INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2019, VOL. 65, NO. 1, PP. 51-56
Manuscript received July 19, 2018; revised January, 2019. DOI: 10.24425/123565

An Experimental Test Bench for the Tire Pressure Monitoring System – Discussion of Measurement and Communication Issues

Sławomir Gryś

***Abstract*—The paper presents a method for wireless measurement of car wheel air pressure and temperature using the Tire Pressure Monitoring System, or TPMS module - one of the latest safety systems introduced by the automotive industry - with readings taken on a specifically designed test bench. The paper describes the structure and operating principle of the test bench key elements and how they work with the sensors, the TPMS module, and reference instruments, as well as the data format and accuracy of data transmission between TPMS and the host computer. The software designed for an embedded system emulating the real on-board computer allows for observing raw sensor readings and the effect of calibration in two points of the characteristics.**

***Keywords*—automotive technology, driving safety, temperature and pressure measurements, calibration**

I. Introduction

A significant increase in road traffic over the last decade has raised the risk of a collision or accident. To improve the safety of drivers, passengers and other road users, today's vehicles have been equipped with a number of ADAS systems (Advanced-Driver Assistance Systems), both passive and active. The role of the former is to minimize the effects of a traffic event while the latter are designed to reduce the probability of an incident occurring on the road. Classic safety systems include: ABS (Anti-Lock Braking System), BAS (Brake Assist System), EBD (Electronic Brakeforce Distribution), and the Electronic Stability Program (ESP), all helping the driver retain control of the vehicle under hazardous driving conditions. Contemporary cars also provide a wealth of additional information gathered by a variety of sensors, cameras or radars to enable semi-autonomous driving. Some good examples here include the automatic switching on/off of car lights, the lane keeping assist system, blind spot detection, traffic jam assist, airbags, side curtains, and automatic seat belt pretensioners. Another advantage comes from a car featuring automatic road sign recognition systems or systems detecting driver fatigue [1-2]. Top of the line cars will also be fitted with thermal imaging cameras, very useful for driving at night as they allow the driver to respond quickly to pedestrians, domestic animals or wildlife unexpectedly crossing in urban areas and undeveloped or forested regions. The tire pressure (and optionally temperature) monitoring system, or TPMS, represents one of the many useful functionalities of modern cars. The TPMS alerts the driver about tire pressure loss, helps keeping it at an optimum level - so important to assure tire long life, and improves fuel efficiency owing to low tire friction on the road. A pressure value lower than nominal may dangerously lengthen the vehicle braking distance, which plays a most crucial role in saving life. And conversely, an unusually elevated tire temperature may point to a problem with the wheel geometry or excessive friction of mechanical parts. Effective from November, 2012 Regulation (EC) No 661/2009 of the European Parliament, the tire pressure monitoring system has become a mandatory component of all motor vehicles applying for type approval in the European Union countries with maximum authorized mass below 3500 kg [3]. Since November 2014, the TPMS system has been installed in every new car manufactured and sold in the EU member-States. The European Union has followed the example of the US, where the tire pressure measurement system has been mandatory since 2007 for cars, vans, and trucks whose maximum authorized mass does not exceed 4536 kg [4].

Author is with Częstochowa University of Technology, Faculty of Electrical Engineering, Poland, (e-mail: grys@el.pcz.czest.pl).

II. An Overview of TPMS Solutions

The history of tire pressure measuring systems dates back to 1907, when a Northern vehicle manufactured in the US was first fitted with a pneumatic braking system and a vehicle wheel pressure gauge. The Porsche 959 was the first passenger car to introduce the solution - the hollow spoke wheel system - in the European market in 1986. Nowadays, systems may be classified into direct and indirect types, with both solutions differing from each other in terms of measurement, operation, assembly, viability, usage, service and operating costs. More general information about the history, certain technical aspects of tire pressure sensors, and communication issues may be found in numerous scientific papers, e.g. in [5]. An example of the new sensor construction optimized for passive telemetry was proposed in [6]. A battery-less system with piezo ceramic mode energy harvesting is presented in [7]. The chip converts mechanical strain energy to DC current, delivering stable voltage output and current to power the sensor, MCU, and the data transmitter so they all work properly. The problem of the signal strength range between the transmitter and a receiver is discussed in [8].

A. Indirect Measurement

The indirect pressure measurement system uses readings from ABS/ESP sensors. The ECU determines the pressure adjustment by detecting apparent changes of the wheel diameter. Anomalies are detected when a significant difference in the wheel speed relative to the speed of all the other wheels is found. The system does not strictly measure the pressure, but rather signals any deviation from the nominal value, usually ±30÷40% (after inflating all the wheels to the same value). When the pressure in all the wheels is incorrect, but at a similar level, the system is blind and cannot detect abnormalities. Another disadvantage of the indirect system consists in its inability to control the pressure when the vehicles comes to a full stop as the system requires a speed of minimum 40 km/h to operate properly.

B. Direct Measurement

The TPMS direct system consists of sensors located inside every wheel and a receiver module communicating with an on-board computer. The module connects wirelessly with each sensor, analyses the data, and then transmits it to the device which informs the driver about the current wheel pressure value. Depending on the option, the driver receives information about the general or detailed conditions. In the case of a Low version, when the warning light comes on, it means that the pressure in at least one of the wheels has dropped below the nominal value. In a more complex High version, the system displays the current pressure value and - optionally – the temperature inside every wheel. Figure 1 shows differences in data visualization for both versions.

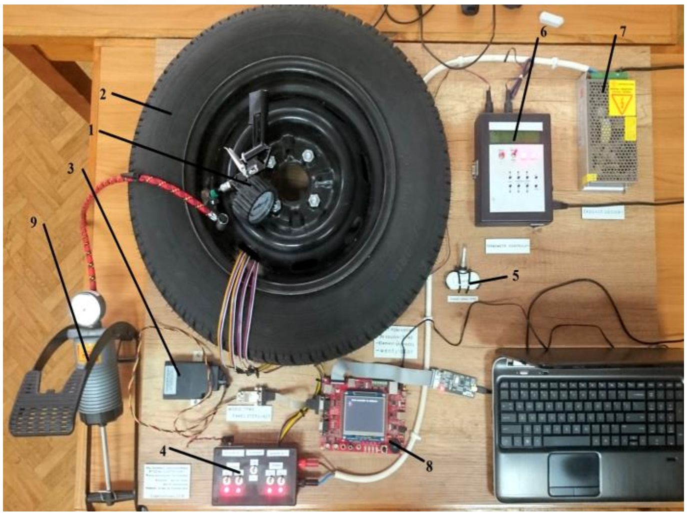
(a) (b)

Fig. 1. Visualization for Low (a) and High (b) versions - adapted from [9]

III. An Experimental TPMS Testing Stand

The proposed testing stand presented in this section makes it possible to operate and test the TPMS system components, including the measurement systems, software and measurement techniques, sensor accuracy by comparing readings with those of reference instruments, calibration, estimated uncertainty of predicted adjustments to raw measurements, and visualization results. Figure 2 shows the entire structure of the testing stand.

The stand consists of a car wheel (2), with three TPMS wireless battery-operated sensors and two 45 W heaters mounted inside. Typical car bulbs with two separated sections are used as heaters. They simulate changes in ambient conditions, e.g. summer or winter. In addition, a small fan is mounted inside the wheel for faster temperature equalization. With the fan turned on, the sensors inside the wheel show almost the same temperature, allowing the operator to compare readings to the same reference value. The control panel (4) is used to control the fan and four heating sections. The heaters, fan, and the TPMS module (3) are all supplied by power unit (7) of 120 W and maximum load of 10 A. The sensor (5) was placed outside to measure the ambient pressure and temperature. The tire pressure may be changed using the foot pump (9) and lowered with a manual valve integrated with the pressure gauge. The reference electronic two-channel



(a)

(b)

Fig. 2. Experimental testing stand for wireless measurement of temperature and pressure (a): 1 - reference pressure gauge, 2 - wheel, 3 - TPMS module, 4 - control panel of the fan and heaters, 5 - pressure and temperature sensor, 6 - reference thermometer, 7 - power supply, 8 - stm32 (ARM) microprocessor system, 9 - foot pump; MEMS sensor and TPMS module (b)

thermometer (6) measures the ambient temperature and the temperature inside the wheel. It displays the temperature in real time and may be set by the user to sound an alarm to prevent exceeding the maximum temperature. The data sent by the TPMS module (TPMS MY07 Receiver) designed for Hyundai cars is received on a PC or an embedded system (8).

A. Integrated Pressure and Temperature Sensor

A typical TPMS sensor consists of a sensor and crafted electronics encapsulated in a plastic enclosure and integrated with a classical valve. The system includes a piezo resistor to measure tire pressure and a semiconductor temperature sensor. The system is equipped with an internal antenna that communicates with the TPMS receiving module at 315 MHz for the US market. In Europe, the system works in the UHF radio spectrum, i.e. 433 MHz. The TPMS sensor electronic circuit is powered by a 3.6 V lithium-ion battery and has a service life of approximately 5-7 years. In more sophisticated systems, the battery discharge rate is transferred to an on-board computer application and optionally available to the driver. Air pressure measurement is taken using a classical bridge circuit with 4 piezo resistors. In the absence of pressure, resistances of all the branches of the bridge are identical and a zero output is obtained. Under pressure, bridge resistors change their resistance: two of them increasing and two of them lowering it; thus, the higher the pressure, the greater the imbalance of the bridge. The output of the bridge is therefore a measure of the pressure [10].

B. TPMS Receiver Module

The purpose of the module is to assess communication between the sensors and the on-board computer which displays data on the vehicle dashboard. The receiver features three operating modes: sleep, test, and standard operation. In the idle mode, the module is entirely inactive. In the test mode, signal reception is enabled, but the automatic sensor identification function remains inactive. In the standard mode, the sensor operates at full functionality. The receiver is designed to operate correctly at temperatures between -40°C and +120° C.
Under real-life conditions, the module is connected to the CAN or LIN car network. For purposes of our stand, the CAN interface was replaced with USART for easy connection to popular devices, such as a PC computer.

C. Communication with TPMS Receiver Module

The TPMS receiver module can be connected directly to a PC equipped with software for monitoring serial port, e.g. HyperTerminal or Realterm. Another possibility is connection to the embedded system via a wired RS232 interface - Figure 3. In both cases, the transmission mode is asynchronous, with no parity, 1 stop bit and speed 9600 bauds. S1-S4 are four MEMS sensors.

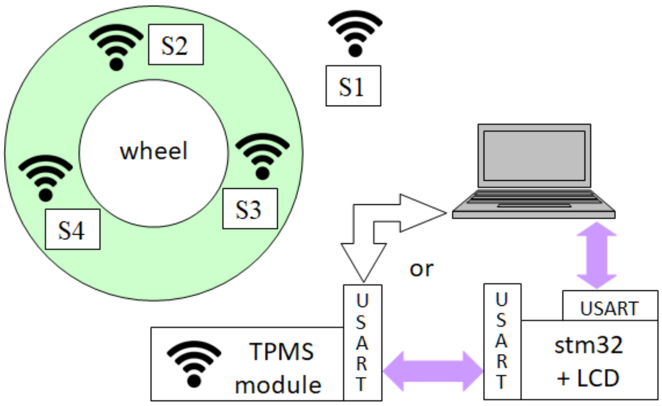


Fig. 3. Diagram of connections

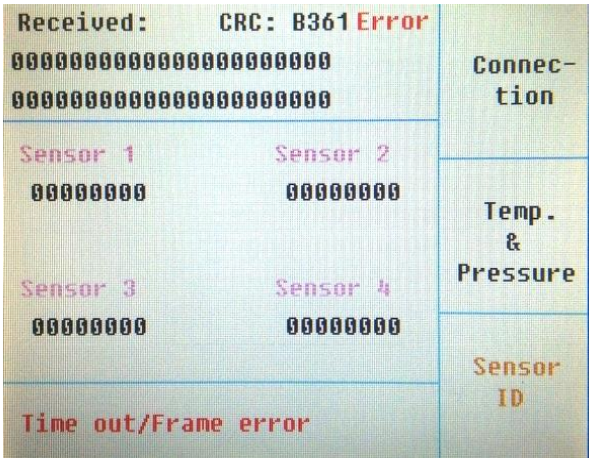
The embedded system is based on the Redbull v3 development platform with a 32-bit ARM Cortex-M3 (STM32F103ZE) microprocessor and equipped with peripherals, i.e.: two USART ports, an LCD graphic display, timers and a touch panel. Processor programming is accomplished using a JTAG-compatible programmer/debugger working in OpenOCD mode. The communication involves sending a data frame from a PC computer or embedded system to the TPMS module. Each query and response frame consists of three fields, as below:
- 1 byte packet identifier,
- packet length dependent data,
- 2-byte CRC-16-CCITT code (polynomial 0x1021).

The response ID is a query ID with added offset 0x80. The following query formats are available:
A. Verification of module presence and transmission correctness:
- query ID 0x00, query data length 0 bytes, CRC 0xE1F0;
- response ID 0x80, response data length 18 bytes: bytes 0-15 contain an invitation string in ASCII format, byte 16 and 17 represent the main and additional firmware version numbers; CRC depends on a string content.
B. Reading data from sensors
- query ID 0x01, query data length 0 bytes, CRC 0xF1D1;
- response ID 0x81, response data length 16 bytes, data include temperature and pressure information for each of the 4 sensors individually; each reading is recorded using two bytes in the following order:
0-1 - temperature measured by sensor No. 1; 2-3 - pressure measured by sensor No. 1; 4-5 and 6-7, respectively for sensor no. 2; 8-9 and 10-11, respectively for sensor no. 3; 12-13 and 14-15 - the same for sensor 4; CRC response depends on sensor readings.
C. Reading the sensor ID
- query ID 0x02, query data length 0 bytes, CRC 0xC1B2;
- response ID 0x82, response data length 16 bytes, data contains hexadecimal notation with TPMS sensor numbers recorded on 4 bytes for each sensor: 0-3: ID of sensor no. 1; 4-7: ID of sensor no. 2; 8-11: ID of sensor no. 3; 12-15: sensor no. 4; CRC response depends on sensor IDs.

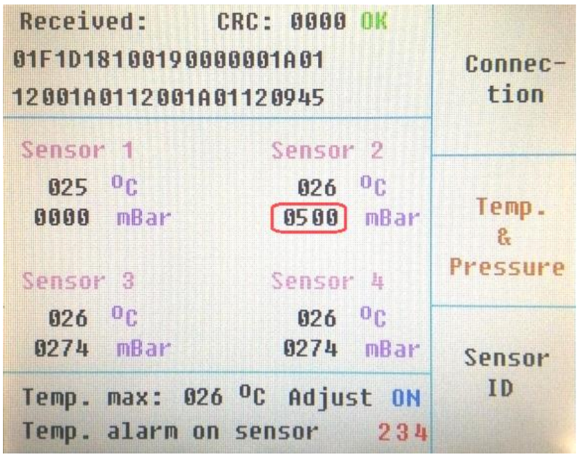
D. Software for an Embedded System

The C code was written for the stm32 platform emulating functionality of car dashboard. The program was developed using the CooCox CoIDE package. Any data received from the TPMS module is visualized on the LCD as a hexadecimal number and additionally sent to the second serial port of the embedded system for data archiving by any external device, e.g. a PC computer. The basic function of the program, i.e. A. Connection, is responsible for checking the transmission. As a result of the query, the TPMS module re-sends the message containing the text with its nick. An unsuccessful attempt to complete the data frame at a time of 1800 ms results in an error message on the LCD. In addition, the CRC checksum is calculated for the received data. Its non-zero value indicates a transmission error. This situation caused by a physical disconnection is illustrated in Figure 4a.

A warning is displayed because of a missing valid response to the C. Sensor ID query. The correct answer should bring up the individual sensor numbers. The open source code with C functions that is available on the website [11] was used to calculate CRC, because the CRC hardware unit being a part of the stm32 microprocessor calculates and validates the checksum only for the fixed CRC-32 polynomial. Data sent to the TPMS module is also protected by the CRC algorithm. The theoretical approach, the influence of the polynomial degree and its values on the efficiency of double and group error detection, as well as some practical aspects of CRC have been discussed in the paper [12]. The key important function of the software running on the embedded system consists in the ability to read the temperature and pressure from sensors via the TPMS module.



(a)



(b)

Fig. 4. A view of the user display: CRC error detected (a), readings of measurement data with active calibration of pressure sensor No. 2 and temperature alarm (b)

Figure 4b shows the response to the query B. Temp. & Pressure. The user can also set the maximum temperature using the mini-joystick. At the bottom of the screen one can see the sensor IDs whose readings have exceeded the accepted alarm threshold. The data presented here corresponds to the pressure approaching 500 mbar (uncalibrated readings, except sensor No. 2) and the temperature close to ambient. The alarm threshold is set to 26°C, hence the system reports alarms for sensors 2, 3, and 4.

IV. Sensor Calibration

The test stand is equipped with an external reference thermometer and a Bourdon tube type manometer, both of them with negligible uncertainties for the assumed circumstances. It allows for constructing a calibration curve for the selected sensor. The idea of sensor calibration will be presented in more detail below. Using the same axis scale for the measured value and the reference value, the characteristics of an ideal sensor (say for temperature) is described by the straight line $t_{ref}=a\cdot t+b$, with coefficients $a=1$ and $b=0$. The subscript *ref* refers to the reading of a reference instrument, here the external electronic thermometer. The real sensor is, of course, imperfect. Adjusting the sensor reading requires determining the values of a and b coefficients. In the next step, the predicted correction based on a, b may be applied to the current reading based on two or more points of the calibration curve.

A. Two Point Calibration

The a, b coefficients are calculated from the equation of the straight line passing through two points $\{t_{ref1}, t_1\}$ and $\{t_{ref2}, t_2\}$ of the curve, where $t_{ref1}\neq t_{ref2}$ and t_1 and t_2 are readings of the temperature measured by the TPMS sensor and – additionally - $t_{ref1}<t_{ref2}$. The designation t' refers to the reading adjusted after calibration. An example of the calculation procedure for two arbitrarily taken pairs of temperature is presented below in Equation (1), where: $t_1=30$ °C, $t_2=46$ °C and $t_{1ref}=31$ °C, $t_{2ref}=48$ °C:

$$a=\frac{t_{2ref}-t_{1ref}}{t_2-t_1}=1.0625 \qquad b=\frac{(t_{1ref}+t_{2ref})-a\cdot(t_1+t_2)}{2}=-0.875 \tag{1}$$
$$t_1^{'}=a\cdot t_1+b=31.00^{\circ}\mathrm{C} \qquad t_2^{'}=a\cdot t_2+b=48.00^{\circ}\mathrm{C}$$

After applying correction factors a and b, the sensor readings should be close to the reference values, with a small difference due to a limited precision of the arithmetic calculations and the assumed linearity of the characteristics. This calibration method was applied in C code of the software for the embedded system. Pressures $p_{ref1}=0.2$ bar and $p_{ref2}=0.5$ bar were assumed *a priori* to represent two reference points. The software assumes the real pressure equals p_{ref1} and after pushing the button, it assigns the current reading to p_1 and repeats it for p_{ref2}. Pushing the button for improper reference values will result in incorrect a and b parameters. Figure 4b presents the effect of correction applied to sensor No. 2 for tire pressure equal to 0.5 bar. It can be observable (red rim) that the correct value for this sensor is 500 mBar and almost twice underestimated value 274 mBar is for uncalibrated sensors no. 3 and 4.

B. Multi Point Calibration - Linear Regression Method

Assuming a zero measurement error and linearity of the calibration curve, it is sufficient to select two arbitrary points on the curve. In real world, any measurement is burdened with an error, so the true values fall within certain unknown ranges. To reduce the uncertainty of determining the calibration curve position, selecting more than two points is recommended. The least squares optimization can be applied to obtain the a and b parameters of the linear calibration curve. This methodology is adapted from [13] and will be presented together with real readings recorded at the discussed stand for sensor No. 3. The correction quality will be compared for points 3 and 10 taken from the characteristics. The parameters of the fit, the intercept - b, the slope - a, and their estimated variances / covariance, are used to assess the standard uncertainty of a predicted correction. Let us assume that the pressure readings range between 0-2.25 bars and are noted as p. The p_{ref} is a known reference pressure read by a high quality analogue pressure gauge - 1 in Fig. 2. Its reading can be considered a conventional true value with an uncertainty appropriate and negligible for this purpose. A linear calibration curve $p_{cor}=a\cdot p+b$ is fitted to the reference readings to minimize the correction $cor=p_{ref}-p$ using the least squares method. Finally, the predicted correction can be taken into account in readings by a simple addition, i.e. $p'=p+p_{cor}$. If fitting is done, one should expect $p'\approx p_{ref}$ at any point of the characteristics. The sought coefficients a and b are obtained by minimizing the function:

$$S=\sum_{i=1}^{N}\left(p_{ref_i}-p_i^{'}\right)^2=\sum_{i=1}^{N}\left(p_{ref_i}-p_i-a\cdot p_i-b\right)^2 \tag{2}$$

where sums are from i=1 to N and will be omitted later for better clarity. The a and b can be calculated using the following formulas:

$$a=\frac{N\cdot\sum(cor_i\cdot p_i)-\sum cor_i\cdot\sum p_i}{D} \tag{3}$$

$$b=\frac{\sum cor_i\cdot\sum p_i^2-\sum(cor_i\cdot p_i)\cdot\sum p_i}{D} \tag{4}$$

where:

$$D=N\cdot\sum\left(p_i-\overline{p}\right)^2 \tag{5}$$

and

$$\overline{p}=\frac{\sum p_i}{N} \tag{6}$$

The estimated variances and covariance of a and b are very helpful in estimating the predicted correction uncertainty, which determines the quality of the calibration:

$$u_a=u_{fit}\sqrt{\frac{N}{D}} \tag{7}$$

$$u_b=u_{fit}\sqrt{\frac{\sum p_i^2}{D}} \tag{8}$$

$$r=-\frac{\sum p_i}{\sqrt{N\cdot\sum p_i^2}} \tag{9}$$

Where: u_{fit} is a measure of the overall uncertainty of the fit; the factor N-2 reflects the fact that because two parameters are determined by the N observations, the degrees of freedom of u_{fit} is $N-2$. Thus,

$$u_{fit}=\sqrt{\frac{\sum\left(cor_i-b-a\cdot p_i\right)^2}{N-2}} \tag{10}$$

The expression for the combined standard uncertainty of the predicted value of a correction may be obtained by applying the law of uncertainty propagation [13]. Finally, the result is

$$u_C=\sqrt{u_b^2+u_a^2\cdot p_i^2+2\cdot u_a\cdot u_b\cdot r} \tag{11}$$

where: u_a, u_b are the standard uncertainty of a and b, and r is the correlation coefficient between them.

The appropriate MatLab® script showing the implementation of all the above mentioned equations is presented below. It was applied to real measurements for pressure sensor No. 3 - Table I.

The evaluated a, b coefficients were applied to calculate the corrected pressure value. The curves before and after 3 and 10 point calibration are shown in Fig. 5. Looking at the plot, it is very hard to visually distinguish differences between the curves after calibration for these two cases.

TABLE I
MATLAB® SCRIPT WITH THE IMPLEMENTATION OF MULTI POINTS CALIBRATION

```
% Calibration of a pressure sensor and estimation
% of uncertainty of a predicted correction
% inputs:
%     p - readings of pressure
% p_ref - known reference pressure
% outputs:
% pcor - predicted correction of reading
%     u_c - complex standard uncertainty of correction
% additional information:
%       cor - measured correction
%         p_adj - adjusted reading of pressure
%         a - slope and b - intercept of the calibration curve
%         r - correlation coefficient between a and b
%         u_a and u_b - standard uncertainty of a and b
%         u_fit - standard uncertainty of the fit
%        N-2 - degrees of freedom
% for 10 readings
% p=[0.014 0.164 0.288 0.411 0.575 0.712 0.849 1.000 1.123
1.288]
% p_ref=[0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25]
% for 3 selected readings from above set
p=[0.164 0.712 1.288]
p_ref=[0.25 1.25 2.25]
cor=p_ref-p
N=size(p,2);
p_mean=mean(p);
denominator=N*sum((p(:)-p_mean).^2);
a=(N*sum(cor.*p)-sum(cor)*sum(p))/denominator
b=(sum(cor).*sum(p.^2)-sum(cor.*p)*sum(p))/denominator
r=-(sum(p))/sqrt(N*sum(p.^2))
u_fit=sqrt(sum((cor-b-a*p).^2)/(N-2))
ua=u_fit*sqrt(N/denominator)
ub=u_fit*sqrt(sum(p.^2)/denominator)
pcor=b+a*p
p_adj=p+pcor
u_c=sqrt(ub^2+p.^2*ua^2+2*p*ua*ub*r)
% end of the script
```

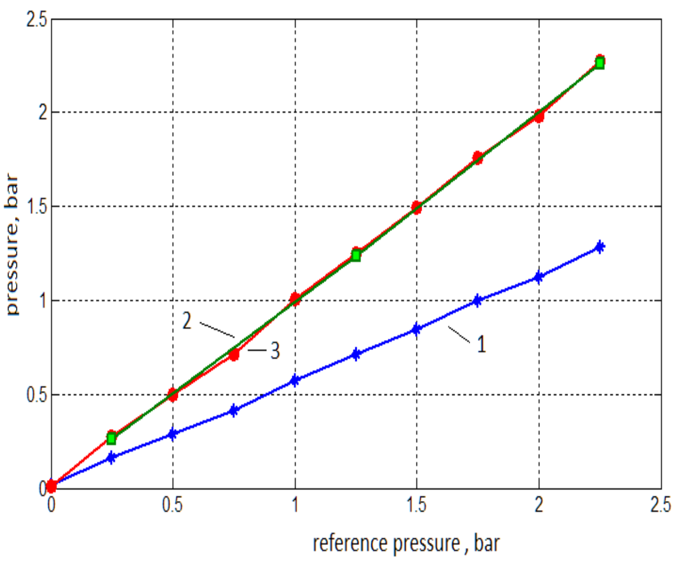


Fig. 5. Calibration curve, where: 1 - uncalibrated, 2- calibrated in 3 points, 3 - calibrated in 10 points

Table II gives more detailed information of the calibration quality. Data presented in the first two columns of the table are used to calculate curve coefficients *a* and *b*. From an objective point of view, the column with predicted correction (cor_{pre}) and its uncertainty is most important.

TABLE II
DATA USED FOR CALIBRATION

a) for *N*=3 readings

p, bar	p_{ref}, bar	a	b	cor_{pre}	$u_c(cor_{pre})$
0.164	0.250			0.095	0.019
0.712	1.250	0.779	-0.033	0.521	0.012
1.288	2.250			0.970	0.019
r		$u(a)$	$u(b)$	N-2	u_{fit}
-0.844		0.026	0.022	3	0.020

b) for *N*=10 readings

p, bar	p_{ref}, bar	a	b	cor_{pre}	$u_c(cor_{pre})$
0.014	0			-0.006	0.012
0.164	0.250			0.111	0.010
0.288	0.500			0.207	0.008
0.411	0.750			0.303	0.007
0.575	1.000			0.430	0.006
0.712	1.250	0.778	-0.017	0.537	0.006
0.849	1.500			0.643	0.007
1.000	1.750			0.762	0.008
1.123	2.000			0.856	0.010
1.288	2.250			0.985	0.012
r		$u(a)$	$u(b)$	N-2	u_{fit}
-0.847		0.016	0.012	8	0.019

Comparing the results in Table II a) and b) the following conclusions may be made:
- even though *a* and *b* seem to be very close and u_{fit} appears almost the same in both cases, a better result, i.e. lower uncertainty of corrections, was obtained when considering 10 readings instead of 3;
- an almost twice lower uncertainty for selected 3 readings (shadowed in the Table) was obtained if 10 points were analysed for the least squares optimization.

CONCLUSIONS

Many aspects of the testing stand used to examine the TPMS module and its uncertainty after semi-automated calibration of the readings were discussed. After minor modifications, the embedded software created in C language may be adapted for another hardware platform using any processor equipped with USART. The created software for the embedded system emulating an actual on-board computer allows for observing uncalibrated or calibrated sensor readings. The calibration routine was implemented in the code in two points. To obtain a higher quality of the calibration, the methodology of the least squares multi-point fitting can be applied as shown. The estimation of standard uncertainty of a predicted correction was also discussed.

ACKNOWLEDGEMENTS

The author is very grateful to the Director and the Engineers of the ZF Czestochowa Engineering Center, Poland for generously contributing their inspiration and technical support to the TPMS module with sensors.

REFERENCES

[1] ZF TRW, the products manufacture, website: http://www.zf.com.
[2] SAE J3063 Standard - Active Safety Systems Terms & Definitions, SAE International, 2015, p. 7, website: http://standards.sae.org.
[3] Regulation (EC) No 661/2009 of the European Parliament and of the Council of 13 July, 2009 concerning the type-approval requirements for the general safety of motor vehicles, their trailers and systems, components and separate technical units intended therefor, website: http://eur-lex.europa.eu.
[4] SAE J2657 Standard - Tire Pressure Monitoring Systems for Light Duty Highway Vehicles, SAE International, 2014, p. 13, website: http://standards.sae.org.
[5] Aini Hussain et al., Characterization of MEMS Automotive Sensors for TPMS, Journal of Applied Science, vol. 6 (4), pp. 810-815, 2006.
[6] M. Nabipoor, B.Y. Majlis, A New Passive Telemetry LC Pressure and Temperature Sensor Optimized for TPMS, Journal of Physics: Conference Series, vol. 34, pp. 770-775, 2006.
[7] Liji Wu, Yixiang Wang, Chen Jia, Chun Zhang, Battery-less Piezoceramics Mode Energy Harvesting for Automobile TPMS, 2009 IEEE 8th International Conference on ASIC, 2009, DOI: 10.1109/ASICON.2009.5351190.
[8] H.J. Song, H.P. Hsu, R. Wiese, T. Talty, Modelling Signal Strength Range of TPMS in Automobiles, IEEE Antennas and Propagation Society Symposium, 2004, DOI: 10.1109/APS.2004.1332051.
[9] Expert website: http://www.rdks.expert.
[10] Sensors in Motor Vehicles. Bosch Technical Newsletter, Issue II Extended, Transport and Communication Publishers, Warsaw 2014.
[11] CRC Calculator, www.zorc.breitbandkatze.de/crc.html.
[12] R.N. Williams, A Painless Guide to CRC Error Detection Algorithms, website: http://www.zlib.net/crc_v3.txt.
[13] GUM 1995 with minor corrections, Evaluation of Measurement Data - Guide to the Expression of Uncertainty in Measurement, JCGM 100:2008, 2008.