Intelligent Industrial Transmitters of Pressure and Other Process Parameters

Miloš P. Frantlović, Vladislav J. Jovanov, and Budimir LJ. Miljković

Abstract — **An overview is given of industrial measurement instruments (transmitters) of pressure and other process parameters. It is followed by a description of the technology used in the current generation of intelligent transmitters featuring two-way digital communication. A recently developed product of IHTM–CMTM, the intelligent pressure transmitter is presented, including a description of the software temperature compensation method for the used pressure sensor. Features and application possibilities of the developed hardware and software platform are discussed, as well as its suitability for the realization of wireless sensors.**

Keywords — **Measurement, sensor, transmitter.**

I. INTRODUCTION

In order to perform measurements of physical values (most commonly temperature and pressure) in industrial processes, a special kind of electronic measurement instruments is used, usually called "industrial transmitters". This name originates from the way the instruments are used, since the indication they provide is seldom read directly in the field (i.e. at the location where the transmitter is installed). Instead, it is sent in a form of an electrical signal, either using cables or by a wireless link, to a remote measurement or control equipment, usually centralized and placed in a control room. According to the contemporary terminology, this group of devices belongs to sensors, but the traditional name "transmitters" will be used in this paper.

Besides the adequate metrological properties, the industrial transmitters must fulfill some special construction requirements pertinent to harsh operating conditions in industrial environments. In industrial plants the transmitters are often installed at measurement sites where the operating temperature belongs to a very wide range (-40°C to +85°C, i.e. the industrial temperature range). Mechanical stress (vibrations) and prolonged exposure to a harsh environment, including chemically aggressive and flammable substances, are quite possible. The distances between the measurement sites and the control rooms can be long (up to the order of km). For this reason, electrical current is chosen instead of voltage for signaling, because current signals are less susceptible to degradation when transmitted over long distances.

During the several decades long development of various kinds of sensors and industrial transmitters, several generations of these devices have appeared on the market [1].

At the Center of Microelectronic Technologies and Single Crystals (CMTM) of the Institute of Chemistry, Technology and Metallurgy (IHTM) silicon piezoresistive pressure sensors and industrial transmitters of pressure and other process parameters are produced. The proprietary technology of sensor fabrication is used, which has been developed since the 1980s and includes micromachining techniques.

II. A SHORT OVERVIEW OF INDUSTRIAL TRANSMITTERS

A. *Analog Transmitters*

For industrial transmitters, the usual way of transmitting the measurement data is by an analog current signal, and the most commonly used current range is from 4 mA to 20 mA, where the current depends linearly on the measured parameter value. This technique is a *de facto* industrial standard. The connection between a transmitter and the rest of the system is made by two wires, establishing a so-called current loop, so the same two wires are used for both power and signal transmission. The transmitter generates the current signal by varying its own current consumption. This kind of industrial transmitters performs analog signal processing and generates a standardized output signal, so it belongs to the third generation [1]. Such transmitters are still in production and are typically used in older industrial plants, where a capability of digital communication is not required.

B. *Smart Transmitters*

Smart transmitters are similar to the analog transmitters by the way they are installed and used, since they use the same two-wire connection and analog signaling (4 mA to 20 mA). However, in this kind of transmitters, the signal from the sensor is digitized, then digital processing is performed by a microprocessor, followed by D/A conversion to produce the analog current signal. This approach has two important advantages: 1) it enables good

---

This paper is a result of the research which is partially funded by the Ministry of Science and Technological Development of the Republic of Serbia, within the project TR-11025.

M. P. Frantlović is with the Institute of Chemistry, Technology and Metallurgy (IHTM-CMTM), University of Belgrade, Njegoševa 12, 11000 Belgrade, Serbia (phone: 381-11-2638188; fax: 381-11-2182995; e-mail: frant@nanosys.ihtm.bg.ac.rs).

V. J. Jovanov is with the Institute of Chemistry, Technology and Metallurgy (IHTM-CMTM), University of Belgrade, Njegoševa 12, 11000 Belgrade, Serbia (phone: 381-11-2638188; fax: 381-11-2182995; e-mail: tze@nanosys.ihtm.bg.ac.rs).

B. LJ. Miljković is with Merni Instrumenti Miljković Budimir i Drugi o.d. sa p.o., Ljubomira Stojanovića 38, 11000 Belgrade, Serbia (e-mail: per_buda@eunet.rs).

compensation of sensor nonlinearity, 2) it enables the use of additional sensors in order to compensate the influence of parasitic parameters. The built-in microprocessor executes a program (firmware) which uses calibration parameters to perform compensation and to calculate the value of the measured parameter. A smart transmitter provides the user (or the automated control system) with a linearized and compensated indication, which can be considered a linear function of the measured value regardless of the type of sensor, the model of the transmitter and all other data pertinent to a given measurement site. Smart transmitters also belong to the third technology generation [1].

C. *Intelligent Transmitters*

By the end of the 1980s, due to a rapid development of digital data acquisition and control systems, the need arose for digital two-way communication with industrial transmitters, which resulted in development of several industrial communication interfaces, also known as fieldbuses. The name "fieldbus" originates from the words "field" and "bus", where "field" denotes the area where the plant is located, and "bus" denotes a communication medium shared by several devices. A measurement and/or control system based on a fieldbus has significant advantages over older systems: simpler data acquisition (the measurement data are transmitted in digital form), lower measurement uncertainty, remote identification of transmitters, remote adjustment (including changing the measurement range without the need for calibration), performing measurements of several parameters using one transmitter, built-in diagnostics, networking capability.

A number of industrial interfaces exist on the market, with different capabilities, but incompatible with each other. In the literature they are often called protocols (for example the HART protocol). The most widely used are HART, ProfiBus and Foundation Fieldbus. An industrial transmitter with both digital signal processing and digital two-way communication using one of the industrial protocols is called an intelligent transmitter. Such transmitters belong to the fourth technology generation [1].

D. *Wireless Sensors*

In many cases, classic industrial transmitters can be replaced with wireless sensors. Although wireless sensors exist for a long time, their development has become increasingly intensive from the beginning of the 21st century, following the development of wireless computer networks. Systems based on wireless sensors have some unique advantages, especially when moving objects are involved or when temporary installations are required. The newest developments in the field of wireless sensors are focused on wireless sensor networks. Such networks may comprise thousands of intelligent sensors and they are based on complex networking protocols, enabling formation of different network topologies. Contemporary wireless sensors typically use the frequency band around 2.4 GHz (ISM band). Currently the ZigBee standard (based on IEEE 802.15.4) is widely used.

III. THE INTELLIGENT INDUSTRIAL TRANSMITTER

A. *Block Diagram*

A block diagram of an intelligent pressure transmitter is shown in Fig. 1. Except for the sensor, it is quite similar for industrial transmitters that measure other parameters. The block diagram is generalized, as it has an analogue current output block as well as a block for digital data transfer. Probably the only intelligent transmitters that have both of these blocks are those with HART communication, since their digital signal is superimposed on the analog current signal. The transmitters based on other industrial interfaces are made without an analog output, and with separate data and power connections.

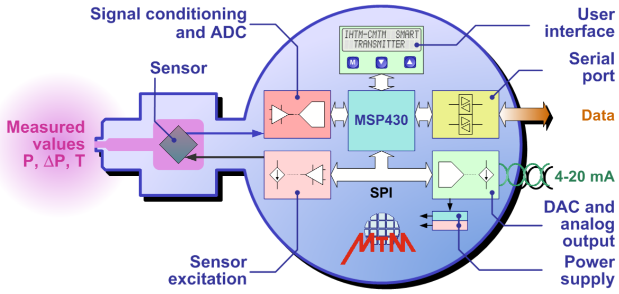

Fig. 1. Block diagram of an intelligent industrial pressure transmitter (IHTM-CMTM)

B. *HART Protocol*

HART (Highway Addressable Remote Transducer) is a communication interface that enables two-way digital communication between industrial measurement and control equipment. As an early implementation of the fieldbus concept, HART was developed by Rosemount during the 1980s, and has been an open protocol since 1986. Established in 1993, the HART Communication Foundation (HCF) is the technology owner and standards setting body for the HART Communication Protocol [2]. The HART protocol is based on the Bell 202 modem signaling. It uses binary frequency shift keying (BFSK) with 1200 Hz for mark (1) and 2200 Hz for space (0), with continuous phase and 1200 b/s data rate (half-duplex). Industrial transmitters with the HART protocol are backward compatible with old analog equipment, since the digital signal is superimposed on the analog current signal (4 mA to 20 mA) which is still widely used in industry. The HART signal and a typical sequence of messages are depicted in Fig. 2.

HART is a master/slave protocol, which means that the slave devices transmit messages only as a response to commands received from a master. Some HART devices support the optional burst communication mode: the master instructs the slave to continuously broadcast a standard reply message (e.g., the indication of the measured value). The HART network consists of up to 15 slaves and up to two masters. The primary master is typically a computer equipped with a HART modem and the secondary master is usually a hand-held HART communicator.

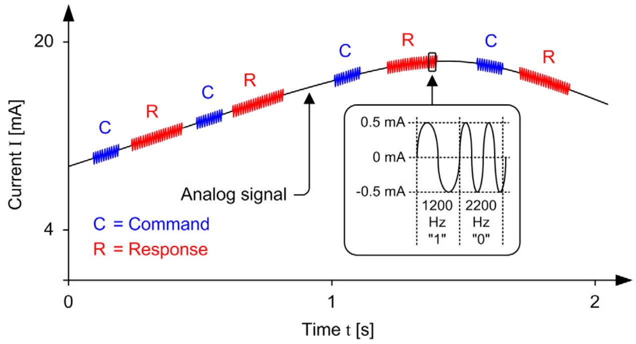

Fig. 2. Analog current signal with the superimposed HART signal

Point-to-point mode of operation: a slave device (e.g. a transmitter) and a master device are connected by a two-wire cable. The HART signal is superimposed on the analog current signal, which is proportional to the value of the measured parameter. In this mode only one slave can be connected to a master.

Multidrop mode of operation: up to 15 slave devices can be connected in parallel and share the same two-wire cable. Only the digital signal is used. The analog signal of each slave device is fixed to the minimal value (4 mA). All slave devices must be configured to have different polling addresses greater than zero.

C. Digital Temperature Compensation

The intelligent pressure transmitter developed at IHTM-CMTM contains a pressure sensor based on a silicon piezoresistive sensing element. When this type of sensor is used, it is necessary to minimize its sensitivity to temperature changes, since this sensitivity can cause significant measurement uncertainty. The minimization technique is usually called temperature compensation. In intelligent transmitters the compensation is performed in the digital domain, using software [3].

Since the pressure sensor has four piezoresistors connected in a Wheatstone bridge, it has two electrical ports: input and output. A constant current source is connected to the input, and the voltage is measured at the output. Voltages at both electrical ports depend on both the applied pressure and the temperature. However, the pressure sensitivity of the output voltage is much higher than the temperature sensitivity. Similarly, the temperature sensitivity of the voltage at the input port is much higher than the pressure sensitivity. Therefore the output voltage is used for pressure measurement (the primary measurement channel) and the voltage at the input corresponds to the temperature (the second measurement channel).

In order to develop the temperature compensation algorithm, the measurements are performed at the IHTM-CMTM laboratory, which is accredited for pressure and temperature measurements. For acquisition of signals from the pressure sensor a modified wireless liquid level meter was used [4]. It was connected to a personal computer wirelessly (using Bluetooth technology). The wireless connection enables electric isolation of both the sensor and the acquisition unit from the rest of the measurement system, thus eliminating parasitic currents. As a source of pressure, a high accuracy automatic pressure calibrator was used (Mensor APC600). The temperature was controlled by a temperature chamber (Vötsch). For the measurement of the pressure sensor temperature, a Pt-100 sensor was used, which was connected to the same acquisition unit. The temperature sensor is used only during the pressure sensor calibration process and it is not a part of the final product. The measurements are performed on the sensors with the IHTM SP-9 sensing element. For the purpose of the measurements, the software was made for the wireless acquisition unit and for the personal computer. The acquisition unit digitizes the signals from both the pressure and the temperature sensor and transmits the data over a wireless link. The computer controls the pressure calibrator, receives the data from the wireless acquisition unit, displays the indication of the measured values on the monitor and saves the data to a file. The pressure values were set from 10 mbar to 2 bar, and the temperature was set from -30°C to 70°C.

The data acquired during the measurement are analyzed in order to create a mathematical model intended for both temperature compensation and linearization. The measurement data are organized in a form of the inverse function, i.e. the applied pressure values are expressed as a function of both measured voltage signals. The measured voltages depend on the values of sensor excitation currents. For this reason, ratiometric measurements are performed. The voltage produced by the excitation current on a precision resistor is used as the reference voltage for the A/D converter.

A computer program is made that approximates the data with a bivariate analytical function shown in Fig. 3a. The calculated relative error of approximation, i.e. the difference between the applied pressure values and the calculated pressure values obtained using the approximation function, is shown in Fig. 3b (percents of the full scale, %FS). It can be concluded from Fig. 3 that a low relative error is achieved (less than ±0.025 %FS).

In order to utilize the obtained results, a program is made for the microcontroller in the pressure transmitter. Based on the measured signals from the sensor and using the supplied approximation function parameters, the current pressure value is calculated in the real time. In this way both the temperature compensation and the linearization are performed. Unfortunately, the above-mentioned low value of the relative error cannot be achieved in practice, mostly for the reason that the pressure sensor does not have the ideal repeatability. Additionally, there is a certain temperature drift of the transmitter electronic components. Finally, if the analog signal (4 mA to 20 mA) is used for measurements, additional errors are introduced inside the transmitter (by the DAC and the analog circuitry), as well as outside the transmitter. If measurement results are transferred by using digital communication, the additional errors are not introduced.

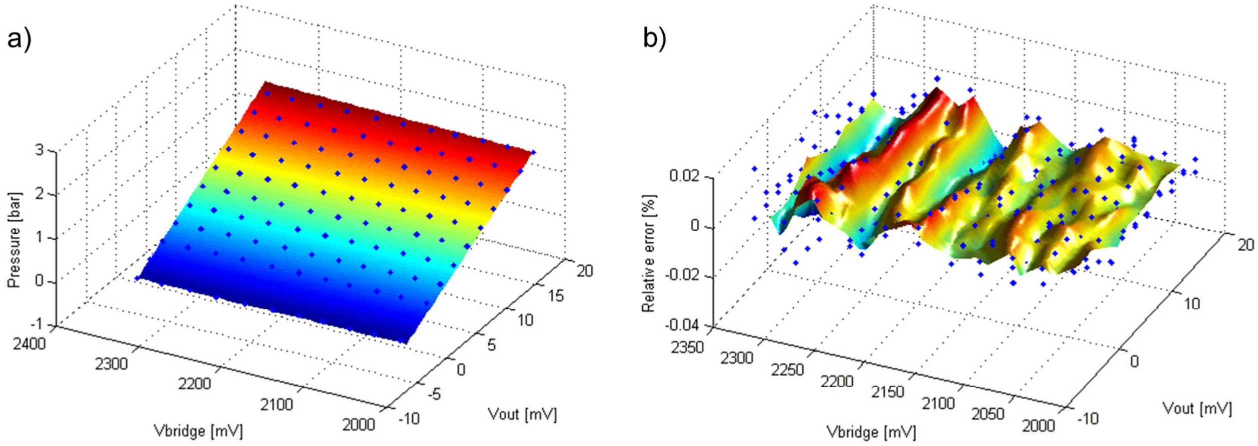

Fig. 3. a) The approximation surface (pressure as a function of the two measured voltages), b) The relative error of approximation [%FS] as a function of the two measured voltages

D. Realization of the Transmitter

As a base for the new generation of IHTM products, the intelligent instrument platform is developed that enables realization of several types of intelligent transmitters. In comparison to the block diagram in Fig. 1, the circuitry is added for the second sensor, so that two pressure (or temperature) sensors can be used. Since the platform is modular, it is possible to change the communication interface and the power supply block by fitting a different output module. A possible option is a wireless communication module.

Two sigma-delta A/D converters are used, both with 24-bit resolution, programmable gain amplifier and a digital filter. The effective resolution is ≥ 18 bits at 16.7 Hz update rate. The resolution of the D/A converter used for the output is 16 bits. The microcontroller is from the Texas Instruments MSP430 family. It consumes less than 550 μA in the active mode at 3.3 V and 1 MHz clock frequency. The total current consumption of the pressure transmitter is less than 3 mA. The total measurement error is within ±0.1 %FS (after calibration of the analog output).

The laboratory prototype and then the industrial prototype of the intelligent pressure transmitter are realized. They are shown in Figs. 4 and 5, respectively.

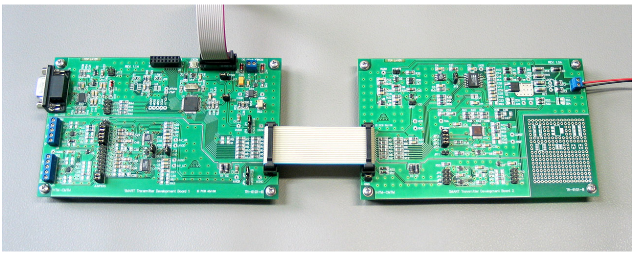

Fig. 4. The laboratory prototype of the intelligent pressure transmitter

IV. CONCLUSION

According to the data available to the authors, the presented intelligent pressure transmitter is the only product of this kind developed and manufactured in Serbia.

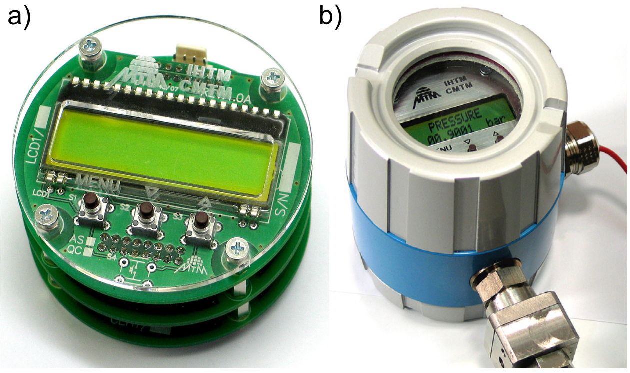

Fig. 5. The industrial prototype of the intelligent pressure transmitter: a) electronics, b) assembled product

Tests performed at IHTM have shown that this product fulfills electrical, mechanical and metrological requirements. Since the transmitter has not been subjected to compliance tests by HCF, we do not claim that it is HART compliant. However, our tests have proven its interoperability with HART compliant equipment that was available to us.

The intelligent instrument platform enables development of different new products. Realization of intelligent transmitters of differential pressure, liquid level, liquid flow and temperature is planned for the near future. Development of wireless sensors based on the ZigBee standard is also planned. ZigBee transceiver modules can be integrated into the developed hardware. However, the existing software must be significantly modified in order to enable wireless networking and a suitable source of energy for wireless sensors must be considered according to the intended application.

REFERENCES

[1] D. K. Stanković, *Fizičko tehnička merenja: senzori.* Belgrade, Yugoslavia: Zavod za grafičku tehniku TMF, 1997 (in Serbian)

[2] HART Communication Foundation, http://www.hartcomm.org

[3] V. Jovanov, M. Frantlović, "Measurement Process Optimisation for Digital Compensation of IHTM-CMTM Piezoresistive Pressure Sensor", in *Proc. 51st Conf. ETRAN*, Herceg Novi, Montenegro, 2007, vol. IV (in Serbian)

[4] M. Frantlović, I. Jokić, D. Nešić, "A wireless system for liquid level measurement", in *Proc. 8th International Conf. TELSIKS,* Niš, Serbia, 2007