

Wireless sensor system for monitoring of compressed air filters

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This study presents a wireless filter monitoring system (WFMS) for compressed air filters based on a very low power consumption microcontroller. Proposed system consists of two separate units (sensor and base), which constantly monitor filters. It is very easy to install in existing manufacturing systems, simple and efficient for production and use, inexpensive, non-invasive, and continuous system with almost real-time update possibilities. It can be easily extended for monitoring other components that cause pressure drop.

Keywords: Air pollution, Data acquisition, Energy efficiency, Filters, Predictive maintenance, Wireless sensor networks

Introduction

Compressed air systems (CAS), widely used in factories and workshops, are reported very expensive to operate¹. Contaminants in compressed air lead to a loss of air pressure. Therefore, there is an increase in electricity to produce required pressure for a system's application². Compressed air filters (CAFs), if not replaced or cleaned regularly, reduces systems' efficiency significantly. Pressure drop of one bar in CAS results in a 7% increase in electrical power input required to compress air³. A 2% reduction of annual energy consumption in CASs can be expected by more frequently changing filters⁴. A poorly selected filter medium could result in contamination downstream. Filter element, in that situation, requires frequent maintenance, and has a high cost of operation⁵. Replacement of systematic maintenance by condition-based maintenance (CBM) strategies based on online monitoring^{6,7} is very important. Companies (65%) are reported⁸ to perform cleaning air line filters regularly. One of the critical elements related to efficiency and safe use of filter cartridges is their operational life span⁹. CASs could include filter service indicators¹⁰ to warn for change of cartridges. Major disadvantages with this kind of indicators are active

monitoring by user⁹. Inaccessible locations, rotating machinery, hazardous or restricted areas, and mobile assets can now be reached with wireless sensors¹¹. According to a survey¹², more than 58% of respondents plan to implement wireless technology for CBM and 24% plan to increase usage of technology. Usage of wireless monitoring systems include measurements of meteorological data (solar radiation, air temperature, relative humidity, pressure, wind speed, etc.) based on wireless data acquisition system monitoring¹³, monitoring of respirator filter cartridges⁹, monitoring of ambient air filters in HVAC systems¹⁴, tilt measurement¹⁵, monitoring of engines in aircraft and ships and land-based applications¹⁶, wireless hull monitoring system¹⁷, wireless bridge monitoring system¹⁸, wireless structural health monitoring system¹⁹, water quality monitoring system²⁰ and health monitoring²¹. Most of these devices communicate using IEEE 802.11b standards and wireless LAN that exists in the plant or is planned to be installed²². In order to avoid dependence on LAN, a low cost, autonomous wireless acquisition system²³ had been developed. Wireless communication can remedy cabling problem and significantly reduce maintenance cost associated with cabling²⁴.

This study presents implementation of wireless filter monitoring system (WFMS) along with proof of stability, and laboratory and field validation tests. Even though other network topologies (peer-to-peer) are more suitable

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for industrial control and monitoring²⁵, WFMS is based on a simple star topology wireless sensor network.

Experimental Section

Principle of Wireless Filter Monitoring System (WFMS)

In WFMS, central device is base unit (BU) that communicates with separate sensor units (SUs), connected with differential manometer on compressed air filters, and PC. The data collected by BU are transmitted to a PC, with an USB connection, where they could be displayed on monitor or stored for further processing. Base station receives incoming data (Fig.1), processes locally on an integrated microprocessor²⁴, shows it on alphanumeric display,

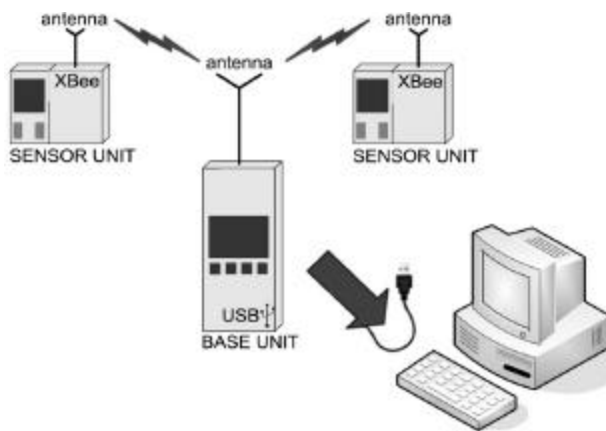
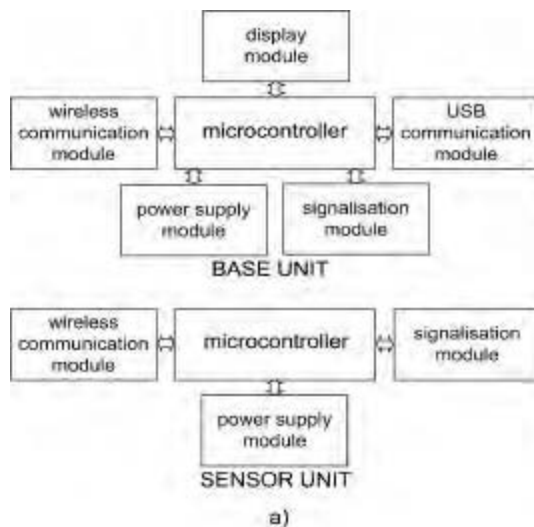


Fig. 1—Communication within WFMS



buffers it in internal memory, and later transfers it via an USB connection to a PC for processing. Display and buttons provide a convenient-to-use environment for system operator. WFMS enables continual monitoring of level of dirtiness of CAFs based on digital outputs of differential manometer, processing of those data, wireless communication, audio and visual signalization and storing the collected data.

Prototype of Wireless Filter Monitoring System (WFMS)

WFMS consists of up to 10 SUs and one BU (Fig.2). Each SU is connected with differential manometer placed on compressed air filter and registers the level of pressure drop on it. SUs transfer collected data only when receive a request from BU (half-duplex communication). Wireless communication between BU and SUs is based on ZigBee technology, which is based on IEEE 802.15.4 standard and mostly used in applications that require a low data rate, long battery life, and secure networking²⁶, so it is suitable for developed WFMS²⁷. In order to achieve a long range, XBee-PRO 802.15.4 was chosen instead of basic XBee radio modules²⁸. Xbee modules build wireless personal area network (WPAN), which is reliable in heavy industrial conditions (-40 to 85°C), fast ($1\,200\text{ b/s}$ - 250 kb/s), and secure (AES encryption). Due to simple technology, the costs of production, use, and maintenance of these devices are very small. Energy consumption during communication is very low. XBee provides security, data integrity and very good performances even in noisy



Fig. 2—Wireless filter monitoring system (WFMS): a) Block diagram; and b) Prototype

circumstances. Integrated wire antenna, which was chosen for data transfer between BU and SUs, is the best solution for WFMS, if one considers the size of antenna and its range. For realization of WFMS, the most important pins of XBee PRO module were DI (Data In), DO (Data Out), CTS (Clear To Send) and RTS (Request To Send)²⁸. DI and DO module pins are used for serial communication with microcontroller (MC). RTS and CTS module pins provide RTS and/or CTS flow control. CTS flow control provides an indication to the host to stop sending serial data to the module. RTS flow control allows host to signal the module not to send data in serial transmit buffer out the UART (universal asynchronous receiver/transmitter).

Base Unit (BU)

BU is a small portable remote device that enables staff to acquire data on filter condition, shows collected data, and transfers it to a PC. Handling of BU is very simple, with only three buttons; one for sending requests and receiving data from SU, second for displaying data and third one for data transfer to PC. It consists of six modules (MC ATtiny 2313²⁹, power supply module, module for wireless communication, display module, module for USB communication, and signalization module). Main component of BU is MC (memory capacity: 128 bytes SRAM, 128 bytes EEPROM, 2 kB Flash), which provides a highly flexible and cost effective solution to many embedded control applications. While primary function of MC is to coordinate the activities of wireless sensors (collect, store and communicate data), it is also used to perform some rudimentary processing of raw sensor data (calculating pressure drop and displaying filter current state)³⁰. Prototype was designed like system for one step data collecting and then transferring to PC. Therefore, this MC was the best solution. Extremely small amount of RAM available on processing board prevented storage of accumulated data. This memory limitation was dealt with by implementing damage detection algorithm in a recursive manner at the cost of consuming additional processing time, and a lower sampling rate. Typical power consumption is 1 MHz, 1.8V and 230 μ A in active mode and < 0.1 μ A in power-down mode. Idle mode stops CPU while allowing SRAM, timer/counters, and interrupt system to continue functioning. In standby mode, crystal/resonator oscillator is running while the rest of device is sleeping. This allows very fast start-up and low-power consumption.

MC communicates with both, modules for wireless and USB communication, using RS232 standard through RX and TX pins. It had been necessary to find the way to route these signals to one or the other module. This problem was solved by using two-way four-channel multiplexer (demultiplexer) CD4052, and used just two channels. Multiplexer is connected in such a way that binary combination of its inputs, A and B, decides whether RX and TX signals would be connected with XBEE_TX and XBEE_RX pins of wireless communication module, or FT_TXD and FT_RXD pins of USB communication module. Since there are two possible choices, one output is enough. Therefore, input B was set to be always "0", connecting to the ground (GND), and input A is connected to microcontroller. Depending on the situation on input A, one has following scenario:

- A = 0 - radio communication between base and sensor unit: RX $\leftarrow$ XBEE_TX and TX $\rightarrow$ XBEE_RX;
- A = 1 - USB communication between base unit and PC: RX $\leftarrow$ FT_TXD and TX $\rightarrow$ FT_RXD.

Pressing button T1, MC sends request to SUs and then waits for a response. When MC through its TX output sends a request in the form of 10-bit data (1 start bit, 8 data bits, no parity control, 1 stop bit), the data through multiplexer (A = 0) coming to XBee input XBEE_RX, XBee forwards that request to SUs. Communication takes place by RS232 standard, at a speed of 9600 bit/s. This module also has to receive the data from SUs. Received data are processed in Xbee and then sent to RX input on MC via XBEE_TX output. Before transmission, SUs briefly check to see that no one is talking before start. In many applications it is not critically important if a small percentage of packets are lost³¹, but for WFMS it is vital to have reliable transmission of data.

For communication between BU and PC, FT232R (a USB to serial UART interface device) was used. During USB communication, MC sends data through its TX output to FT_RXD input of FT232 chip of the module for wireless communication. Chip FT232RL needs power supply of 4 - 5.25 V at 15 mA from USB port or its own power supply. Internal oscillator frequency is 12 MHz. Data transfer rates from 300 baud to 3 Mbaud (RS422, RS485, RS232) at TTL levels. FT232RL has an integrated 1 024-bit EEPROM for storing device descriptors and CBUS I/O configuration. This chip then adapts the data to requirements of USB protocol and

sends data to PC via USBDP and USBDM signals. The device should draw current up to 100 mA on plug-in to USB and up to 2.5 mA in USB suspend mode. Pressing button T2, the current state of SUs had been displayed. This study chosen alphanumeric display AC-082A³², which has two lines (8 character positions); first line to write the name of a filter (Filter 1) and second line to write the condition of filter. Conditions of all units are alternately displayed.

Signalization module has to warn the stuff, visually and acoustically, that there has been a change in certain SU. This module consists of an electromagnetic loudspeaker and red light emitting diode. In a case that all filters are clean, this module is inactive. If at least one of the 10 filters is dirty, signalization module is active.

It is necessary to provide autonomous power supply for BU. Due to the characteristics of components used in this device, a battery source (min. voltage, 7 V) should be provided. According to the dimensions and nominal battery voltage, the best solution for power supply is block battery of 9 V. To minimize power consumption, main MC and wireless transmitter operates in two modes (active and sleep). Each component is capable of being placed in sleep mode where power usage is significantly reduced.

Sensor Unit (SU)

SUs perform local data acquisition. Construction of each SU is identical; only difference is that each SU has unique address, which allows BU to access them separately. SU is connected to a differential manometer, piezoresistive pressure sensor³³, which measures pressure drop on a CAF. This study used differential manometer with two digital outputs (PNP or NPN). It is possible to define two pressure limits on differential manometer. When pressure drop reaches any of these limits, there is a signal on the certain output. With pressure limits, one can define three possible level of dirtiness of each filter: i) If a pressure drop is below the low limit, there is no signal on outputs, meaning that filter is clean; ii) If a pressure drop reaches the first limit, there is a signal on one output, indicating that filter is dirty and need to be changed soon; and iii) If a pressure drop is equal or higher than the high limit, there is a signal on both digital outputs, indicating that filter has to be changed immediately.

SU has to respond on BU's request and to send information on filter condition. SU consists of four modules (MC, power supply, module for wireless

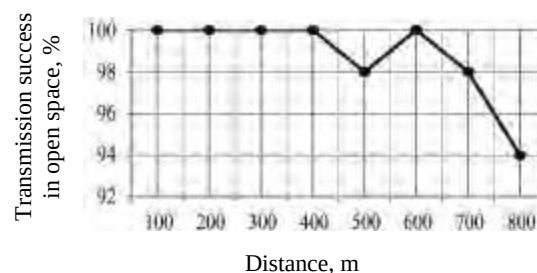


Fig. 3—Outdoor testing results

communication and signalization module). MC ATtiny2313 constantly monitors outputs of differential manometer. On the basis of these outputs, it gives information on the condition of CAF. MC communicates with the module for wireless communication and controls operation of signalization module. When the value of pressure drop reaches any of the defined pressure limits, differential manometer signals output. Operation and implementation of modules for wireless communication are same as in BU. SU is fixed and connected to differential manometer. Therefore, industrial power source (24 V) was used for its power supply. If, for some reason, communication between BU and SU is disabled, signalization module will provide sound and light signalization. If filter is contaminated and warn the stuff, it is necessary to change the filter.

Results and Discussion

SUs and BU were tested by several laboratory and field experiments to determine sensitivity of sensors, communication reliability & bandwidth, and robustness of system components. WFMS testing included: i) Range testing, where range of device was tested in open air with optical visibility and closed space, where data communication was carried out through obstacles such as walls, windows, doors, furniture, etc.; ii) Accuracy of registered pressure drop was tested during 16 weeks, when SU was connected to two different filters and each measurement was made for three different air flows; iii) Current consumption of BU during communication with SU at different distances in open space; and iv) Consumption of SU in listening and transmission mode. Outdoor range was tested for eight different distances, with 50 readings for each distance (Fig. 3). For up to 400 m distance, 100% successful data transmission was found. For longer distances, rate of successful transmission varied. Therefore, a safety factor of 0.75 was adopted, and claimed that WFMS is 100% current and reliable in data transmission for distances up to 300 m (manufacturer specifications)²⁸.

During indoor testing, BU and SUs were placed in different rooms having brick walls (30-40 cm thick), and communication was done through common barriers in the building (walls, windows, doors, furniture, equipment, etc.). Total length of facility was 36 m. SU is fixed in one room, and BU is transferred from one laboratory to another. For each position, 50 readings were made. It was achieved 100% of success and accuracy of data transfer. Manufacturer guarantees reliability for up to 100 m for indoor range²⁸. It was verified that glass, metal, wood, equipment, and furniture do not have a major impact on data in tested range.

Second testing method enclosed accuracy of registered pressure drop. SU was connected to two different filters mounted on CAS for an automated device (air pressure, 6 bar). First filter (LF-D-5M-MINI, Festo) has 5 µm grade of filtration and second one (LF-D-40M-MINI, Festo) 40 µm; both sintered filter with centrifugal separator. Every measurement, conducted once a week, was made for three different air flows (200, 400 and 600 l/min). Data from differential pressure gauge (Fig. 4) was compared and displayed on BU (transferred via WFMS) and matching rate was found 100%. Consumption of SU in listening and transmission mode (Fig. 5) showed average consumption at 27 mA during listening, and at 35 mA during transmitting mode.

For battery life, one could propose a filter monitoring schedule in a single plant. With a weekly inspection of condition of 10 filters, battery life can be estimated as²¹

$$I_{avg} \approx \frac{T_L}{T_{SFC}} \times I_L + \frac{T_T}{T_{SFC}} \times I_T + \frac{T_{SFC} - T_L - T_T}{T_{SFC}} \times I_I \quad \dots(1)$$

where T_{SFC} -Super frame cycle (estimated on 30 min), T_T -Transmission time (0.908 s per SU), T_L -Listening time (estimated on 30 min), I_{avg} -Average current of BU, I_T -Average current during transmission and I_L -Average current during listening.

If 10 messages (10 SUs) are sent per super frame cycle ($T_L = 1800$ s, $T_T = 9.08$ s), average current is 5.32 mA. One 9-volt battery has 565 mAh capacity, so if SU is in operation for 30 min per week, expected operating time is 106 h (or 4 y). WFMS is designed to be used occasionally, daily, weekly, monthly and the period of its use (0.908 s transmission time per SU) is irrelevant for energy efficiency analysis in terms of electric energy from battery.

Energy Efficiency of Compressed Air System (CAS)

On both filters and for all air flows (Fig. 4), there is growing trend in pressure drop. For highest flow

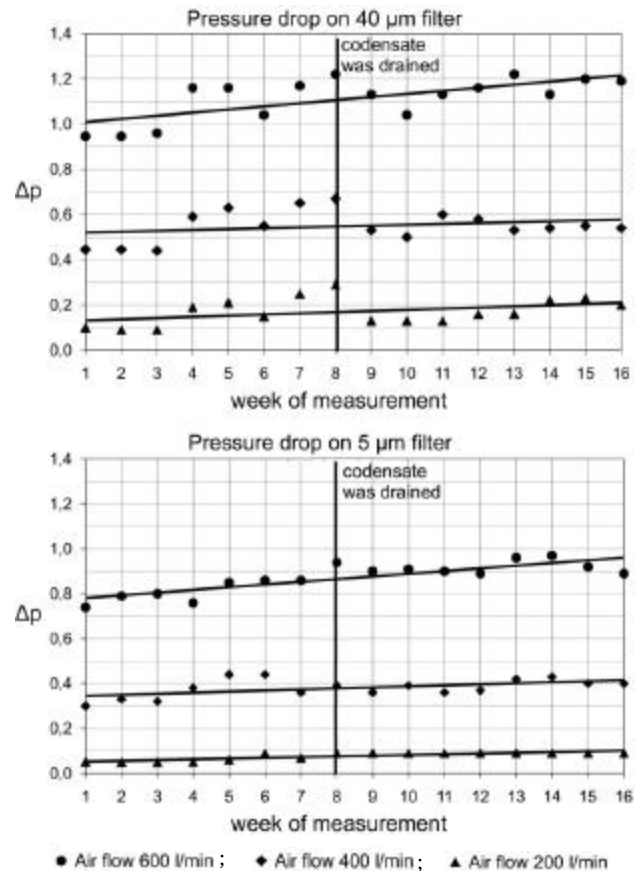


Fig. 4—Pressure drop ranges for testing WFMS

(600 l/min), for which pressure drop was measured on just one filter, one gets annual compressed air consumption of 216,00 m³. With average price³⁴ of 0.02 €/m³, total production costs of these volume of compressed air takes to 4,320 €. It is possible to achieve savings of 2% by more frequently changing filters. In this case, it would be 86.4 €. If costs (new filter cartridge, 6 €; staff time, 4 €) for filter cartridge changing amount to 10 €, there is savings of 76.4 €. In the case of more frequent filter replacement and greater number of filters, it is obvious saving capacity in this segment of CASs. If WFMS can monitor ten filter units, saving can go up to 760 € per year.

Application Program

For displaying and storing the data on filter condition from up to 10 SUs (filter stations or service units) on the computer, Visual Basic was used. After receiving the data on filter condition, these data are stored in BU memory, so it is necessary to connect it to PC. During data transmission, BU must be switched on. Upon receiving the data, filter conditions are automatically

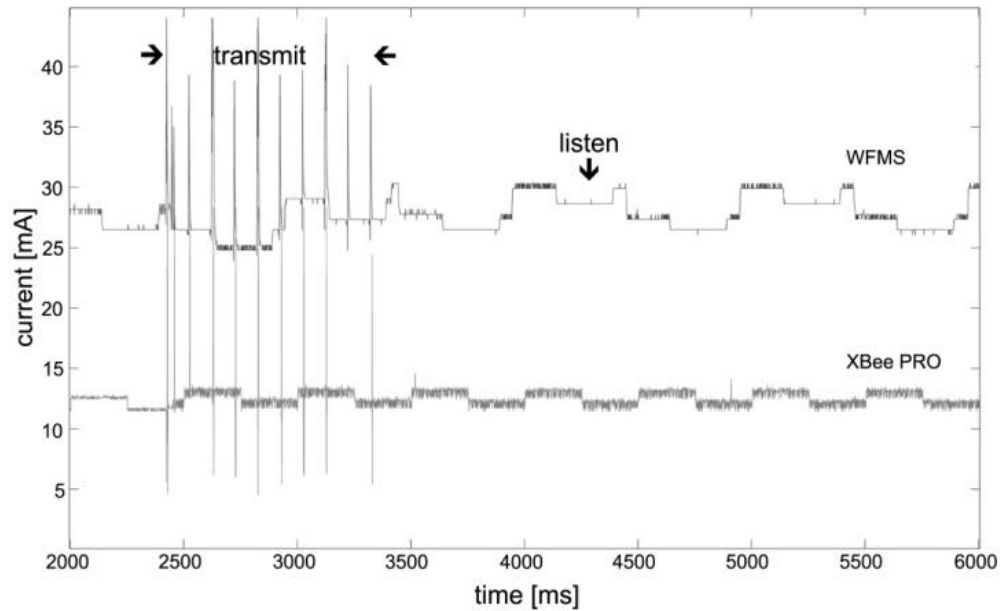


Fig. 5—Power consumption of WFMS during operation

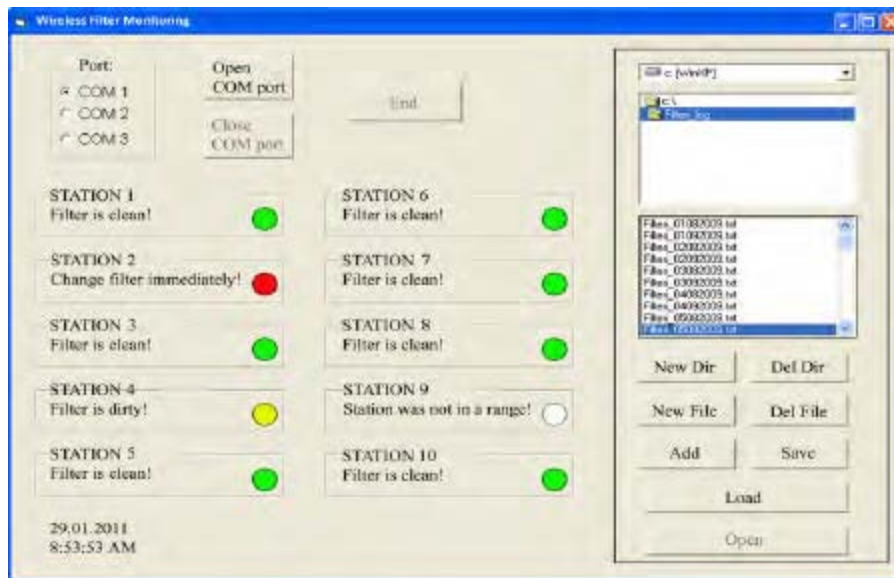


Fig. 6—WFMS monitor window

displayed on the monitor (Fig. 6). For each filter, program shows one of three possible states: i) Filter is clean. (green mark); ii) Filter is dirty! (yellow mark); and iii) Change filter immediately! (red mark). If filter state were not read for any reason, it would be displayed a message: Station was not in a range! The transferred data on filter condition could be saved and if necessary re-examined. The application allows creating and deleting files and folders in order to facilitate data handling.

Conclusions

This study described a general WFMS architecture, important implementation issues, and prototype WFMS made for monitoring the actual level of dirtiness of CAFs. Developed WFMS is very easy to install in existing manufacturing systems. It is very simple, efficient, and cheap for production and use. Components of BU and SUs are readily available in the market. Testing has found high reliability and accuracy during the operation of the

device. Further improvement of WFMS is planned to be related with: i) Integration of a differential manometer and SU to a single device; ii) Improvement in design of BU and SUs; iii) Improvement of BU such that data can be stored locally in a compressed format and then later transmitted; iv) Output signal could be used to stop the production of compressed air, until certain filter is changed; and v) Improvement of the application program in the manner of predicting the trend.

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