INNOWACYJNA GOSPODARKA NARODOWA STRATEGIA SPÓJNOŚCI
INSTYTUT TECHNOLOGII EKSPLOATACJI PAŃSTWOWY INSTYTUT BADAWCZY RADOM
UNIA EUROPEJSKA EUROPEJSKI FUNDUSZ ROZWOJU REGIONALNEGO

Project co-financed by the European Union from the European Regional Development Fund

Jacek WOJUTYŃSKI, Andrzej ZBROWSKI
Institute for Sustainable Technologies – National Research Institute, Radom
jacek.wojutynski@itee.radom.pl, andrzej.zbrowski@itee.radom.pl

CALIBRATION METHOD FOR A LASER TRIANGULATION DISTANCE SENSOR

Keywords

Prototype testing, calibration, laser triangulation distance sensor

Summary

The article presents a calibration method for a measuring circuit with a laser triangulation distance sensor. The authors describe factors influencing the accuracy of measurement using a laser triangulation sensor. The computer software supporting calibration procedure was developed, and the control-measuring software of the penetrometer was modified. The method is the result of the process of improvement of the penetrometer. The application of the developed penetrometer calibration method helps to achieve assumed measuring accuracy of ±2 units of penetration.

Introduction

The penetrometer is used to analyse the consistency of petrochemicals, food products, cosmetics, mortars, as well as plastic explosives. The analysis involves measuring 5-second free-fall distance of a standardised mandrel with a cone (or a pin, ball, hemisphere, cylinder and ballast) located directly above the sample (Fig. 1a). The unit of penetration is displacement of 0.1 mm.

The popularity of this method can be supported by the list of regulations regarding penetration measurement: **ISO**: 2137, 6873; **EN**: 1426, 13179-2, 13880-2+3; **ASTM**: D5, D217, D937, D1321, D1403, D1831, D2884, D5329, D7342; **DIN**: 10331, 51579, 51580; **IP**: 49, 50, 179, 310, 376; **FTM** 791-313; **JIS**: K2207, K2220; **NF** T60-132; **PN**: C-04133, C-04161; **industry standards:** AASHTO T 49, American Institute of Baking – Chicago; AOSC-Duralkonus 20º, AOSC-NormCc 16-60, BS 2499-3; DAB 10-V.5.8.1, Deuroback (Hannover) testing proposal, European Pharmacopeia; MIL-G-10924, SMS 658, Van der Baan Bitumen Index.

When designing the penetrometer, it was assumed that measuring range is 620 units of penetration, which translates to the measurement of mandrel displacement of 63 mm. The mandrel is located in a mounting of a moving measurement head. In the process of improving the penetrometer, a laser distance sensor was installed (Fig. 1b). A set of right triangles is used as the basis for calculating the position of analysed surface [1]. A laser diode emits a measuring beam of light that, after being formed by an optical system, travels towards the mandrel's surface. A dot then forms on that surface, measuring from tens to hundreds of μm. The dot's image is reproduced by the optical system as a projection on the photodetector. Due to high sampling frequency, the device can be used for analysing moving objects.

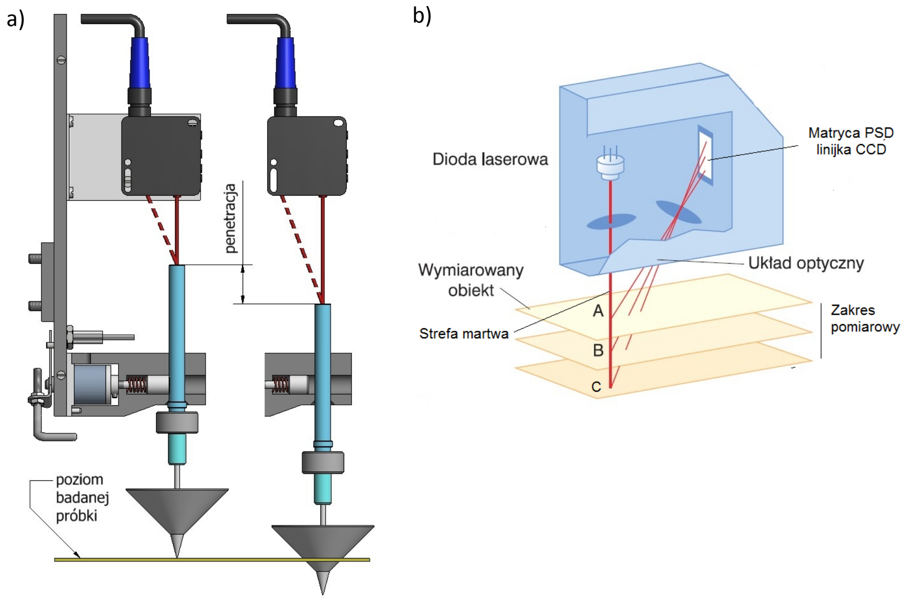


Fig. 1. Laser penetrometer: a) measuring head – principle of penetration measurement, b) principle of laser distance sensor's triangulation measurement

A problem of calibrating the laser sensor's measurement track appeared because of the modification of the measuring system. The aim was to ensure the desired precision of ±2 penetration units (±0.2 mm).

As mentioned before, in the solution designed, the number of units of penetration is determined by calculating the difference between the starting position and the final position of the mandrel after a set amount of time, which is 5 seconds by default.

Utilising a laser technology enables contact-free measurement of the mandrel's displacement with a sampling frequency making it possible to measure the characteristic of displacement in the ongoing process of penetration.

1. Mechanical design of the penetrometer

The design of the penetrometer has been developed since 2000 and has gone through subsequent mechatronic design improvement phases that have included the following:

– The cone's mounting system – two types of electromagnetic clamps;
– The cone's displacement measurement – optical fork sensors, rotary measuring impulse transmitters, laser triangular sensors (analogue current or voltage output, RS232/485);
– The movement of the measuring head (or fork sensor) – stepper motors, DC motors, both with adjustable speed, including microswitches – mechanical and induction;
– Penetrometer control – a specialised keyboard, an alphanumeric panel, a touchpad, specialised buttons;
– Software – data transfer to a computer (RS323, USB, RJ45), CCD camera for inspecting the measuring cone; and,
– Measurement-control system – 51' family microchip, PLC controller (two generations of controller's family).

The first two penetrometers built for ITeE – PIB were equipped with microchip controllers, a specialised touch keypad, fork sensors, DC motors with a disc indicating displacement mounted on a calibrated metric screw [2, 3]. The subsequent versions of the penetrometer (Fig. 2) were equipped with a laser distance sensor that made it possible to measure the displacement of the mandrel with a cone contact-free [4, 5].

The interest in the product and unusual requirements of the customers [6] led to the search of solutions in the penetrometer's design to make it easy to customise and inexpensive to manufacture.

The current design of the penetrometer (Fig. 3) is characterised by a minimal number of mechanical elements and utilises the following:

– For measuring the mandrel's displacement – triangular sensor with current output 4–20 mA;
– An electromagnetic clamp for the mandrel's cone, allowing its free-fall;

– ~1W DC motor for positioning the measuring head – two speeds of movement: slow or precise approach of the cone to the sample and fast for lifting the head; and,
– PLC controller with a webserver and touch panel for the operator – predefined communication protocols, ease of programming to suit particular needs, multiple language options, independence from new versions of the controller with no additional buttons.

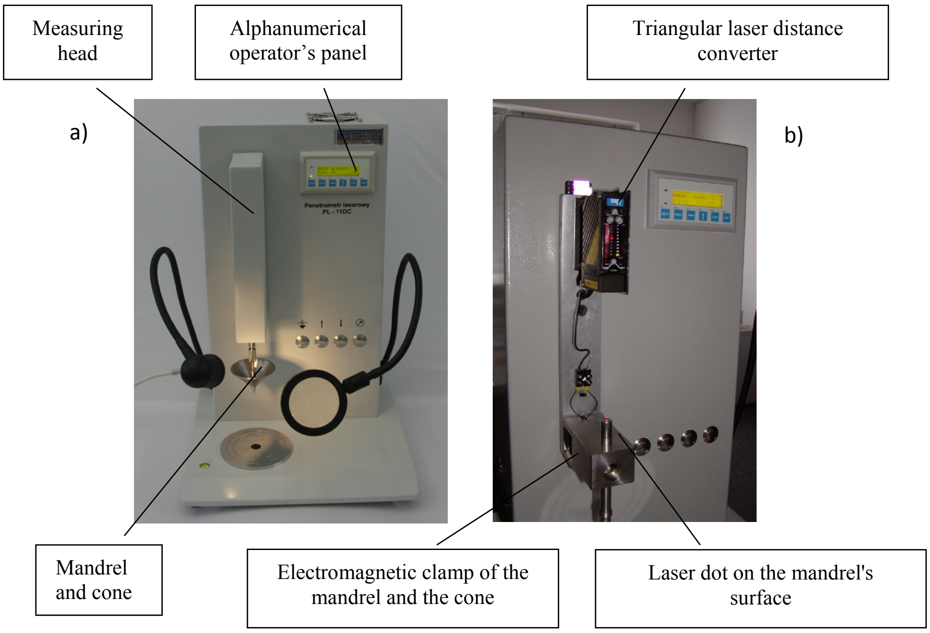


Fig. 2. Laser penetrometer with an alphanumeric operator's panel: a) laser penetrometer general view, b) measuring head's element with case removed

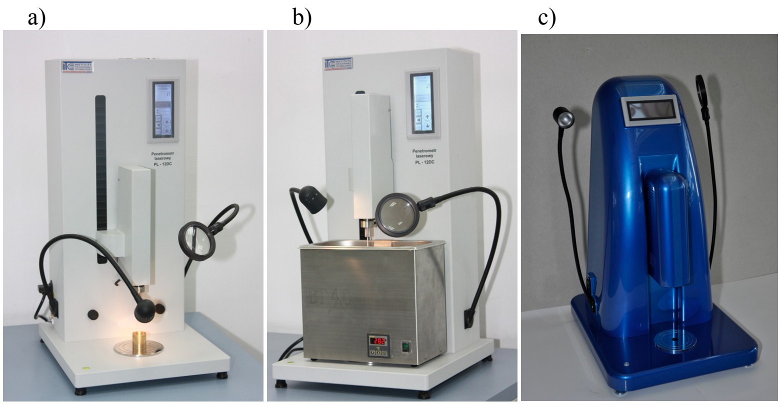


Fig. 3. Current penetrometer's design [5] a) PL-12DC version with a touch keypad b) PL-12DC version with a water bath c) new design in prototype phase

The penetrometer can work in all ranges of voltage and power grid frequency values. There is an option to manufacture an automobile version supplied from the 12VDC socket. The penetrometer has a certificate of electromagnetic compatibility. The touch keypad with graphic symbols (icons) allows intuitive operation of the penetrometer.

2. Mandrel with a cone displacement track measurement

The laser triangulation sensor is the most expensive element of the penetrometer. The cost limit of the laser sensor is an important factor that dictates finding a balance of price and cost of the calibrating procedure of the displacement track measurement.

In the course of development, a problem emerged regarding calibration of the track measurement of the laser sensor. Measurement precision is affected by the following:

– The design of the laser distance sensor (Fig. 1b) – the measurement error and sensor's resolution depend on the distance measured and the sensor's measurement scale. The nature of laser triangulation sensor measurement causes an initial "dead zone" which enlarges the size of the measuring head. The typical measurement ranges within our 620-unit penetration range are 70 mm, 75 mm, and 100 mm. The triangulation method also creates the dependency which says that the larger the range of measurement, the bigger the resolution of the sensor. This is because PSD matrix or CCD ruler of the same resolution are used as the processing element. This absolute error is denoted as Δ_{LAS}.
– The mounting of the sensor in the measuring head – tilting the laser sensor's axis influences the measurement's precision [7]. This absolute error is denoted as Δ_{MON}.
– The workmanship of the mandrel's front, where the cone is installed, as well as possible contamination of the front during operation. The mandrel's front's surface is not one with a standardised colour (usually white), for which characteristics of the laser sensor are determined [8, 9]. This absolute error is denoted as Δ_{TRZ}.
– The measuring track of the PLC controller – AC/DC converter's parameters, bitrate, conversion speed. The penetrometer uses 16-bit analogue converter module. This absolute error is denoted as Δ_{PLC}.
– The precision of measurement – mounting the mandrel in the measuring head in a secure position, preparing the sample and putting it in a standardised vat, precision of locating the cone above the sample. This absolute error is denoted as Δ_{POM}.

The absolute error of the laser penetrometer measurement is denoted as

$$\Delta_{PEN} = \Delta_{LAS} + \Delta_{MON} + \Delta_{TRZ} + \Delta_{PLC} + \Delta_{POM} \text{ [penetration units]}$$

Thus, it has been assumed that there is a need to calibrate the entire measuring track.

Each error source was eliminated or the effect it had on the process was limited. The mandrel's manufacturing process was examined to determine that the surface texture after machining and its roughness and coating material match the parameters of a standard colour surface or create no inconsistency during random mandrel's positioning in the measuring head. As a result, proper manufacturing technology for the mandrel's front was determined.

The analysis of the laser distance sensors' characteristics was conducted using Mistral 100705 device. A triangulation laser distance sensor was installed on the measuring table and the sensor's current was measured. Furthermore, a proper-coloured flat reference object was carefully installed. The distance was calculated from the sensor's current, assuming 4–20 mA mapping ↔ 65–135 mm (Fig. 4). The reference object was moved closer to and further from the sensor. It was concluded that the sensor has a large measurement error near the extremities – almost 5.5 penetration units. For all laser sensors, these graphs are similar. In the sensors' documentation, the precision field is listed below the parabolic characteristic presented in the technical documentation [10–14].

Laser distance sensors in use are offered as a solution for measuring distances, but their main use is to detect missing elements, exceeding element dimensions, checking microchips' legs, etc. in automation systems. There are solutions allowing precise laser distance measurement, but their price exceeds the value of the penetrometer by several times.

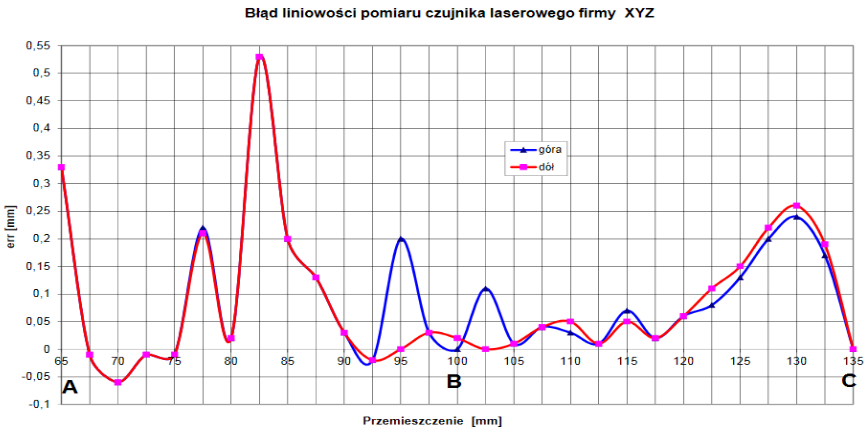


Fig. 4. Characteristics of one of the tested laser sensors with highlighted points: A – the starting point of the range B – the middle point of the range C – the end of the measuring range (Fig. 1b)

In the designed solution, a less expensive head with a lower measuring precision was implemented. This precision was later improved using an additional calibration procedure.

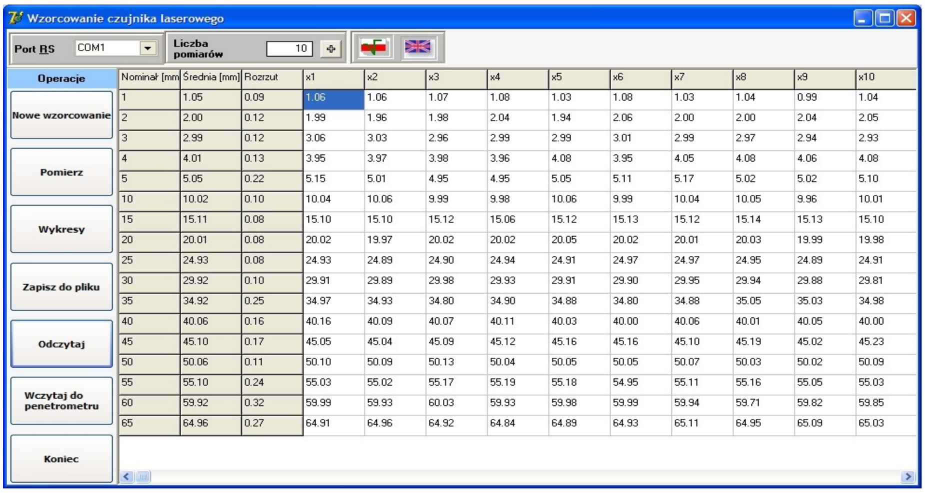
3. Calibration procedure

By design, the front of the mandrel is located near point A (Fig. 1b) which is the least desirable position. The measuring of the displacement of the mandrel with a cone is calculated as the difference between point A and points in the range A-B-C. In the worst-case scenario, the measurement errors can accumulate.

The measurement-control system of the penetrometer is based on a PLC controller for which the read-write protocol of the controller's registries are openly available. Due to this, it was possible to automate the calibration procedure of the laser sensor's track using proper software (Fig. 5) The software enables saving the results of the measurements in various formats, including Excel.

It was assumed that the calibration of the laser penetrometer's track is performed using template tiles for 1–5 mm displacements with a 1 mm step and for 10–65 mm displacements with a 5 mm step (1 mm is 10 penetration units). The calibration of the measuring track is made for 17 points. There is a minimum of 10 measurements in each point. The thickness values of the template tiles make an X set saved in the registry table of the PLC controller.

The first phase of the calibration is entering the 4–20 mA initial mapping ↔ laser sensors' measurement range. It is done automatically by software and consists of setting one bit in the PLC controller.



Nominał [mm	Średnia [mm]	Rozrzut	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10
1	1.05	0.09	1.06	1.06	1.07	1.08	1.03	1.08	1.03	1.04	0.99	1.04
2	2.00	0.12	1.99	1.96	1.98	2.04	1.94	2.06	2.00	2.00	2.04	2.05
3	2.99	0.12	3.06	3.03	2.96	2.99	2.99	3.01	2.99	2.97	2.94	2.93
4	4.01	0.13	3.95	3.97	3.98	3.96	4.08	3.95	4.05	4.08	4.06	4.08
5	5.05	0.22	5.15	5.01	4.95	4.95	5.05	5.11	5.17	5.02	5.02	5.10
10	10.02	0.10	10.04	10.06	9.99	9.98	10.06	9.99	10.04	10.05	9.96	10.01
15	15.11	0.08	15.10	15.10	15.12	15.06	15.12	15.13	15.12	15.14	15.13	15.10
20	20.01	0.08	20.02	19.97	20.02	20.02	20.05	20.02	20.01	20.03	19.99	19.98
25	24.93	0.08	24.93	24.89	24.90	24.94	24.91	24.97	24.97	24.95	24.89	24.91
30	29.92	0.10	29.91	29.89	29.98	29.93	29.91	29.90	29.95	29.94	29.88	29.81
35	34.92	0.25	34.97	34.93	34.80	34.90	34.88	34.80	34.88	35.05	35.03	34.98
40	40.06	0.16	40.16	40.09	40.07	40.11	40.03	40.00	40.06	40.01	40.05	40.00
45	45.10	0.17	45.05	45.04	45.09	45.12	45.16	45.16	45.10	45.19	45.02	45.23
50	50.06	0.11	50.10	50.09	50.13	50.04	50.05	50.05	50.07	50.03	50.02	50.09
55	55.10	0.24	55.03	55.02	55.17	55.19	55.18	54.95	55.11	55.16	55.05	55.03
60	59.92	0.32	59.99	59.93	60.03	59.93	59.98	59.99	59.94	59.71	59.82	59.85
65	64.96	0.27	64.91	64.96	64.92	64.84	64.89	64.93	65.11	64.95	65.09	65.03

Fig. 5. Table with displacement measurements conducted

An average distance value for each template tile is calculated for each measurement series (Fig. 5). The quality of the measuring track is visible on the chart (Fig. 6.) Significant scattering of measurements is noticeable.

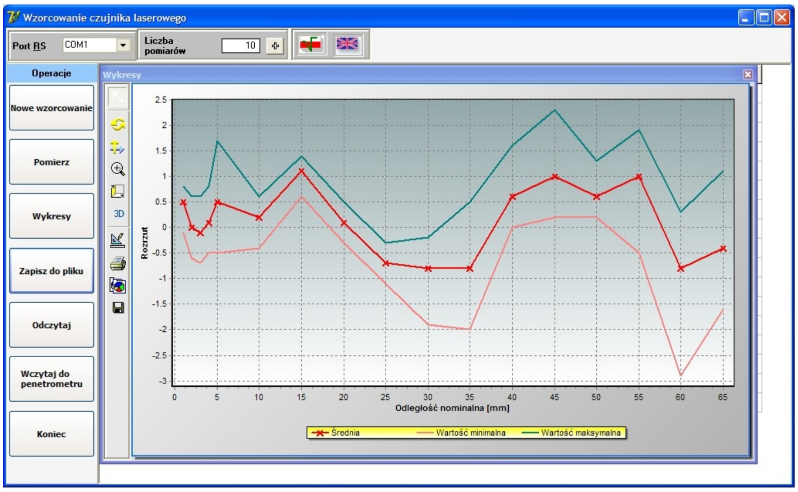


Fig. 6. Chart of conducted measurement of the laser track before calibration

The values of template tiles' thickness (X set) and average values of the measured mandrel's displacements (Y set) are the basis for implementing measurement correction using distance-linear approximation. Proper programming tools are provided by the firmware of the PLC controller [15]. Two tools are available:

1) XYFS macroinstruction to define the segment-linear approximation's characteristic for the maximum of 32 points. The primary mapping before calibration, as previously mentioned, is substituting Y = X. After calibration, the average values of the mandrel's measured displacement are saved in the Y set.
2) MYTX macroinstruction, based on this approximation, enables one to obtain the conversion of the measured Y → X automatically.

After sending the template software to the PLC controller of the X and Y sets, a calibrated track of the laser sensor is generated.

The same software facilitates the procedure of checking the measuring track with the laser distance sensor after calibration (Fig. 7). A clear improvement of the precision of the displacement measurement is visible. All measurements have the measuring error below 2 units of penetration.

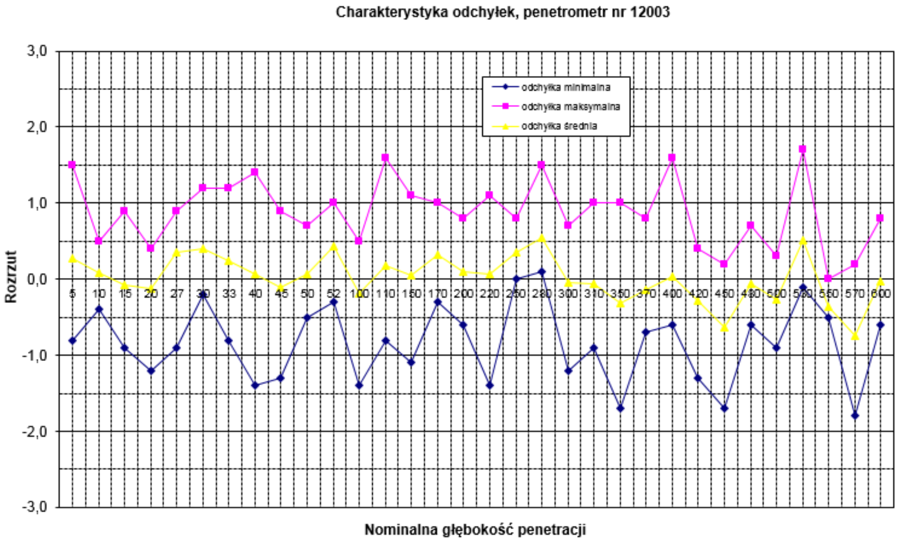


Fig. 7. Chart of the control measurement of the laser track after calibration

Each penetrometer has its serial number imprinted in its registry to facilitate saving calibration files with the manufacturing number of the penetrometer and the date. On start-up, the software automatically imports saved calibration files.

Summary

Utilising a modern PLC controller as the measurement-control system enabled us to automate the calibration procedure. Employing a typical triangulation distance sensor greatly reduces the costs of the penetrometer while maintaining the desired penetration measurement precision. In the penetrometer calibration method presented, 17 points of calibration were used. In order to further improve the precision of measurement track mapping, additional 15 points can be included. It has been concluded that the default number of calibration points is sufficient and leads to an optimum between precision and the time of calibration (340 measurements of penetration). The method developed facilitates testing new laser sensors on the market. It is expected that, during the testing of a new type of laser sensor, a full 32 calibration points will be utilised. Then, the number will be limited to less than twenty.

Acknowledgements

Scientific work executed within the Strategic Programme "Innovative Systems of Technical Support for Sustainable Development of Economy" within Innovative Economy Operational Programme.

References

1. Dorsch R., Häusler G., Herrmann J.: Laser triangulation: fundamental uncertainty in distance measurement. Applied Optics, Vol. 33, Issue 7, 1994, pp. 1306–1314.
2. Molenda J., Samborski T., Wojutyński J.: Penetrometr. Wzór użytkowy. Decyzja UP, wpis do rejestru dn. 16.01.2008 r.
3. Zbrowski A., Wojutyński J.: Klawiatura penetrometru. Patent nr 185897 z dn. 12.01.2004 r.
4. http://www.katalog.itee.radom.pl/images/stories/karty/30.penetrometr.pdf
5. Molenda J., Brzózek M.: Badania nad zastosowaniem ciągłego pomiaru konsystencji do identyfikacji efektu relaksacji naprężeń w mikrostrukturze smarów plastycznych. Tribologia nr 3/2011, pp. 105–117.
6. Molenda J., Samborski T., Wojutyński J.: Penetrometry do badania właściwości reologicznych smarów plastycznych. Problemy Eksploatacji 3/2003, s. 111–125.
7. Zbrowski A., Matecki K.: The influence of the angular position of the laser triangular head on the readings of the measurement system. 9th International Conference Mechatronic Systems and Materials MSM 2013. 01–03 July 2013 Vilnius, Lithuania. Abstract book, pp. 6–7.
8. Zbrowski A.: The impact of the texture and the roughness of the surface on the results of tests executed with the use of a triangular laser head. Przegląd Elektrotechniczny (Electrical Review), nr 10/2013, pp. 298–300.
9. Zbrowski A.: The impact of the colour of the surface on the results of measurements taken with the use of a triangular laser head. Przegląd Elektrotechniczny (Electrical Review), nr 11/2013, pp. 93–97.
10. Dokumentacja czujnika MX1C idec.pl
11. Dokumentacja czujnika CP24MHT80 http://www.wenglor.de/
12. Dokumentacja czujnika OD100-35 sick.pl
13. Dokumentacja czujnika ILD1302-100 http://www.micro-epsilon.com
14. Dokumentacja czujnika ZX1-LD100 i ZX2-LD100 omron.pl.
15. FC5A series. Micro Programmable Logic Controller. FC9Y-B927. Idec Corporation

Metoda kalibracji penetrometru laserowego

Słowa kluczowe

Badanie prototypu, kalibracja, laserowy triangulacyjny czujnik pomiarowy.

Streszczenie

W artykule przedstawiono metodę kalibracji toru pomiarowego z laserowym triangulacyjnym czujnikiem odległości. Omówiono czynniki wpływające na dokładność pomiaru za pomocą triangulacyjnego czujnika laserowego. Opracowano oprogramowanie komputerowe wspomagające procedurę kalibracji oraz zmodyfikowano oprogramowanie pomiarowo-sterujące penetrometru. Metoda jest wynikiem procesu doskonalenia penetrometru. W wyniku aplikacji opracowanej metody kalibracji penetrometru uzyskano zakładaną dokładność pomiaru ±2 jednostki penetracji.