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Experimental Systems for Acquiring Technical Knowledge and Practical Skills on Electronic Measurements

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Abstract: An efficient training in the measurement systems field requires theoretical knowledge and practical skills in using sensors, transducers, electronic devices and circuits. The paper presents a guideline for thorough understanding the operation and programming of inductive, capacitive and ultrasonic sensors, resistance temperature detector and intelligent temperature sensor. The information from user manuals and datasheets is selected, explained and completed with suggestive graphic representations and static transfer characteristics. Three experimental systems allow the sensors' testing and monitoring and implement a temperature control system and a motion control system. The sensor monitoring and remote programming and the applications' implementation require a programmable logic controller. These experimental systems have been proved very useful in academic study for experimental training on measurement systems.

Keywords: education, sensors, monitoring, testing, programmable logic controller, programs.

1. INTRODUCTION

The education in measurement and instrumentation has been a concern for more researchers over the past few years; among these may be mentioned (Frota et al., 2006, 2013), (Olowokere, 2015), (Koch et al., 2017), and (Purcaru et al., 2009a). Experimental systems are very useful for engineering education in Electronics and Measurement systems; such systems were presented in (Purcaru, 1998), (Purcaru et al., 2000, 2009b, 2011), and (Ibrahim, 2015) easing the students' learning process.

The paper presents a guideline for studying more sensors and three experimental systems that implement applications of these devices. The engineering undergraduates acquire technical knowledge and practical skills using inductive, capacitive and ultrasonic sensors, resistance temperature detector and intelligent temperature sensor. The sensors' applications are implemented using a programmable logic controller (Özerdem, 2016). The programs loaded on this programmable logic controller allow the sensor monitoring and programming, implementing an on-off temperature control system and a motion control system.

2. UNDERSTANDING THE OPERATING AND PROGRAMMING OF STUDIED SENSORS

2.1 Sensor Output Function and Type

Each studied sensor has an analogue or switching (digital) output (Catalog, 2011, 2014). The signal provided from the analogue output is current or voltage type and it

depends on the physical quantity measured by the sensor; this dependence is usually linear.

The output function is *normally open (NO) contact* or *normally closed (NC) contact* at each switching output (Catalog, 2015), the contact being implemented with a bipolar transistor at the sensor output. The *NO contact* function means that the output voltage is high and the output transistor is *on* (closed contact) when the sensor is activated. The *NO contact* function meets the situation of high output voltage and *on* output transistor (closed contact) when the sensor is activated. The *NC contact* function notifies that the output voltage is low and the output transistor is *off* (open contact) when the sensor is activated.

The output function and type of the studied sensors are presented below.

The intelligent temperature sensor has two outputs: the first is switching and the second can be programmed as switching or analogue (current). The output function of each switching output is programmable (*NO contact* or *NC contact*).

The ultrasonic, inductive and capacitive proximity sensors have switching outputs. The output function is *NO contact* for all sensors excepting the intelligent ultrasonic sensor, which provides a programmable output (*NO contact* or *NC contact*).

2.2 Intelligent Temperature Sensor Operation and Programming

A studied intelligent temperature transducer consists of the TP-203A-CF-H1141-L100 resistance temperature detector connected to the TS-500-LI2UPN8X-H1141 intelligent sensor. The resistance temperature detector is a Pt100 probe with $-30...350^{\circ}\text{C}$ temperature range (Datasheet, 2015). The intelligent temperature sensor of the TS500 series is a processing unit with a 4-digit, 7-segment display, two outputs and a PNP transistor at each switching output (User manual, 2012, 2016). This device processes signals from a resistance temperature detector or thermowell. The status of each switching output is displayed with a yellow LED which lights when the output transistor is *on*.

The intelligent temperature transducer has two switching functions: *Hysteresis* and *Window*. The diagrams from Fig. 1- 4 graphically explain the two switching functions. These diagrams were obtained by completing and detailing the graphical representations from (User manual, 2012, 2016) and (Purcaru, 2012) for *Hysteresis* and *Window* functions.

The *Hysteresis* function ensures a stable switching status around the adjusted set point, independent of the system inherent temperature fluctuations. There can be two situations: *Hysteresis* with *NO operation* (acronym *Hno* in (User manual, 2012)) and *Hysteresis* with *NC operation* (acronym *Hnc* in (User manual, 2012)), respectively. The yellow LED status, U_o output voltage level, output contact and Q_s transistor status are all specified in Fig. 1 with the T temperature rising and decreasing. The user sets the switching range through a *switch point* (SP) and a *reset point* (rP); the notations are the same as in (User manual, 2012).

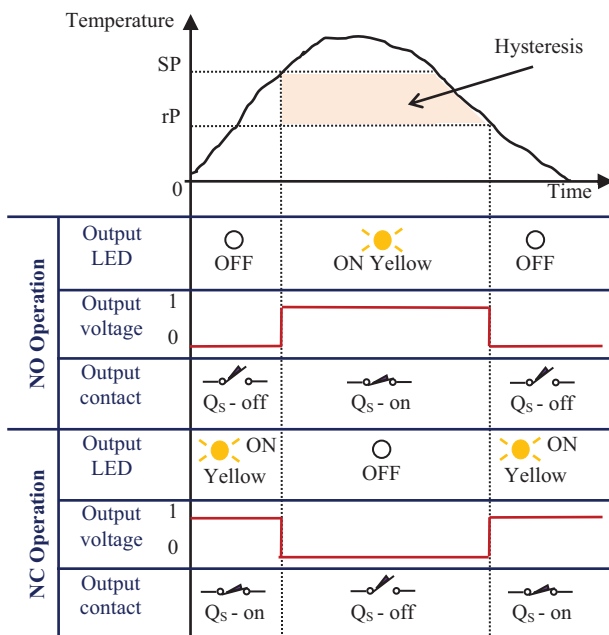


Fig. 1. Output status and signalling of intelligent temperature transducer for *Hysteresis* switching function.

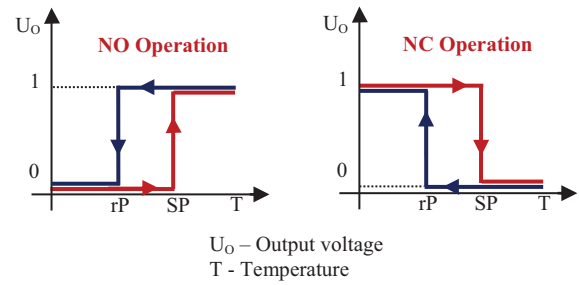


Fig. 2. The static transfer characteristics of the intelligent temperature transducer for *Hysteresis* switching function.

The graphical representation from Fig. 1 allows the thorough understanding of intelligent temperature transducer operating in all situations for *Hysteresis* function, and the correspondence between U_o voltage level, Q_s output transistor, output contact and yellow LED status at the switching output.

The static transfer characteristic (U_o output voltage versus T temperature) of the studied temperature transducer for *Hysteresis* function is drawn in Fig. 2 based on the graphical representation from Fig. 1. The transfer characteristic is travelled on a path to temperature increasing and on another path to temperature decreasing. The two paths are marked with different color and arrows. This characteristic clearly highlights the hysteresis and the engineering undergraduates can observe the similarity with the static transfer characteristic (output voltage versus input voltage) of voltage comparators with hysteresis, studied to Electronics. The *Window* function (User manual, 2012, 2016) provides a temperature range in which the sensor's output switch assumes a defined status (Fig. 3).

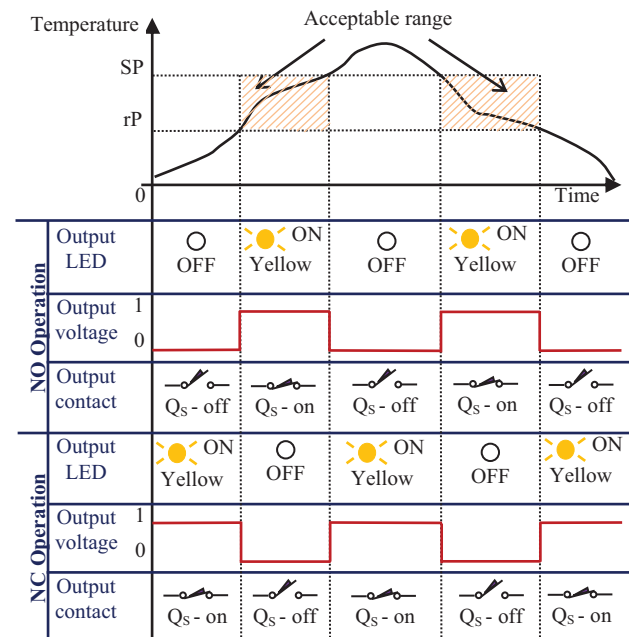


Fig. 3. Output status and signalling of intelligent temperature transducer for *Window* switching function.

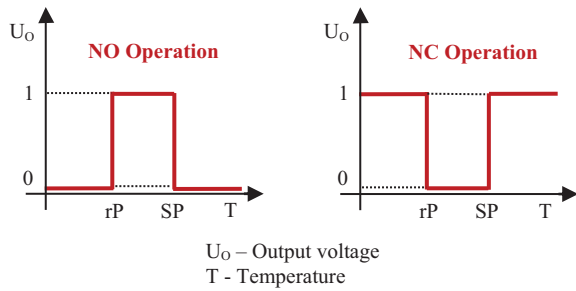


Fig. 4. The static transfer characteristics of the intelligent temperature transducer for *Window* switching function.

The user defines this range by setting an *upper window limit* (*SP*) and a *lower window limit* (*rP*) specified in Fig. 3 and 4. The *T* temperature versus time, the corresponding U_o output voltage versus time and the status of yellow LED, output contact and Q_s transistor can be seen in Fig. 3. The analysed situations are the following: *Window* function with *NO operation* (acronym *Fno* in (User manual, 2012)), and *Window* function with *NC operation* (acronym *Fnc* in (User manual, 2012)). The corresponding static transfer characteristics $U_o=f(T)$ of the studied temperature transducer for *Window* switching function are shown in Fig. 4, based on the graphical representation from Fig. 3, for NO and NC operation. The absence of hysteresis is observed.

The second output of the intelligent temperature sensor can be programmed as analogue. In this situation, the transducer's output current depends linearly on temperature in the measuring range.

Additional external devices (for example laptop) are not required for the intelligent temperature sensor programming. With the menu structure presented in (User manual, 2012) it is possible to set the output function, the values for the setting points, the range of analogue output current, increasing or decreasing transfer characteristic and many special functions such as switch delays or display rotation by 180°.

The temperature sensors of the TS500 series can be easily programmed with three push buttons: *Mode*, *Set*, and *Enter*. The *Mode* and *Set* buttons can be used to select and set different parameters; these buttons can be operated with fingers without tools. It is possible to scroll up and down through the values for improved operation. If the set value is to be saved and the programming is to be changed, the *Enter* button must be pressed. This button is recessed in order to avoid unintentional modification of the data stored in the sensor. Only after a tool is used can the operator permanently modify the sensor setting.

2.3 Ultrasonic Sensors Operating and Programming

The ultrasonic sensor emits a sound pulse that reflects off of an object entering the wave field. The reflected sound is then received by the sensor and it generates an analogue or digital output signal (Catalog, 2005, 2016). Ultrasonic sensing technology is based on the principle that sound

has a relatively constant velocity. The time for an ultrasonic sensor's beam to strike the target and return is directly proportional to the distance from the object (Busslinger, 2001). Ultrasonic sensors are capable of detecting most objects (metal or non-metal, clear or opaque, liquid, solid, or granular) that have sufficient acoustic reflectivity. The basic components of each ultrasonic sensor are transducer/receiver, comparator, detector circuit, and output circuit (Yousefimanesh, 2012). The signal from digital sensor indicates the presence or absence of an object in the sensing field, and the signal from analogue sensor indicates the distance to an object in the sensing field. Some typical applications are presented in (Catalog, 2016) and (User manual, 2013).

The sound cone of ultrasonic sensor - shown in Fig. 5 - contains the following characteristic zones:

- blind zone (unusable area, dead zone) – the object positioned in this zone cannot be detected;
- sensing range (operating range) – the object positioned in this zone can be detected;
- detection zone (measuring interval, switching interval) – the object positioned in this zone is detected.

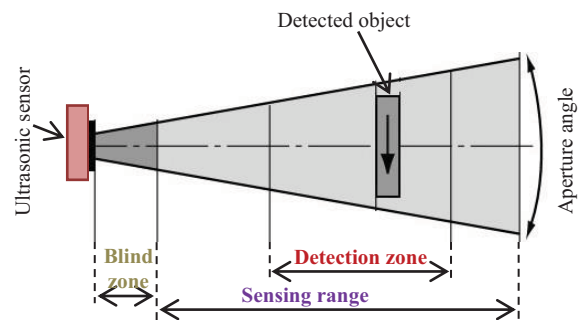


Fig. 5. The sound cone of ultrasonic sensor.

One of the experimental systems presented in this paper allows the study of two ultrasonic sensors: a diffuse mode sensor (RU30-Q30-AP8X-H1141) and a miniature ultrasonic sensor with Teach-mode programming (QS18UPA). Each sensor has a switching output and the output contact is implemented with a PNP transistor. The output function is programmable for QS18UPA and *NO contact* for RU30 only. The switching output is *window mode* with *switching hysteresis* for both studied ultrasonic sensors. Using the specifications from (User manual, 2007) and (Datasheet, 2010, 2016) we have drawn the static transfer characteristics (U_o output voltage versus d distance to target) shown in Fig. 6 and 7 for NO and NC operation. We denoted with *A* and *B* the lower limit and upper limit of the detection zone; each limit has two values (A_1, A_2 , and B_1, B_2 , respectively) due to hysteresis. The transfer characteristic is travelled on a path when the object approaches the sensor and on another path when the object moves away from the sensor; the two paths are marked with different color and arrows. The running

mode of studied ultrasonic sensors can be better understood from these static transfer characteristics.

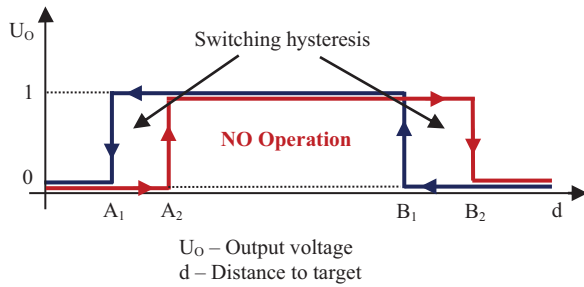


Fig. 6. The static transfer characteristic of ultrasonic sensor for *window mode*, *switching hysteresis* and normally open operation.

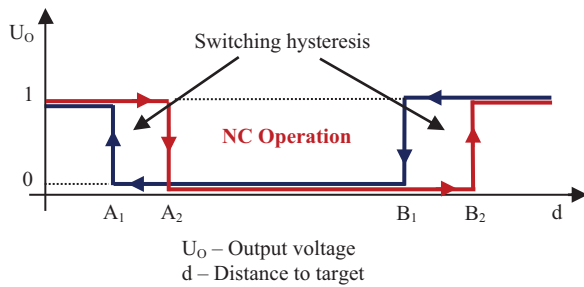


Fig. 7. The static transfer characteristic of ultrasonic sensor for *window mode*, *switching hysteresis* and normally closed operation.

QS18UPA sensor may be programmed either via its push button, or via a remote switch. The output function (*NO contact* or *NC contact*) can be changed and the push button can be disabled by remote programming only (User manual, 2007). The two *Teach* methods for local or remote programming of QS18 ultrasonic sensor (Datasheet, 2010) are the following:

- teach individual lower limit and upper limit of the detection zone;
- use *Auto-Window* feature to center a detection window around the taught position; the window width is 20 mm.

The output status and signalling of QS18UPA ultrasonic sensor during its operation are clearly highlighted in Fig. 8. The Power LED indicates the sensor status: it lights green (if target is within sensing range), red (if target is weak or outside sensing range) or it is *off* (if the sensor power supply is *off*). The Output/Teach LED lights yellow (when target is within taught limits of the detection zone), red (solid or flashing, when the sensor is in *Teach* mode) or it is *off* (when target is outside taught limits of the detection zone or the sensor power supply is *off*). The engineering undergraduates can observe the correspondence between the U_o output voltage level, Q_s output transistor, output contact and bi-color LED statuses at the switching output.

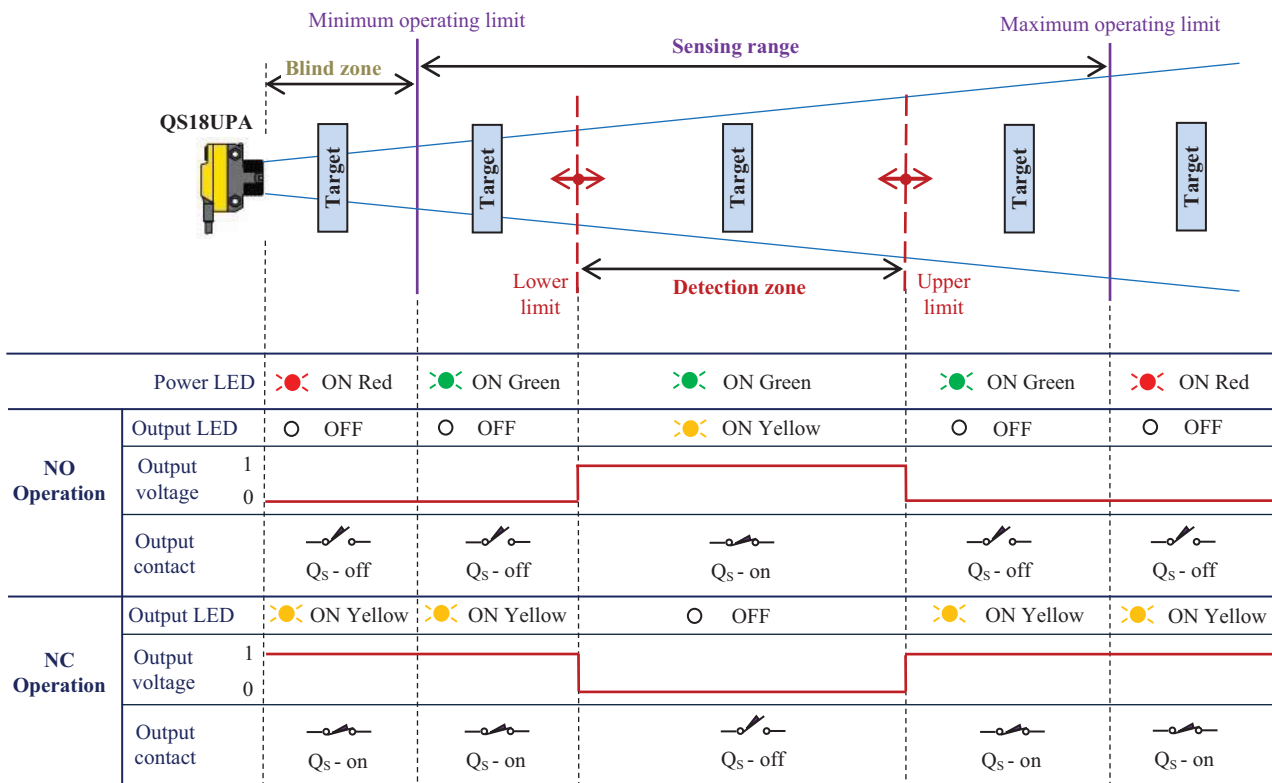


Fig. 8. Output status and signalling of QS18UPA ultrasonic sensor.

The output status and signalling of RU30 ultrasonic sensor during its operation are clearly depicted in Fig. 9. Only the upper limit of detection zone is adjustable via potentiometer (Datasheet, 2016); the near limit is determined by the blind zone. The output LED lights strong yellow (if target is within the limits of the detection zone), yellow (if the sensor power supply is *on*), and it is *off* (if the sensor power supply is *off*). By analyzing Fig. 9, the engineering undergraduates understand the running mode of this ultrasonic sensor better.

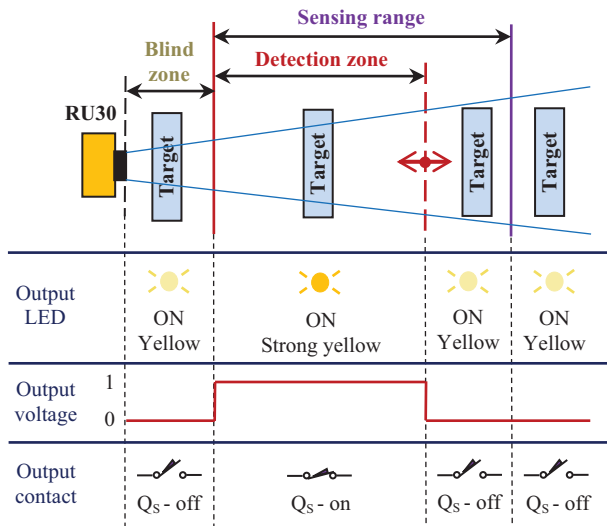


Fig. 9. Output status and signalling of RU30 ultrasonic sensor.

2.4 Inductive and Capacitive Proximity Sensors Operating

The output function is *NO contact* and a PNP transistor implements this contact for both studied proximity sensors: inductive (Ni4U-Q8SE-AP6X-V1131) and capacitive (BC3-M12-AP6X). So, Q_S output transistor is *on*, U_O output voltage is high and a yellow LED lights when the target is within the limits of the detection zone. Fig. 10 clearly presents the running way of inductive or capacitive proximity sensor (Purcaru et al., 2017b). We have drawn this figure based on the specifications from (Catalog, 2012, 2015) and (Datasheet, 2017a, 2017b). The students can comprehend the connection between *d* distance from the sensor to the target and the level of U_O output voltage, Q_S transistor status, output contact status and yellow LED status. The proximity sensor acts like a closed contact when it detects an object in the detection zone.

The switching function is *Hysteresis* for both studied proximity sensor. The sensor behaviour when the target approaches or leaves the sensor face is detailed in Fig. 10. The sensor output switches in high level when the target approaches the sensor face and reaches the *operate point* (A₁ distance in Fig. 10). The sensor returns to its normal state (low level of output voltage) when the target reaches the *release point* (A₂ distance in Fig. 10). So, the sensing distance is delimited by the thresholds A₁ and A₂.

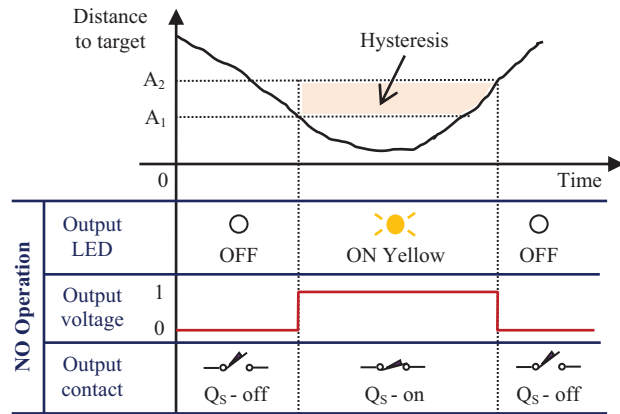


Fig. 10. Output status and signalling of Ni4U and BC3 proximity sensors.

The *hysteresis* or *differential travel* is the dissimilarity between *operate* and *release* points. The hysteresis is factory set at less than 15% (for inductive sensor) or 20% (for capacitive sensor) of the effective operating distance (Catalog, 2012, 2015). The hysteresis is needed in many of the proximity sensor applications (Catalog, 2012, 2015).

The static transfer characteristic (U_O output voltage versus *d* distance to target) of the studied inductive and capacitive proximity sensors is depicted in Fig. 11.b, based on the graphical representation from Fig. 10; the hysteresis is highlighted as in Fig. 2, 4, 6 and 7.

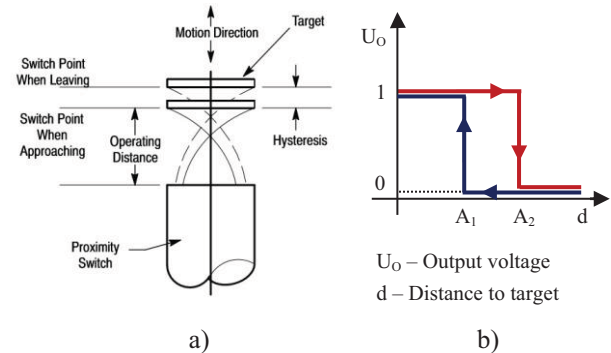


Fig. 11. Hysteresis function for Ni4U and BC3 proximity sensors: a) Functional principle. b) Static transfer characteristic.

The deduction of the sensor static transfer characteristic makes the correlation between sensor information (Catalog, 2012, 2015) and the knowledge gathered at Electronics and System theory possible.

3. TESTING, MONITORING AND APPLICATIONS OF SEVERAL SENSORS

Three experimental systems perform the testing and monitoring of the above presented sensors and the implementation of some simple applications. A programmable logic controller (PLC) allows the sensor remote programming, monitoring and applications' implementation (Purcaru, 2012).

The PLC process control equipment is organized around a microcontroller and it is keyboard, display and interface featured. PLC-03 has 8 digital inputs and 8 digital open collector outputs. Both digital input and output channels have galvanic isolation implemented with optocouplers.

A 24Vdc industrial power supply of the MDR-20 series (Datasheet, 2007) is used both for sensors and auxiliary devices and circuits required for the sensor study or for implemented applications.

The main benefits of using these experimental systems are the following:

the undergraduates are getting to understand and use theoretical knowledge previously acquired at Electronic devices and circuits, Measurement systems, Sensors and transducers, System theory, Programmable logic controllers, Data acquisition systems;

the users acquire practical skills working with real sensors and transducers, programmable logic controller, power supply and other devices and circuits;

the engineering undergraduates thoroughly understand the sensors' operating and programming using the explanations, diagrams and static transfer characteristics above presented;

the students can observe, measure and compare the hysteresis of inductive, capacitive and ultrasonic proximity sensors;

the undergraduates learn to design and implement an on-off temperature control system and a motion control system.

3.1 Monitoring the Sensor Switching Output

Each sensor switching output can be monitored using the programmable logic controller; the sensor connection to PLC is shown in Fig. 12. The equivalent circuit and wiring diagram of the switching output (shown in Fig. 12) are the same for each studied sensor (Purcaru, 2012).

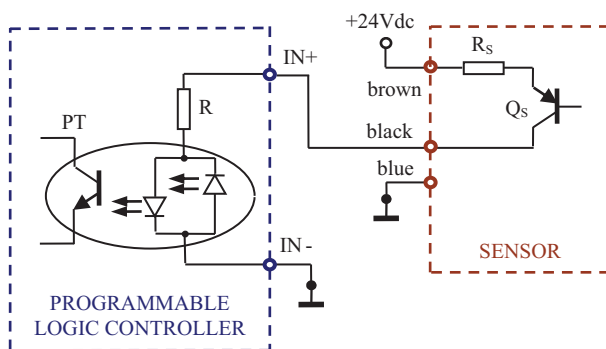


Fig. 12. The sensor connection to the programmable logic controller for monitoring the sensor switching output.

The collector of sensor's Q_S output transistor is connected to one of the two terminals of the selected input of PLC. An optocoupler provides the electrical isolation between PLC input and sensor output.

Students will supply the PLC and the monitored sensor. A program which allows displaying the switching output status of monitored sensor is loaded onto PLC. When Q_S transistor is *on*, the *PT* phototransistor is also *on* and PLC displays *0*. Otherwise, the displayed digit is *1*. If the output function is *NO contact*, digit *0* displaying on PLC means the sensor's activation (e.g. the presence of a target in the proximity sensor's detection zone), and digit *1* displaying means inactivated sensor. Hence, PLC displays *0* when the output LED of proximity sensor lights yellow (for Ni4U, BC3, QS18) or strong yellow (for RU30). If the output function is *NC contact*, digit *1* displaying on PLC signals the sensor's activation. A remote monitoring of sensor switching output is this way implemented.

The programmable logic controller allows both single-ended and fully-differential input voltage because the two terminals of the input circuit. The optocoupler with two LEDs connected in anti-parallel allows reversed polarity of input voltage. A detailed analysis of the circuit from Fig. 12 helps students to better understand the sensor connection to PLC, to assess whether the two devices are compatible, and to acquire practical skills for such connections.

3.2 Experimental System for Testing an Intelligent Temperature Transducer and Implementing an on-off Temperature Control

The experimental system that allows testing of intelligent temperature transducer and implements a simple application of this transducer is shown in Fig. 13. The main components of this system are the intelligent sensor, the temperature probe, the programmable logic controller (PLC), the power supply and several auxiliary devices and circuits.

The temperature around the probe increases when a power resistor ($R_P=39\Omega / 25W$) is supplied with 24Vdc, and a cooler (C_I) is used to lower the temperature. A three-terminal positive regulator with a 12Vdc fixed output voltage supplies the cooler. The power resistor and the cooler are positioned near the Pt100 resistance temperature detector.

The supply of power resistor and cooler can be controlled with mini toggle switches (K_R – for power resistor, and K_C – for cooler) or with PLC as shown in Fig. 14. When K_R is *on* and K_C is *off*, only Q_{R1} transistor is *on*, the current starts flowing through the control coil of REL_1 relay and its contact (NO) becomes closed. This way, only the power resistor is supplied and the measured temperature rises. When K_C is *on* and K_R is *off*, only Q_{R2} transistor is *on*, the C_I cooler is connected to the DC supply (+12Vdc), and the Pt100 probe temperature decreases.

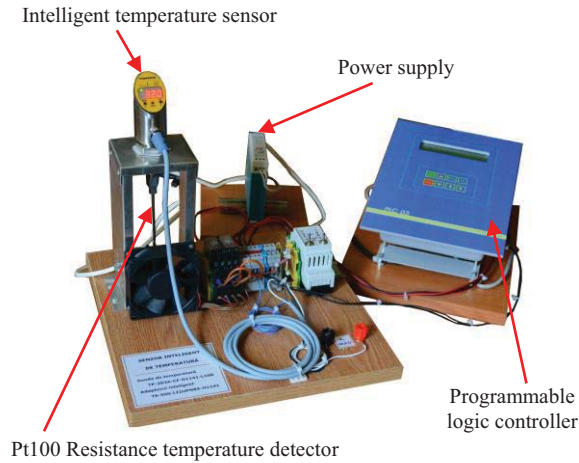


Fig. 13 . Experimental system for studying the intelligent temperature transducer.

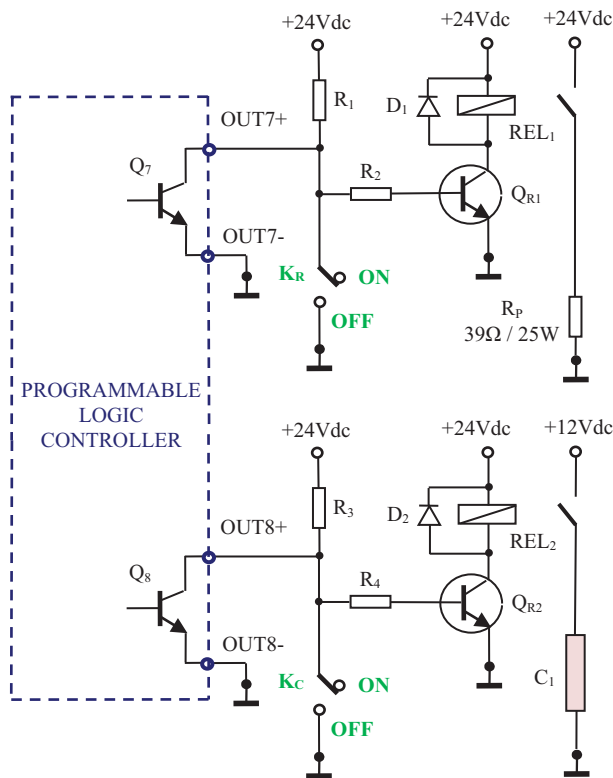


Fig. 14. The voltage supply control for power resistor and cooler.

The undergraduates supply the laboratory model excepting PLC. Initially, K_R and K_C mini toggle switches will be *off*. The testing of intelligent temperature transducer consists in

studying all three operating modes (*Run*, *Menu*, and *Programming*),

locking/unlocking the access to *Mode*, *Set* and *Enter* buttons for secure programming,

testing the operation of both switching functions and analogue output.

The explanations and graphical representations presented above in this paper and the information from (Catalog, 2014) and (User manual, 2012, 2016) are very important for the transducer's testing. The students set the desired values/types for the characteristic points, output functions, analogue ranges and more special functions using the clear menu structure presented in (Purcaru, 2017a).

The parameter settings for testing the temperature transducer functioning with two switching outputs are shown in Table 1. The undergraduates act K_R and K_C mini toggle switches for changing the measured temperature and then observe the intelligent sensor signalling (*Out 1* and *Out 2* LEDs, shown in Fig. 15a) during the temperature increasing and decreasing in accordance with the settings made.

Table 1. The parameter setting for two switching outputs

Parameter	Uni	ou1	SP1	rP1
Value	°C	Hno	35.0	32.0
Parameter	ou2	SP2	rP2	diS
Value	Fnc	37.0	30.0	50

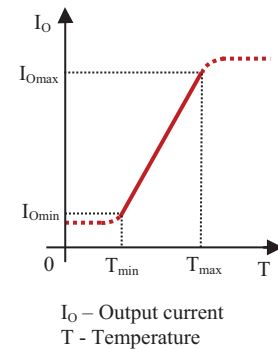
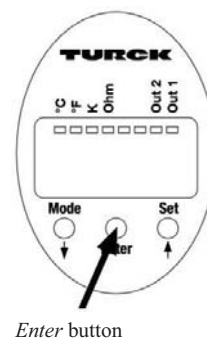


Fig. 15. a) Intelligent sensor signalling and buttons. b) Static transfer characteristic for analogue output.

The circuit from Fig. 16 allows testing the temperature transducer functioning with one analogue output.

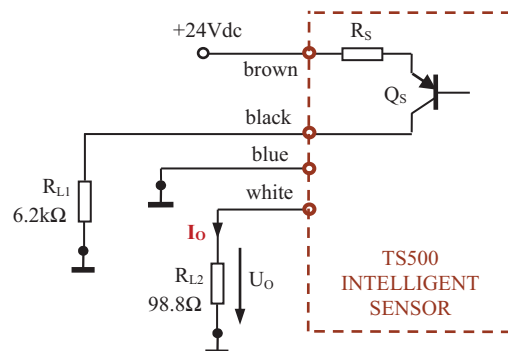


Fig. 16. Circuit for testing the temperature transducer functioning with one analogue output.

The undergraduates must change the settings for the second output as follows: $ou2=4-20\text{mA}$, $ASP=35.0$ and $AEP=50.0$. As a result, the measuring range is $[T_{min}, T_{max}]=[35^\circ\text{C}, 50^\circ\text{C}]$, and the corresponding output current range is $[I_{Omin}, I_{Omax}]=[4\text{mA}, 20\text{mA}]$. The undergraduates change the measured temperature (by using K_R and K_C mini toggle switches), measure the corresponding U_O voltage drop across the R_{L2} resistor (Fig. 16) and calculate the I_O output current through R_{L2} . Some of the measured and calculated values are given in Table 2 and they allow the drawing of the static transfer characteristic (I_O output current versus T temperature) shown in Fig. 15b. The students can observe the linearity of input-output dependence within the measuring range. Knowing I_O output current, the measured T temperature can be calculated:

$$T = \frac{\Delta I_O \cdot T_{min} - \Delta T \cdot I_{Omin}}{\Delta I_O} + \frac{\Delta T}{\Delta I_O} I_O \quad (1)$$

We denote $\Delta T=T_{max}-T_{min}$, and $\Delta I_O=I_{Omax}-I_{Omin}$.

Table 2. Experimental results for the analogue output

$T[^\circ\text{C}]$	30.0	32.0	33.0	35.0
$U_O[\text{V}]$	0.341	0.341	0.341	0.395
$I_O[\text{mA}]$	3.451	3.451	3.542	3.998
$T[^\circ\text{C}]$	38.0	41.0	44.0	47.0
$U_O[\text{V}]$	0.711	1.027	1.344	1.659
$I_O[\text{mA}]$	7.196	10.395	13.603	16.791
$T[^\circ\text{C}]$	50.0	52.0	53.0	55.0
$U_O[\text{V}]$	1.976	2.2	2.26	2.26
$I_O[\text{mA}]$	20.000	22.267	22.87	22.87

If the temperature exceeds by more than 5% the measuring range, OL for overload, respectively UL for underload is displayed.

An on-off temperature control system is implemented using the programmable logic controller; PLC monitors the sensor's switching output 1 and controls the voltage supply of the R_P power resistor and C_I cooler. The settings for output 1 are those specified in Table 1. The intelligent sensor connection to input 8 of PLC is performed as shown in Fig. 12, and the supply control of power resistor and cooler is presented in Fig. 14. A program which allows keeping the temperature between 32°C and 35°C is loaded onto PLC.

Firstly, the undergraduates must supply the PLC, intelligent sensor and auxiliary circuits, with the K_R and K_C mini toggle switches *off*. Then the program starts and students observe the temperature control. When $Q7$ output transistor of PLC is *off*, Q_{R1} transistor is *on* and the current starts flowing through the control coil of REL1 relay; its *NO* contact becomes closed, the power R_P resistor is connected to the DC supply (+24Vdc) and the temperature increases near the Pt100 probe. If $Q7$ transistor is *on*, Q_{R1} is *off*, the current stops flowing through the coil and the temperature decreases. The cooler supply is controlled in the same way using the $Q8$

output transistor of PLC, Q_{R2} external transistor and REL_2 .

3.3 Experimental System for Testing Ultrasonic Sensors

An experimental system allows undergraduates to test the operating and programming of the above presented ultrasonic sensors. The system is shown in Fig. 17 with RU30 and QS18 sensors mounted on a support plate, the PLC programmable logic controller and the power supply for sensors. The projection of each sound cone is figured on the support plate and a ruler marking allows users to measure the distance to target.

The students supply QS18UPA ultrasonic sensor and then test the local programming (via push button) and observe the sensor signalling for both *Teach* method,

measure the blind zone, sensing range and detection zone for various objects (metal or non-metal, clear or opaque with different shapes and sizes).

The undergraduates must connect the sensor to the programmable logic controller, as shown in Fig. 18, for testing the remote programming of QS18UPA sensor. Three programs (denoted *1 Pulse*, *3 Pulse*, and *4 Pulse*) are loaded on the PLC to generate three commands for the sensor (User manual, 2007).

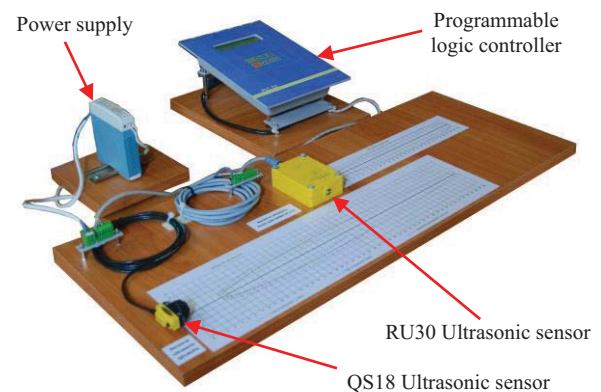


Fig. 17. Experimental system for testing ultrasonic sensors.

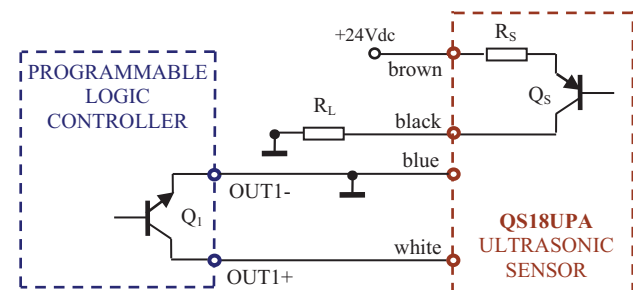


Fig. 18. The QS18UPA ultrasonic sensor connection to the programmable logic controller for remote programming.

1 Pulse program allows implementing of both *Teach* methods for sensor programming as via push button. If *3 Pulse* program is selected, three pulses are sent to the remote line of sensor to toggle between *NO* and *NC*