using an appropriate development tool. In this case, the LON builder development tool is used. A flash EEPROM programmer is used to download the application program to the node.

Each LON module used in the present architecture performs the following tasks for each room/zone:

- Acquires data from the sensors and drives the actuators using its I/O interface.
- Runs the decision support algorithm for the zone.
- Communicates with the PC using the LOONY device.

2.4.2. The LOONY device

The LOONY unit [9] is manufactured by the Italian Company MAC SRL and is a LON node that has a few extra characteristics:

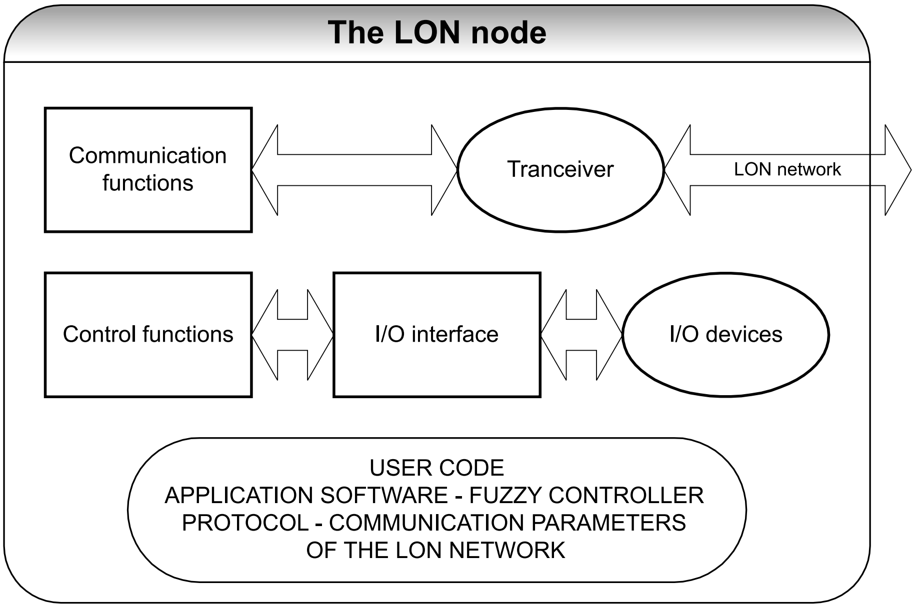


Fig. 8. The LON node.

- It is equipped with an EIA-232C serial interface (with selectable baud rate: 9600 or 19200) to enable any host processor or PC based program to perform network management or download custom applications with simple commands.
- It incorporates a twisted pair transceiver for connection to the rest of the LON network.
- It is equipped with an RS232 port that is used for communication with the PLC or the PC.
- The network variables of the LOONY device are pre-defined and pre-bound, thus minimizing the programming and installation effort.
- The LOONY can also be used as the network manager with a suitable PC program for the configuration of the network and identification of communication problems or errors over the LON network.

2.5. The role of the PC

The PC performs the following functions:

- Evaluates the STP from the delta of preferences polled from the smart card unit.
- Collects the control variables, monitors the system's performance and computes the energy consumption.
- Performs network management by means of a suitable program and the LOONY device.
- Adapts the membership functions parameters and the rules' weights of the fuzzy decision support system, based on an appropriate cost function, aiming to minimize energy consumption and simultaneously satisfy the users preferences.
- Readjusts the LTP of the users.

3. The communication of the various components

3.1. Smart card unit – PLC communication

Every smart card unit has its own eight digit serial number stored in the unit EEPROM by the manufacturer [12], used as the unit identifier in the messages.

The messages that are exchanged between the PLC and the smart card unit are:

Message PLC – Unit 1:	The PLC asks whether there is a card in the unit. The unit replies that the card is absent.

This implies that there is no user in the building zone.

Message PLC – Unit 2:	The PLC asks whether there is a card in the unit. The unit replies that the card is present.

The unit sends the user's preferences stored in the smart card to the PLC. The PLC initializes the fuzzy algorithm operation, which is responsible for satisfaction of the user's preferences (i.e.

the default preferences set by the manufacturer or the PC updated LTP). Simultaneously, the preferences are sent also to the PC (see Section 3.2).

Message PLC – Unit 3: The PLC asks whether a user's preference has been modified.
The unit replies that there is no modification.

In such case the question is continuously repeated.

Message PLC – Unit 4: The PLC asks whether a user's preference has been modified.
The unit replies that a preference is modified.

This delta of preference is used for evaluation of the STP. The deltas of preferences are transmitted via the PLC to the PC for evaluation.

Message PLC – Unit 5: The PLC sends the LTP to the smart card unit.
The unit acknowledges the transmission.

The PLC unit messages have the following format:

<STX><Unit number><Data><CRC><ETX>

where <STX> is start of text = 02 hex, <Unit number> is the unit eight digit serial number in ASCII (8 bytes), <Data> is the information, see the description below, <CRC> is the checking character (two digits translated in ASCII, giving 4 bytes) and <ETX> is end of text = 03 hex. Only the <Unit number> field is mandatory in such a message. So, the <Data> field can be empty. The field values are included in Table 3.

The same format is used for the smart card unit to PLC messages (Table 4).

3.2. PLC–PC communication via the local operating network

The PLC communicates with the PC via the LOONY device. Two LOONY 31 bytes long network variables are used for the communication. In this case, the PC is the master, while the

Table 3
Field values for the PLC to unit messages

Type	Value
01	Date and time, temperature, message to display (i.e. temperature information)
02	Values to modify the LTP: temperature, CO_2 concentration, illuminance level, Fix-L, daylight illuminance level, Fix-S, PMV
03	Values to modify the STP: temperature, CO_2 concentration, illuminance level, Fix-L, daylight illuminance level, Fix-S, PMV
04	Energy level to be stored into the smart card and to be displayed by the unit

Table 4
Field values for the unit to PLC messages

Type	Value
00	Card is absent
01	Card is present – information from the card (LTP stored in the smart card)
02	Card is still present – no modification from the user
03	Card is still present – the following modifications ("delta of preferences") are made from the user
04	Card is present – the data modification of the card is completed successfully
05	Card is present – the data modification is not completed successfully

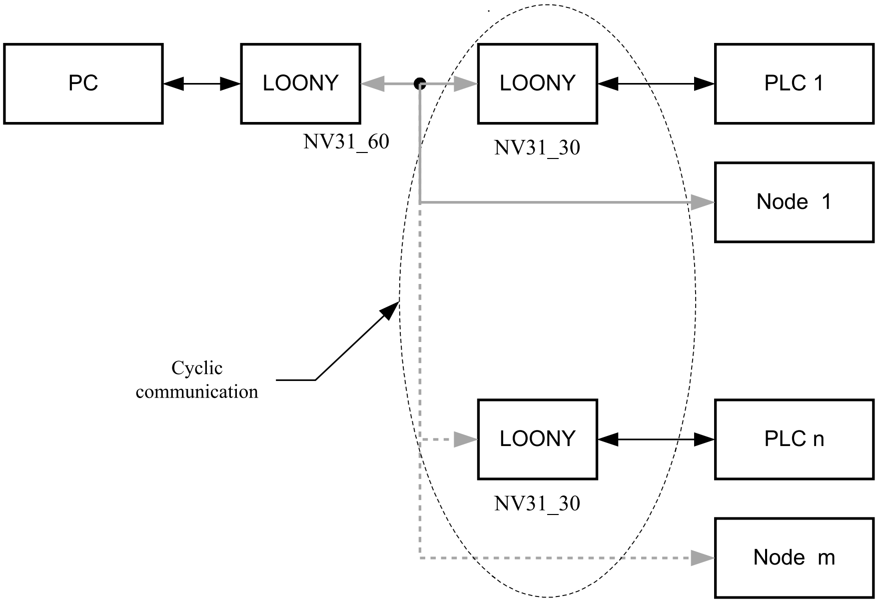


Fig. 9. The communication between the PC and the various zones.

PLCs and/or LON modules are the slaves, as depicted in Fig. 9. The messages exchanged are tabulated in Table 5.

The structure of the network variables used is user defined, as follows. The first byte indicates the message type that follows and is named INDEX. If INDEX is set to 0, then PC (or PLC) requests data. The second byte indicates the type of request. If INDEX differs from 0, then the type of message depends on the INDEX number.

For example, the messages, type 1 and type 2, are shown below:

Table 5
The PC–PLC messages

Message no.	Message type	Message
MSG 0	PC asks PLC	Is there a smart card?
MSG 1	PLC replies	No
MSG 2	PLC replies	Yes and sends the smart card data
MSG 3	PC sends data to the PLC	The set points are…
MSG 4	PLC replies	ACK
MSG 5	PC asks PLC	Request update
MSG 6	PLC replies	The parameters of the zone are… The user's preferences are…
MSG 7	PC sends data to the PLC	The new LTP are…
MSG 8	PLC replies	ACK
MSG 9	PC sends data to the PLC	The parameters of the membership function are…
MSG 10	PLC replies	ACK
MSG 11	PC sends data to the PLC	The rule weights are…
MSG 12	PLC replies	ACK

Index no. 0: The PC asks the PLC whether there is a smart card (SC) in the unit (MSG0)

Index	Type of request: Is SC in the unit?	Bytes
0	1	2

Index no. 1: The PLC replies no card (MSG1)

Index	Data of the variable	Bytes
1	0	2

Index no. 1: The PLC replies that card is in the unit (MSG2)
The PLC must send to the PC the LTP read from the smart card.

Index	Data of the variable	Bytes
1		1
	Temp (LT-TE)	2
	Air quality (LT-CO_2)	2
	Light intensity (LT-LI)	2
	Fix flag for lighting (LT-FL)	1
	Daylighting-shading (LT-SH)	2
	Fix flag for shading (LT-FS)	1
	PMV (LT-PM)	1
	Total bytes	12

Index no. 2: The PC sends the set points to the PLC(MSG3)

The PC sends to the PLC the set points that correspond to the LTP that are stored in the smart card.

Index	Data of the variable	Bytes
2		1
	Temp (S-TE)	2
	Air quality (S-CO_2)	2
	Light intensity (S-LI)	2
	Fix flag for lighting (S-FL)	1
	Daylighting-shading (S-SH)	2
	Fix flag for shading (S-FS)	1
	PMV (S-PM)	2
	Total	13

For example, if the set point for LT-TE is 23.5, the PC sends 235 (2 bytes) that should be multiplied by 0.1.

Index no. 2: PLC ACKS (MSG4)

Index	Type of message	Bytes
2		1
	0 = ACK	1
	Total	2

The communication flow chart for the PC is depicted in Fig. 10, while the corresponding flow chart for the PLC is shown in Fig. 11.

4. Conclusion

The system is already installed in the Electronics Laboratory of the Technical University of Crete. The system's response is tested during real time operation, and it behaves as expected.

The architecture, as well as the communication, could be made simpler if only local operating nodes are used, because the PLC complicates the communication and increases the number of components required (i.e. the LOONY device). The PLC controller can be used alone if the disposal of a PC is not desirable. Furthermore, already existing PLCs in various zones, that are in use for other purposes, can be used for indoor comfort control, with some modifications. The LON devices used are not of commercial type but are custom developed.

The BEMS integrates recent technological developments, such as LON modules with mature components, such as PLCs. One of the major advantages of the proposed architecture is the incorporation of the smart card unit acting as the user machine interface. The occupants

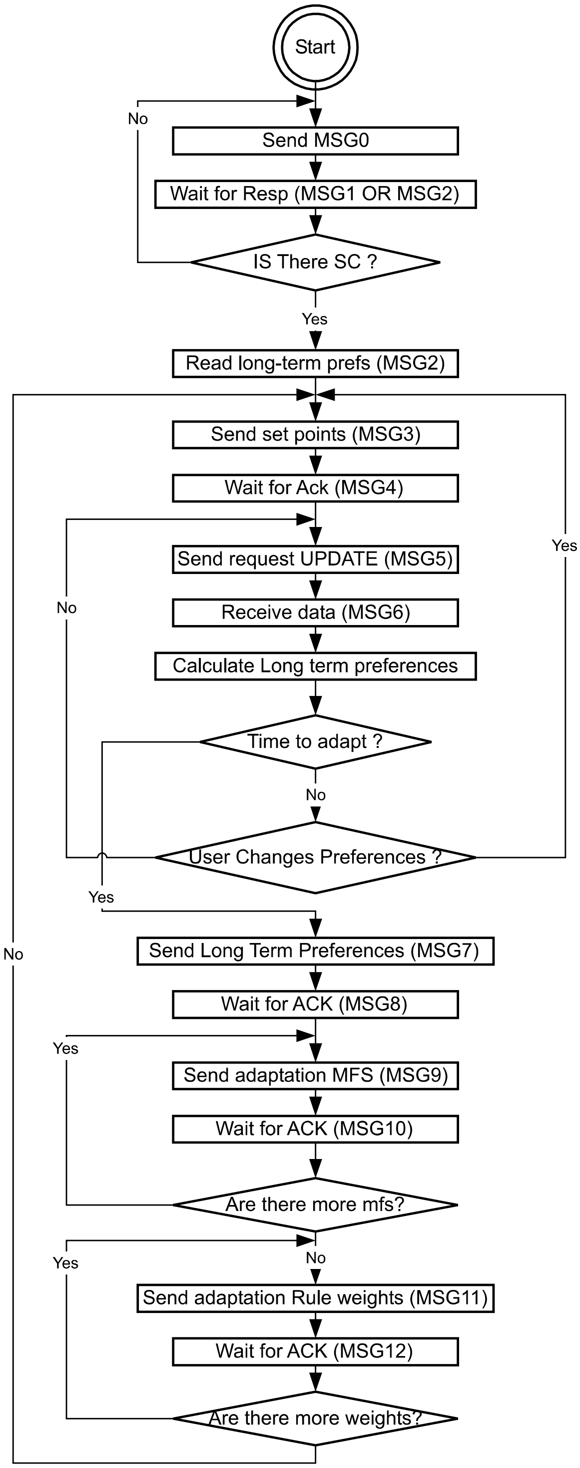


Fig. 10. The PC–LON communication flow chart.

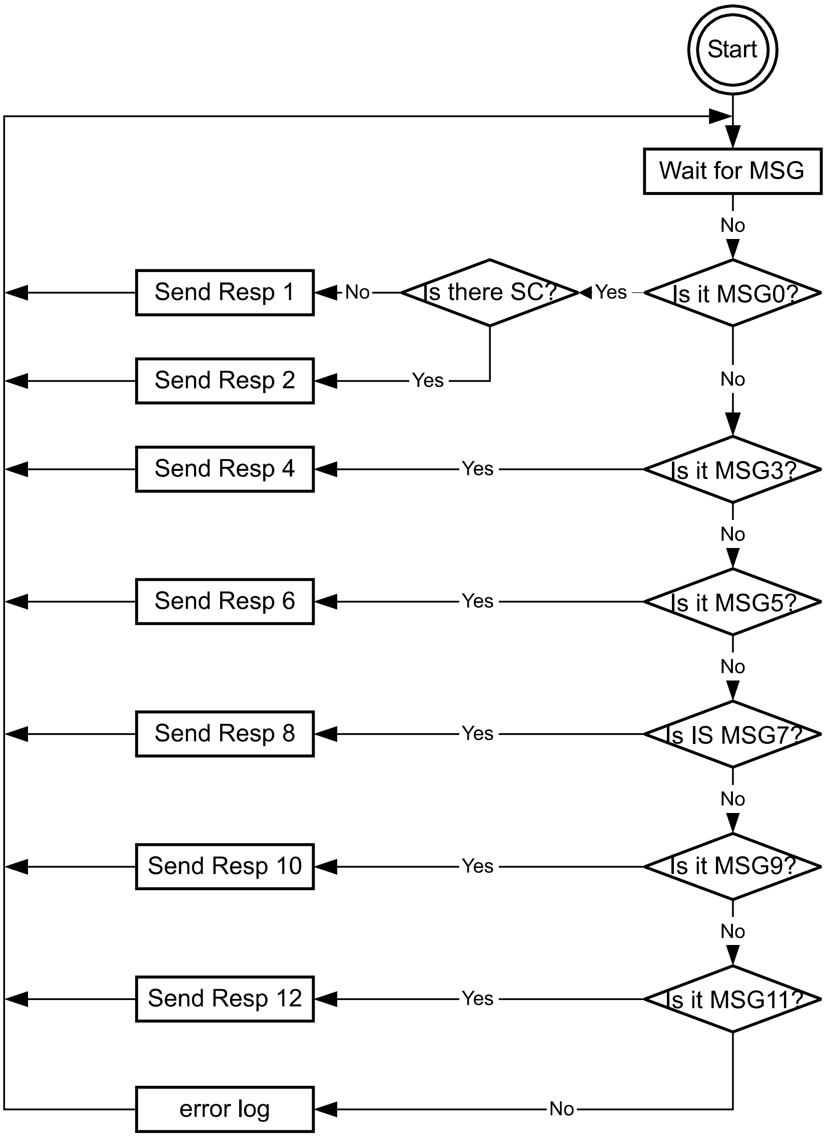


Fig. 11. The PLC–LON communication flow chart.

discomfort, which usually arises when tight control of indoor comfort is applied, is diminished as the users interact with the system.

Acknowledgements

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