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Sensor Interfaces for Private Home Automation: From Analog to Digital, Wireless and Autonomous

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Abstract: In this paper a flexible and reliable system for smart home automation is presented. It is based on standardized hardware and open source communication protocols.

Firstly, a special sensor interface has been developed, which allows the measurement of (slow) analog signals to be determined by inexpensive digital PLC input terminals. Right now, up to eleven different modules have been implemented and the system is being tested in several configurations.

In a second step, the communication is digitized. With the digitalization of the sensor modules, based on the implementation of a PIC Microcontroller, more intelligence is provided to the module, which increases the power and flexibility of the whole system. Thirdly, a wireless sensor-system consisting of a base station and of a mobile measuring unit is developed. The autonomous mobile unit is realized by using solar powering, gold cap energy storage, low-power circuits and a radio communication interface. *Copyright © 2007 IFSA.*

Keywords: PLC, Sensor interface, Frequency coded signal, Wireless sensor, Autonomous sensor

1. Introduction

Private home automation is an increasingly important market. The major tasks are climate control, comfort and remote control, but also energy management [1]. Today, there are several systems for private home automation available, which all suffer from certain problems. Many companies develop their own communication protocol and software for their special sensor/ actor application. With the introduction of the European Installation Bus (EIB) a standard was defined. The aim of this project is the development of a smart home automation system based on wide spread standards. We propose the use of industrial Programmable Logic Controllers (PLC), which are programmed in standardized programming languages according to IEC61131-3. They communicate via Ethernet and use open protocols like MODBUS and HTTP. If new hardware is to be added, the corresponding module can easily be implemented. The program even runs on quite different PLCs due to its standardized programming languages. In the following, the idea behind the flexible smart home system is described in detail. An introduction to the PLC will be given and the novel sensor interface will be introduced. Some examples of already implemented modules will be given and, finally, two ways of communication with the “smart home system" via application programs are described.

2. Idea of a Flexible Smart Home System

The main problems of today’s smart home systems are high costs and low flexibility. This is illustrated in Fig. 1. On the left side of this figure we demonstrate how an automated house with presently available solutions looks like. The house is provided with single solutions for several automation tasks. Each room's heating has its own temperature control circuit [3]. The single tasks are not combined in an intelligent supervision system.

The lack of flexibility results from the fact that many single solutions from several manufacturers are necessary. These solutions are in general not compatible. Each solution has its own control and supervision software and the communication platform is usually not open even for advanced users.

Therefore, it is impossible to set up a completely integrated system. The solution we suggest incorporates the use of an industrial PLC for all automation tasks [4], [5]. These controllers are rather inexpensive and highly reliable. Support will be guaranteed for years because of the high industrial investment which has been put into PLCs. Different bus connections can be integrated (e.g. Ethernet). The controller software and the bus protocol (TCP/IP) accord to open standards and, therefore, are open to the user. A configuration example for such a system is shown on the right hand side of Fig. 1. Platform independent supervisor software can be programmed, which runs on any computer connected to the World Wide Web.

3. Technical Details of PLC Controller

For this project we use the PLC BC9000 from Beckhoff [6]. This controller offers a serial programming port and Ethernet connection. Therefore, it can communicate with PCs and other controllers within the local area network (LAN) and, it can be contacted from anywhere in the world when the house is connected to the world-wide-web. So far, we realized a solution where the house is not directly connected to the world-wide-web, but links via router and ISDN telephone net to another router point. The PLC contains 96 kByte of program memory and 128 kByte of variable memory. Only 4 kByte of this memory can be located externally. Therefore, an effective structure for the use of the exchangeable data had to be found. A structure was created which can be used for every system:

- **Header:** contains information about the implemented system, the kinds and numbers of modules
- **Global variables:** variables which every system contains, for example outside temperatures, radiation, presence switch
- **Current measurement data:** data which is monitored, for example heating status and temperature for a temperature regulation circuit.

The exchangeable memory is organized in a way that the application program does not have to know anything about the implemented system, but can read everything from the information in the header. In the following, the analog, the digital and the wireless sensor interface are described.

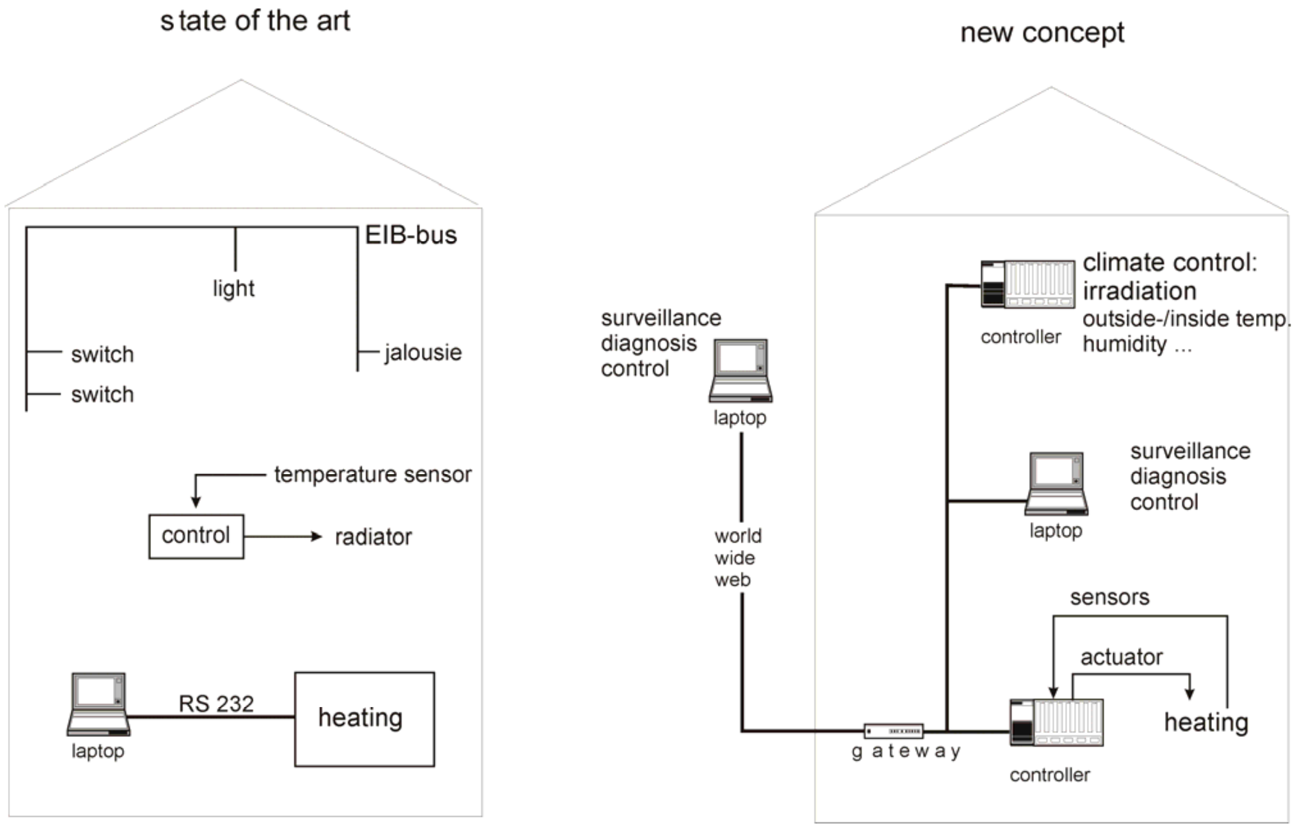

Fig. 1. Principles for home automation.

4. Analog Sensor Interface

We have set up a demonstration system for climate control including sensors for inside and outside temperature, illumination and humidity. A modulated supervisor and control program has been implemented for several climate control tasks (heating, humidity). Furthermore, we have developed a sensor interface for analog sensors, which converts the analog into a digital (frequency coded) signal [8]. This interface offers two great advantages. First, the sensor can be connected simply by two wires to an inexpensive digital PLC input channel. Second, the signal can be transported over long distances in a fail-safe way. Because this is not a field bus system, simple switches and binary sensors without expensive bus interfaces can be connected to the PLC as well.

In Fig. 2 the interface circuit is depicted. The transistor Q1 is controlled by a frequency signal which is proportional to the sensor signal. If Q1 is open, the digital input DI is at low potential which is interpreted as logical LOW or FALSE. In this state we have a high potential difference between the point 1 and 4 of the rectifier bridge and the capacitors C7 and C6 are charged. The voltage control IC MIC5234 generates the 5V supply for the sensor circuit which is not shown here. If the transistor Q1 is closed, the digital input (DI) is pulled to a higher potential, the capacitors are not charged anymore and they have to supply the energy for this state. This is interpreted as HIGH or TRUE. The diode D10 prevents them from discharging into the digital input. This circuit allows transportation of energy in one direction and signal in the other direction with only a two wire connection.

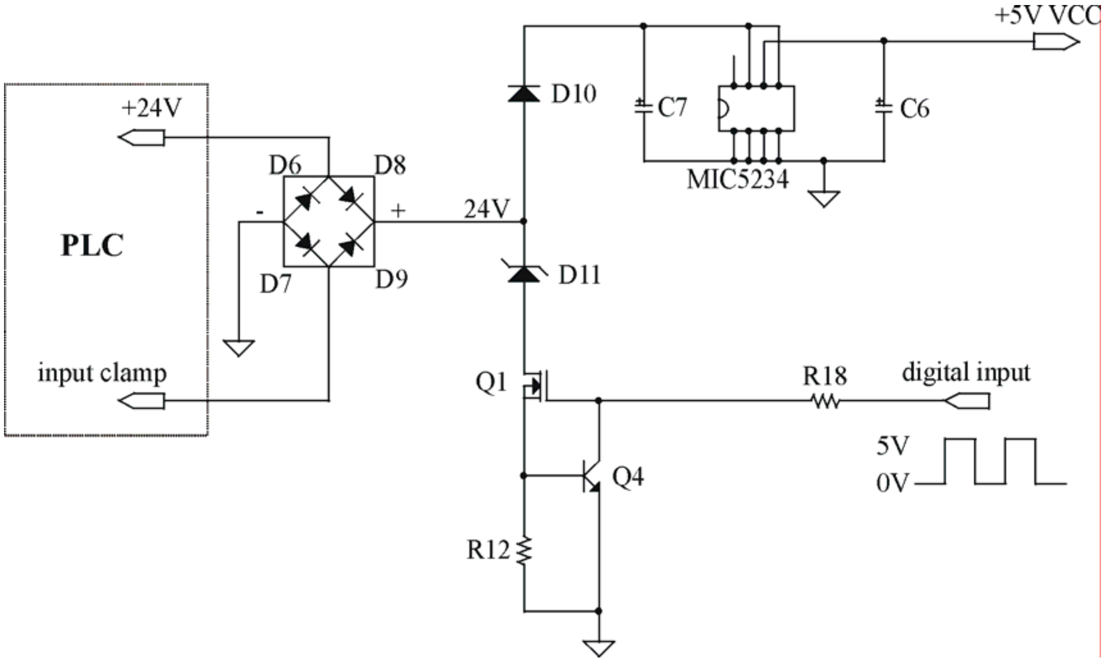

Fig. 2. Circuit of the sensor interface.

4.1. The Modular PLC-Program

One specific working principle of a PLC is, that the program does not have access to the IOs at any time, but only at the beginning and the end of a program cycle. For the frequency measurement routines we need well defined and very short cycle times. On the other hand, the control subroutines take longer, depending on the numbers and kinds of modules implemented in a certain system. This problem has been solved by branching into different program segments at the very beginning of the main program. On the left side of Fig. 3 the frequency measurement branch is shown. It measures up to eight frequencies within a predefined cycle time of 2 ms. If more than eight frequencies are to be measured, a second branch has to be included. The whole frequency measurement takes three seconds in order to achieve a resolution of 1 Hz. The right branch in Fig. 3 contains the actual control routines and is programmed in a modular and object oriented way.

Each control module represents one object. The user defines the needed modules for his project and creates as many instances of this module as needed.

4.2 A Temperature Sensor with Frequency Output

With the above described sensor interface we developed a radiation sensor, a humidity sensor and a temperature sensor (Fig. 4), which will be characterized briefly in the following. The sensor element is a temperature chip MAX6605 from Maxim. It produces an output voltage proportional to the ambient temperature. This voltage is transformed into a frequency signal by a VCO (voltage controlled oscillator) circuit which is part of the interface described above. Fig. 5 shows the accuracy which can be achieved with the temperature sensor.

Although quadratic approximation gives of course better results than linear approximation, we decided to use linear approximation with respect to production costs. In the circuit we implemented a digital potentiometer, which allows a one point calibration, which also is less costly than two point calibration. A tolerance of less than 0.5 K could be reached.

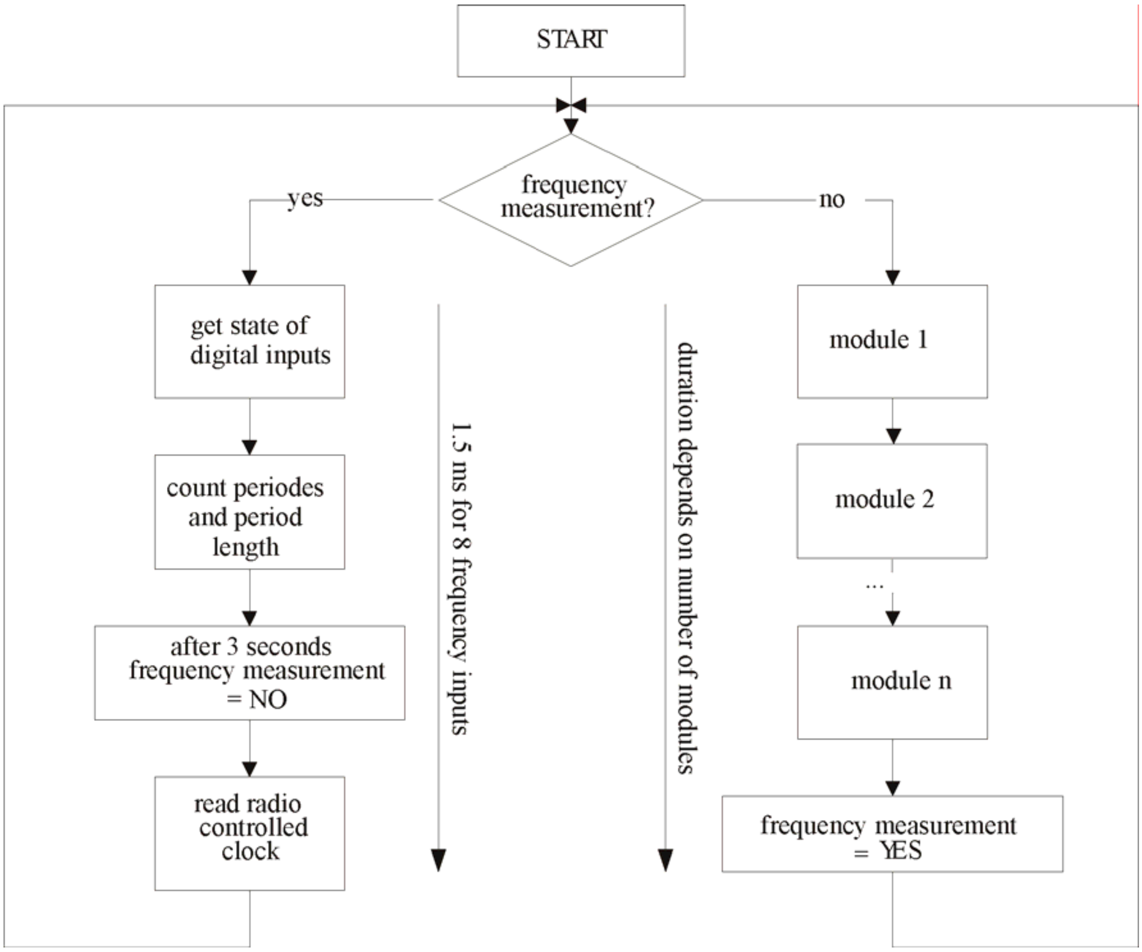

Fig. 3. Structural diagram of the PLC program.

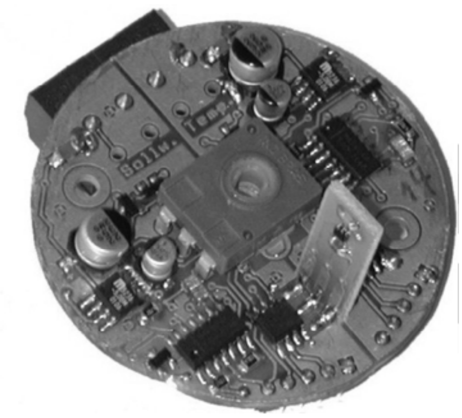

Fig. 4. Temperature sensor.

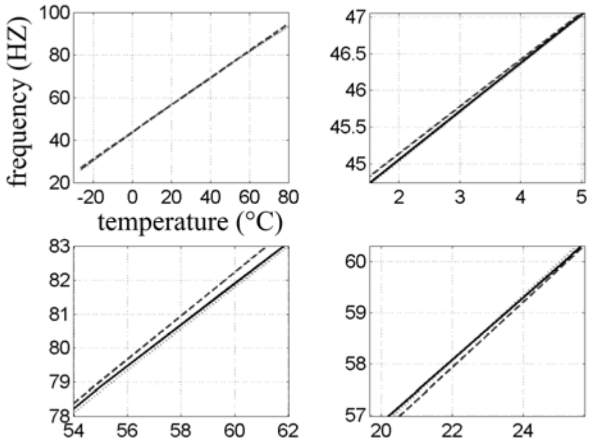

Fig. 5. Highly linear, inexpensive temperature sensor with digital interface; measurement (---), linear approximation (-~-) and quadratic approximation (...).

5. Digital Sensor Interface

The advantages of the analog, frequency coded interface are its relative simple circuit, the two wire connection and its connection to the inexpensive digital input of the PLC. Its disadvantages on the other hand are the relatively slow readout and limitation of information by the frequency coding of the signal. Therefore, the communication has been designed to be a digital communication. This was realized without dropping any of the advantages. The sensor module is divided into two major parts as it is shown in Fig. 6. These two parts, the power supply circuitry and the sensor circuitry, are situated on two different boards. This design offers the possibility to have one power supply unit as a multi-purpose element to use with different sensor units.

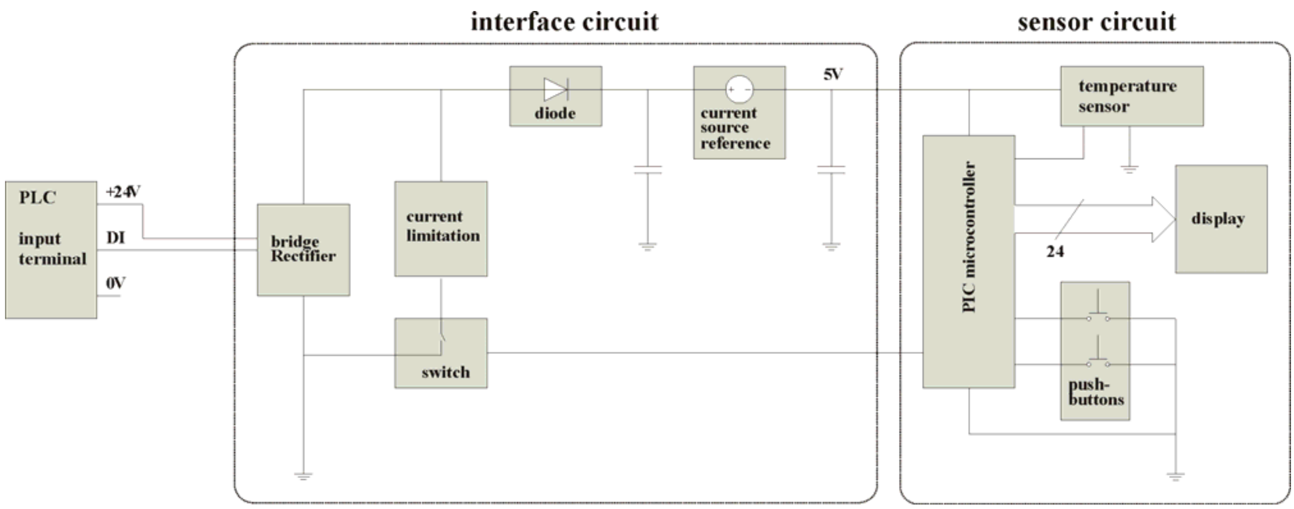

Fig. 6. Structure of the digital sensor modules.

The power supply unit is very similar to the one of the old module. It consists of a rectifier that prevents wrong polarity connection, a signal switch that is driven by the microcontroller and creates square pulses, and a simple reference power source, consisting of a diode, a transistor, a resistor and two capacitors. The fact, that the digital sensor unit does not need an extremely stable reference power source, allows this simple and very cheap version of a supply unit. The power supply unit is connected with a simple two wire cable to the PLC control unit. This connection supplies the sensor module with energy as well as it transfers the data signal. In case of a closed signal switch, the signal input of the PLC control unit is directly connected to 24 V, which is detected by the PLC as a logical 1. By opening the signal switch, the signal input line is in idle position, what is detected as a logical 0. In this state, the reference power source is connected to 24 V and the sensor module is supplied with power.

The heart of the sensor unit is represented by the PIC microcontroller. The temperature sensor is connected to the microcontroller as well as the display, the push buttons and the signal switch. The analog signal of the temperature sensor is directly received, converted and sent by the microcontroller. Therefore, the accuracy of the sensor module depends only on the accuracy of the temperature sensor. Thus, the same sensor module can be used for different requirements by only changing the temperature sensor board. The LCD Display is directly connected to the microcontroller, which requires low power consumption. To prevent a damage of the display, a continuous change of the polarity of the display is necessary. The push buttons to change the rated temperature value are polled by the controller, what prevents a filter to avoid oscillations. To create the sensor signal, the microcontroller directly controls the signal switch.

5.1 Structure of Transmission Signal

As described in the last section, the connection line to the PLC is used for power supply as well as for the data transfer. The analog sensor modules send a continuous rectangle signal. The frequency of the signal represents a linear measure of the temperature. The new sensor module, however, sends a data word, representing the temperature value as a binary word. In Fig. 7, the frequency coded sensor signal (analog version) is compared to the new digital sensor signal. This figure shows, that the old transmission signal only allows the transmission of one data value on one line. The new sensor signal permits a serial transmission of more than one value.

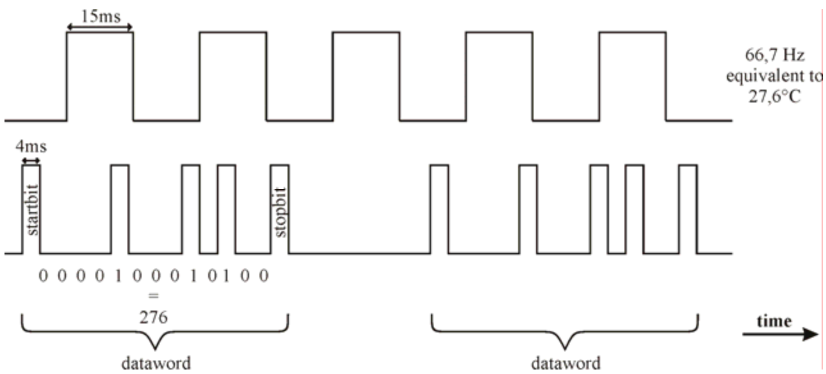

Fig. 7. Comparison of the two sensor signals – Above: Frequency coded signal; Below: Digital data signal.

The digital sensor signal contains a start and a stop sequence, a signal ID to distinguish the different signals and the data value that consists of one bit for sign and 12 bits for the value. A problem by transferring the data was the fact that a synchronization of the PLC and the sensor modules is not possible. To detect errors and prevent false data transmission, one data bit is masked with a falling flank for a low bit and a rising flank for a high bit. An example for a whole data word is shown in Fig. 8.

The development of the new transmission signal is the basis for further development of the smart home system. On the one hand, with the new transmission signal, a wireless transmission is possible, on the other hand, the prerequisite for a bus system is made.

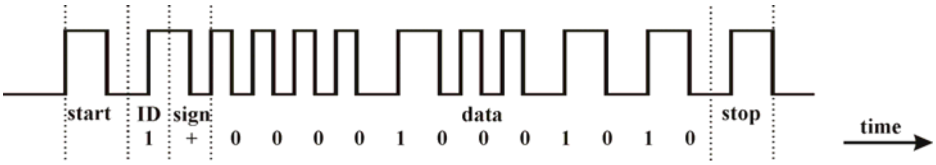

Fig. 8. Data signal of the new sensor modules.

5.2 The Microcontroller Program

The PICmicro microcontroller is the heart of the digital sensor modules. In the case of the temperature sensor, the model PIC 16F877A was used. It reads the temperature sensor and the push buttons, controls the display and sends the data to the PLC main unit. The structure of the microcontroller program is shown in Fig. 9. By powering up the PLC or connecting the sensor to the PLC, the initialization sequence starts. This sequence defines the microcontroller settings, loads the last saved rated temperature value and starts the first temperature measurement. After the termination of this sequence, the main program starts. As long as the sensor module is connected to the powered up PLC, the main program is repeated every 8.8 µs. The first item in the main program is the output of the temperature value to the LCD display. To prevent damage of the display, it is important to change the polarity of the output voltage at every execution of the main program. The next item is to serve the serial output. Every execution of the main program, one data bit is sent to the PLC. In case that the sending of one data word is completed, a new measurement of a temperature value is initiated. After the termination of the measurement, the value is saved in the EEPROM of the microcontroller. The last item of the main program is the polling of the push-buttons and in case of an event, its processing. At the end of this last item, the microcontroller waits until the cycle time of 8.8 µs passes and restarts the main program.

5.3 The PLC Program

As described in section 4.1, the software of the PLC is modularly structured. Similar to the microcontroller program, the main program of the PLC restarts itself after a cycle time. The cycle time of the PLC amounts to 4 ms; that makes it possible to sample one bit sent by the sensor module at least two times. An advantage of the new module is a faster identification of the value. The transfer of the data value is completed after the signal time of 0.35 ms.

5.4 Test Results for Temperature Sensor Module

To test the function of the sensor modules, they were put into a climatic chamber, together with a high precision PT100 temperature sensor. The first test was a temperature cycle, starting at -10 °C, rising the temperature by steps of five degrees to a temperature of 60 °C. The results were quite satisfactory. In Fig. 10 the difference of the digital sensor module, the PT100 and the temperature sensor of the climatic chamber are shown. At room temperature, the difference to the PT100 sensor is less then 0.5 °C. With very low and high temperatures, the difference to the PT100 rises up to 1.5 °C. The values represent the specifications of the utilized temperature sensor chip. The second test was a humidity cycle at a constant temperature of 30 °C. This test proved the independence of the temperature measurement from humidity. During the tests of the digital sensor module, it is constantly connected to an existing system and is working without any problems.

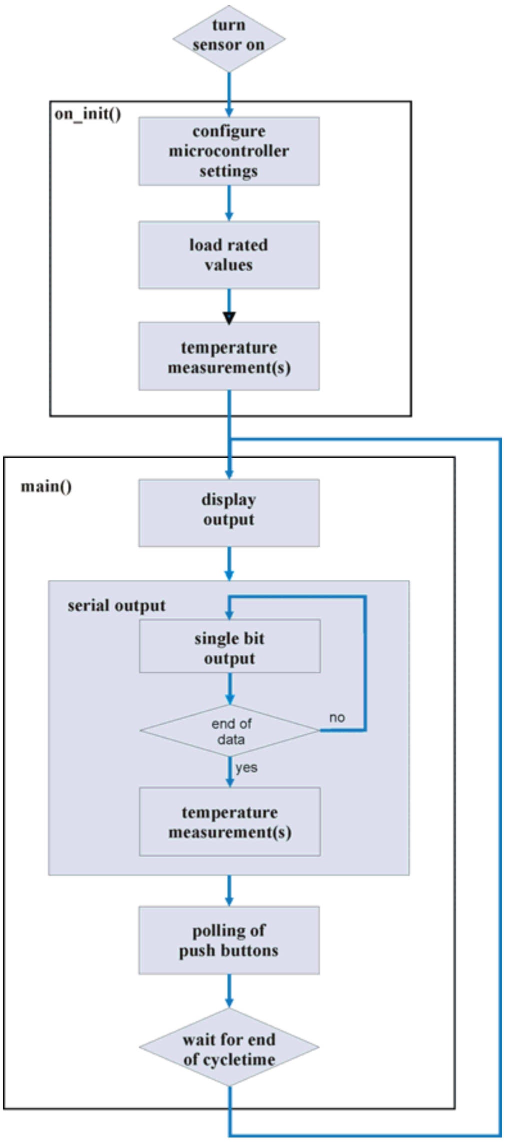

Fig. 9. Structure of the microcontroller program.

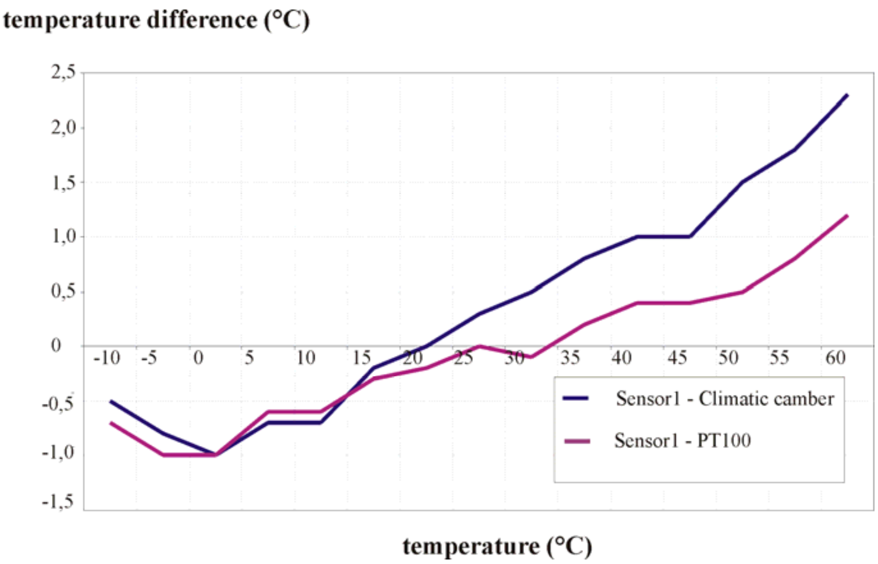

Fig. 10. Test results of the digital sensor module.

6. The Need for Wireless Sensor Systems

Measurements on places, where wires cannot be accepted are in most cases recorded by battery powered devices. Sending information optical or by radio frequency to a receiving unit is commonly used. The disadvantage of those systems is the necessity of batteries. A maintenance-free platform for interfacing sensors has been developed. In this document the platform is also referred to as sensor module with the following features (Fig.11):

- intelligent programmable energy management
- terminals for solar cells (energy source)
- terminals for the double layer capacitor
- microcontroller as central device
- RF-transceiver interface
- user interface (three push-pull buttons; alphanumerical LCD)
- remotely controlled and parameterized measurements by utilizing RF-transceiver technology.

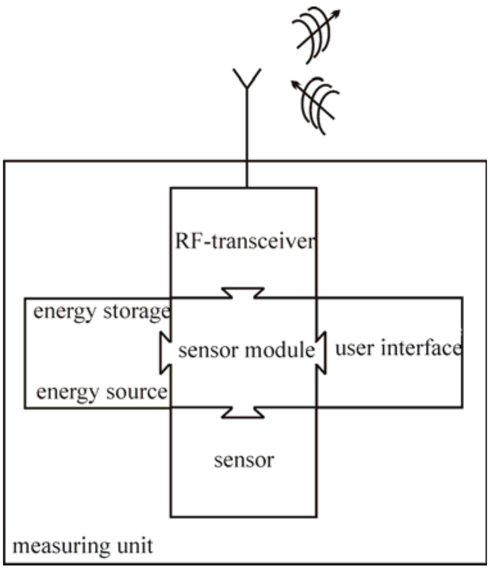

Fig. 11. Measuring unit built with the sensor module.

6.1 Development of a Wireless, Autonomous Sensor

A developed and tested system for the use of one or more measuring units with a PLC and a PC is illustrated by Fig. 12. Units, which receive or convert data are connected to a RS422-bus.

Each measuring unit is defined by a dynamically changing ID code, which has to be initialized by the user interface before the first communication procedure. Compatibility of the base unit with the PLC-protocol described before is achieved by PLC-converters. For every sensor unit, one corresponding converter is required. Alternatively the PLC-converters may be replaced by extending the PLC with RS422-ports.

Measured data can be recorded with LabVIEW and will be shown in this document (DLC-voltage curves, Fig. 18).

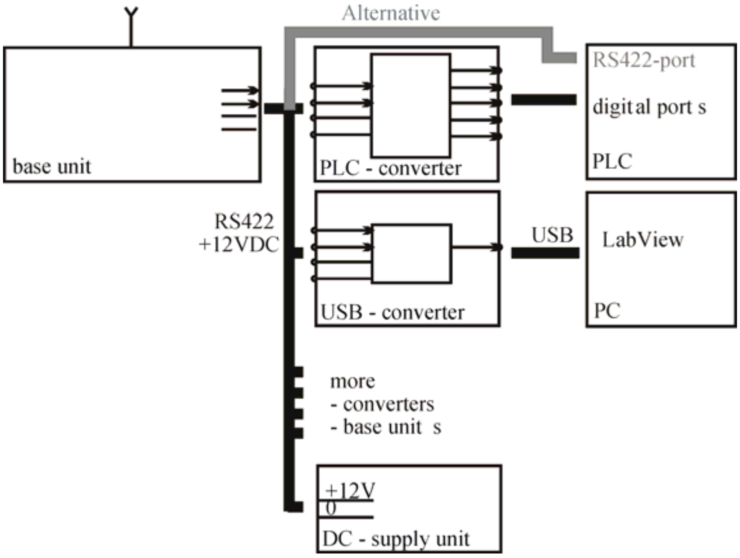

Fig. 12. System with interface to a PLC and a PC for data recording with LabVIEW.

6.2 Energy Management

Basic requirement for miniaturization of the sensor unit is a high efficiency low-power energy management. This leads to a small surface of the solar cells. In addition, the circuit should be implemented with a small amount of components, to reduce PCB-surface and costs. Fig. 13 gives a solution for the mentioned issue, showing the schematic diagram of the developed energy management:

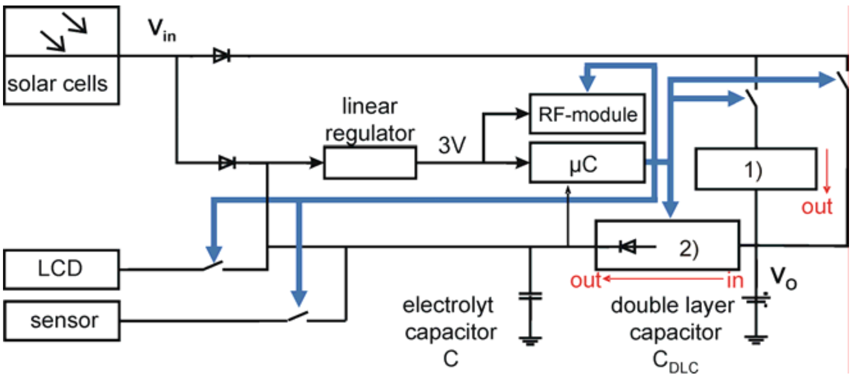

Fig. 13. Schematic diagram of the low-power energy management:
1) Buck converter for optimized charge with regulated Cell Voltage;
2) Microcontroller implemented boost converter for operation in darkness.

The central microcontroller operates over 99.9 % of time in a low-power mode, while a crystal stabilized low frequency oscillator for the real-time clock (RTC) is activated. The power consumption should be less than five microamperes, including the supply current of the linear regulator (used controller: MSP430-microcontroller, Texas Instruments; used regulator: XC6201, Torex Semiconductor).

During the initializations process, all devices, excluding the microcontroller are switched off. The capacitor C is charged by the current of the solar cells within some seconds, while the microcontroller RTC timed measures the current with a switched resistor divider. In addition, the DLC-voltage and the voltage over C is measured. Depending on the states of the capacitors, the current of the solar cells and the requests for transmitting sensor data, the microcontroller activates or deactivates the charging path with or without regulator for optimized energy storage.

Charging Regulator

Solar cells show their maximum efficiency at the maximum power point (MPP). The MPP cell-voltage V_{mpp} and the current density J_{mpp} depend on the illumination, illustrated by Table 1.

Table 1. Typical data for OEM-indoor cells from RWE SCHOTT Solar GmbH.

	100 lx	200 lx	1000 lx
V_{mpp}	410mV	430mV	475mV
J_{mpp}	$7.1\mu A/cm^2$	$14.2\mu A/cm^2$	$71\mu A/cm^2$

Assuming that illumination is between 200 and 1000 lx (typical indoor values), eight solar cells connected in series with the characteristic of those contained in table 1 have a MPP-voltage between 3.4 and 3.8 Volts. A high-efficiency synchronous buck converter (TPS62200, Texas Instruments) and a feedback-circuit with an operational amplifier an some passive devices were used to regulate the cell voltage to a constant value of about 3.6 Volts (V_I =3.4V), see Fig. 14.

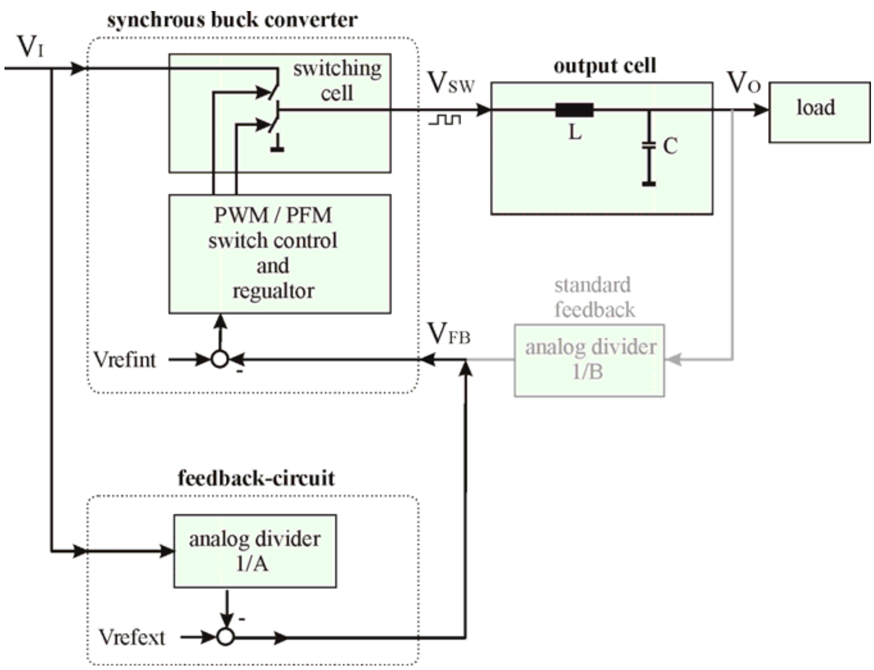

Fig. 14. Control loop for the charging regulator instead of controlling V_O with a standard feedback (grey hatched).

Furthermore, this allows the stable operation of the microcontroller while the DLC is charged with a good compromise of design complexity and efficiency (Fig. 15).

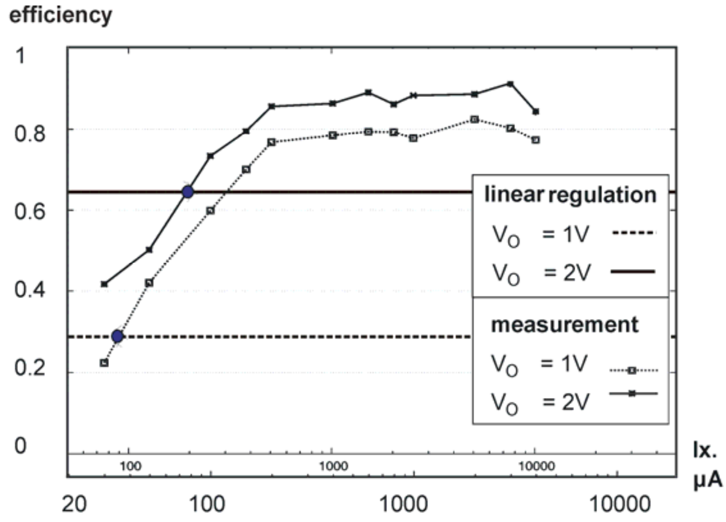

Fig. 15. Control loop for the charging regulator instead of controlling V_O with a standard feedback (grey hatched).

Ideal assumed efficiency of a linear charging regulator and measurement results switched power charging regulator (Lx-scale is approximated for the use of 8 solar cells with an area of $A=56cm^2$).

Microcontroller Controlled Boost Converter

After C and C_{DLC} (Fig. 13) were charged, the boost converter can be activated for burst mode to reach operation in darkness. The Output capacitor of the boost converter is C. The output voltage V_{boost} supplies the steering microcontroller and one selectable device (Fig. 17).

Two peripherals of the microcontroller are used for the boost converter: a PWM-timer and a comparator. The microcontroller directly drives the gate of a trench n-channel MOSFET T. The PWM-voltage V_{PWM} is generated in a low power-mode with the current consumption I_{micro}, which can be approximated by a constant value, caused by the linear regulator. A comparator input is used for switching of the boost converter, when V_{boost} exceeds a certain level defined by R_{div1}, R_{div2}, and R_{divGND}. The resistive feedback dividers are shown in Fig. 17 and are represented by R_{div} in the simplified equivalent network of the boost converter (Fig. 16).

Once activated by enough light, the sensor module operates with a wide ranged DLC-voltage 0.7 V < V_O< 2.5 V. The linear regulator is convenient for the use of the RF-transceiver, when a capacitor (C) is charged with a voltage above 4 Volts. After the short data transmission there is no noise of a switching supply, which could negatively influence the receiving-phase for data acknowledgment.

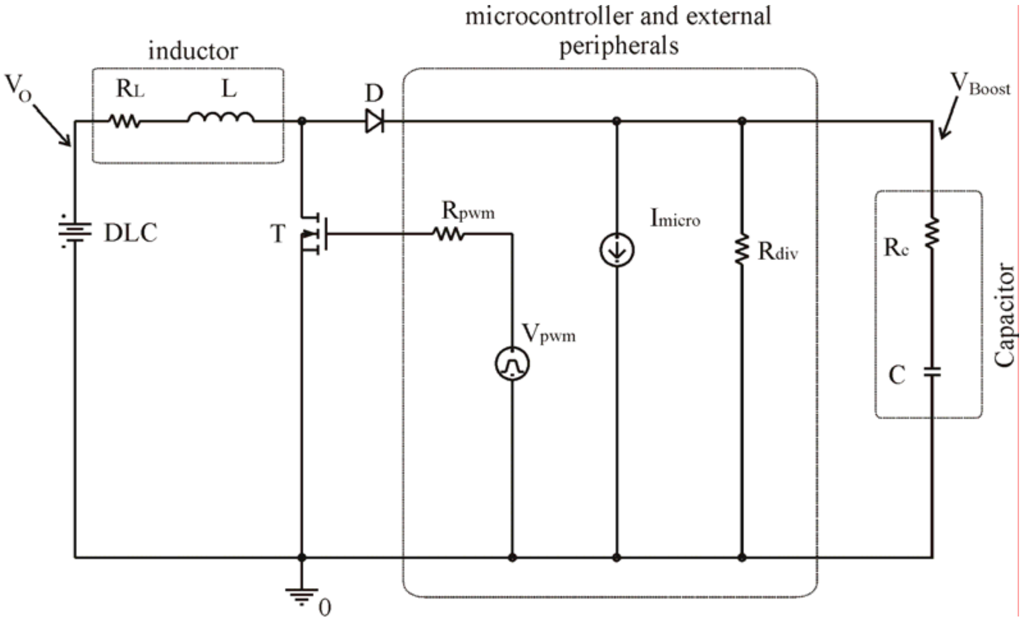

Fig. 16. Simplified equivalent network of the boost converter.

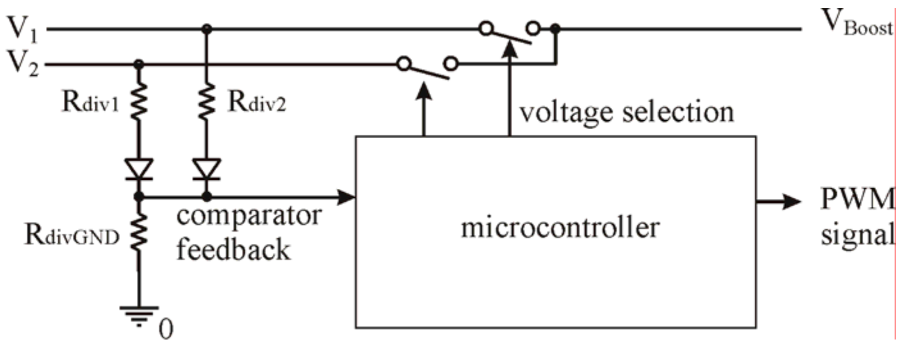

Fig. 17. Comparator feedback for the microcontroller.

Benchmarks

The following configuration was used for benchmarking the energy management:

- C_{DLC} = 4.7F, ELNA, DZ-2R5D475N
- Full operation range between 0.7 and 2.5V
- A_{solar} = 56cm^2 (amorph Si, see Table 1)
- RF-transceiver: TRF6901, 32kBit/s
- Light source: 100 W standard bulb
- Sensor: Temperature and humidity sensor SHT11 from Sensirion
- Analog measurement and data transfer every *x* minutes
- Additional redundancy for RF-traffic: 40 %
- Display not activated.

The charging time

$$t_c = \frac{79.8h}{0.0273 \cdot b \cdot (1/lx) - (1 + \frac{1.36\,\text{min}}{x})}, \qquad (1)$$

for the double layer capacitor depends on the brightness *b* in lx and the interval time *x* in minutes. Operation without light is possible for the time

$$t_O = \frac{136h}{1 + \frac{3.64\,\text{min}}{x}}, \tag{2}$$

measurements of V_O are shown in Fig. 18.

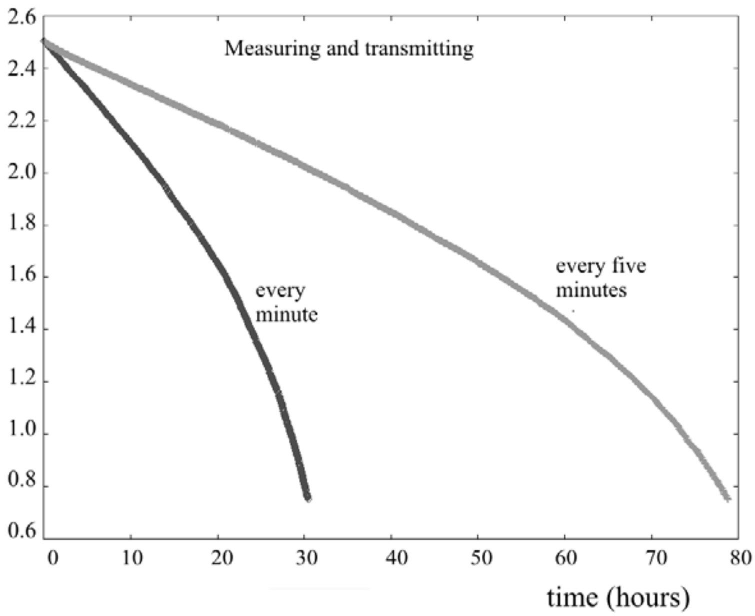

Fig. 18. DLC-Voltage during operation without light.

7. Conclusions

In this paper we presented a flexible, modularized and expandable system for home automation. It is based on an inexpensive and highly reliable hardware and open source software. A modular PLC program has been designed and an application program for control, supervision and visualization has been developed. A special sensor interface has been designed, which allows the connection of an analog sensor directly to an inexpensive digital input. Incorporating this interface, sensors for temperature, solarization and humidity have been manufactured.

A system with mobile and maintenance free sensors, sending their data by a RF-interface, has also been developed. Data receiving components are based on the standard RS422-interface. This leads to compatibility with a lot of standard devices, for example a PLC and a PC.

Focus was spent on the energy management of the solar powered low-power sensor module, which supplies the RF-interface, the sensors and a user interface with (different) voltages. Fewer components for a compact design, lower costs and lower static losses can be achieved.

Operation without light is possible by buffering solar-power with a DLC. A high-efficiency synchronous buck converter with regulation was presented for charging the DLC. Storing energy without batteries makes the sensor module maintenance free. Once activated by light, the sensor module operates with a wide ranged DLC-voltage $0.7\ V < V_O < 2.5\ V$ (Fig. 18). By a RF-transceiver interface the message redundancy automatically adapts to the quality of the RF-link and leads to automatic power-saving and controlled data transfer. The microcontroller based structure offers digital and analog input-ports and makes the sensor module suitable for the flexible use with different types of analog and digital sensors. A user interface with an alphanumerical LCD and push-buttons allows the user to configure the settings of measurement and data communication. Several systems are right now being tested in field tests.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726- 5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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