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Original Research

DEVICE FOR AUTOMATIC ACCURACY INSPECTION OF DIAL INDICATOR READINGS

URZĄDZENIE DO AUTOMATYCZNEJ KONTROLI DOKŁADNOŚCI WSKAZAŃ CZUJNIKÓW ZEGAROWYCH

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Abstract

The authors present a research method and a prototype of a system for automatic accuracy inspection of manual measuring instrument readings. Most commonly used measuring instruments, such as dial indicators and bore gauges, require periodic accuracy inspection. The developed system is intended for inspection automation, minimising potential human errors connected with manual inspection and visual assessment of readings. The precise mechatronic actuators, measurement systems, and inspection software used in the system enable automatic execution of standard inspection procedures in accordance with the formal recommendations of the Central Office of Measures. The scientific and research results obtained will benefit the development of methods for processing and analysing measurement data.

Keywords: measuring instruments, errors, inspection procedures

Streszczenie

W artykule autorzy zaprezentowali opracowaną metodę badań oraz budowę prototypowego systemu do automatycznej kontroli dokładności wskazań ręcznych narzędzi pomiarowych. Narzędzia pomiarowe powszechnie stosowane do pomiarów warsztatowych takie jak czujniki zegarowe i średnicówki wymagają okresowej kontroli dokładności wskazań. Zbudowany system służy do automatyzacji kontroli i uniezależnienia jej wyników od potencjalnych błędów popełnianych przez personel w trakcie jej realizacji, związanych z ręczną metodą kontroli i wzrokową oceną poprawności wskazań. Zastosowane w systemie precyzyjne mechatroniczne układy wykonawcze, układy pomiarowe i oprogramowanie sterujące, umożliwiają automatyczną realizację standardowych procedur kontrolnych, zgodnych z formalnymi zaleceniami Głównego Urzędu Miar. W zakresie efektów naukowo-badawczych główny obszar wykorzystania uzyskanych rezultatów stanowi rozwój metod przetwarzania oraz analizy danych pomiarowych.

Słowa kluczowe: narzędzia pomiarowe, błędy, procedury kontrolne

1. Introduction

Dial indicators are used for precise linear measurements (length and diameter) of the runout of rotating elements with an accuracy ranging from 0.01 to 0.001 mm. Despite significant advancements and availability of sophisticated measurement techniques, such as coordinate measuring machines and optical techniques, dial indicators are still widely used, particularly in the machine industry and research laboratories. This is due to their small size, autonomous operation, satisfactory precision, and availability of accessories that facilitate measurement system configurations. Dial indicators are commonly used for the configuration of precision machining systems, inspection of machine tool accuracy (Zong et al., 2018), industrial robot calibration (Chen et al., 2022), and quality control of batch or one-off production. As for the R&D activity, linear measurements with dial indicators are widely used in diverse scientific and technical fields, such as medical equipment construction (Eslami et al., 2016), lithium–ion cell deformation studies (Grimsmann et al., 2017), innovative human–machine interface development (Gleeson et al., 2010), and concrete deformation measurements during degradation (Macioski et al., 2024).

The operating principle of dial indicators, which involves precise measurement of the movement of the measuring tip using a mechanical or electronic mechanism, makes them highly sensitive to various forms of mechanism wear, contamination, and other factors that can impede proper operation. In the machine industry, their occurrence is even more likely due to the presence of dust, lubricants, and aerosol. The critical importance of measurements employing dial indicators necessitates stringent supervision of their accuracy and functionality. Consequently, many research centres strive to improve the verification process of dial indicators' metrological properties and the apparatus used for this purpose (Arief et al., 2021; Hemming et al., 2001; Iordache et al., 2010; Wang, 2011). Ensuring precision of dial indicator inspection equipment at a level of 0.1 μm constitutes another important issue (Lui et al., 2015). Additionally, research aims to improve the durability of dial indicator mechanisms by applying anti-wear coatings (Stancekova et al., 2015).

In Poland, legal regulations mandate periodic accuracy verification of dial indicators to ensure their reliability. As per orders of the President of the Central Office of Measures published in the Official Journal of Measures and Assay (Order no. 50 and Order no. 53), verification involves a series of tests using precise length standards and auxiliary metrological instruments. These tests require exceptional care and significant expertise from the personnel conducting them. Mechanical dial indicators are subjected to the following tests:

- Verification of the scatter and hysteresis of the measuring pressure.
- Determination of the change in indication caused by lateral pressure.
- Determination of the scatter range of indications at three measurement points.
- Verification of the damping of the indicating system.
- Verification of the influence of indicator tilt on reading.
- Determination of the indication and hysteresis errors.

Conducting the full set of tests using a single automated precision inspection device facilitates and shortens the process of dial indicator verification, significantly reducing dependency on personnel skills and efficiency. In facilities with high technical standards, where precision measuring instruments are commonly used, accuracy inspection is a crucial, yet quite costly, area of operations.

2. Inspection system prototype

The goal was to build a device for technical condition and accuracy inspection of dial indicators used in workshop (laboratory) and inspection measurements, mainly in the machine industry. The authors adopted the concept of an inspection system enabling the automated execution of a complete set of tests provided for in metrological regulations on a single testing device (Figure 1).

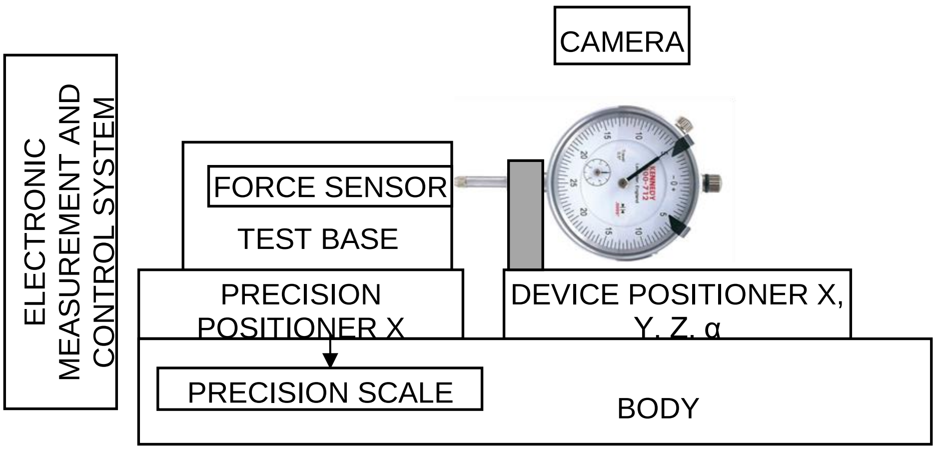

Fig. 1. Diagram of the modular functional system of the inspection system

According to the diagram (Figure 1), the tested instrument – a mechanical or electronic dial indicator, or a bore gauge with interchangeable tips and extensions with a measuring range of up to 500 mm – is mounted in a holder adapted to its construction, ensuring proper and secure fixing and deflection of the measuring tip corresponding to the measuring range (up to 50 mm). The four-axis positioner allows setting the instrument relative to the measurement base and the force sensor, depending on its dimensions and construction, so that the measuring tip rests on the measurement base or the force sensor and slides over its surface, and the entire instrument can assume any angular position. The force sensor is used to measure the pressure force of the indicator's measuring tip, and the measurement base, moved by precision positioner X, to precisely deflect it by distances controlled by the precision scale. The camera is used to record the readings of the measuring instrument (hand or display) in real time. All functional modules of the inspection system are mounted on a stable body resistant to thermal and dynamic interference. The electronic system, in accordance with the programmed pro-cedures, controls the positioners' operation, records camera images and measurement results, and gene-rates a test report. Figure 2 presents the concept in the form of a structural system diagram.

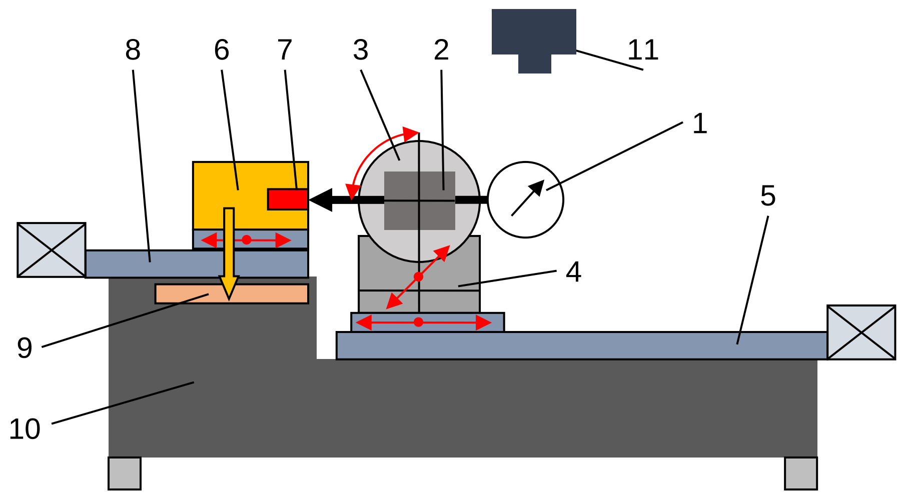

Fig. 2. Structural diagram of the measuring instrument inspection system: 1 – tested measuring instrument, 2 – instrument holder, 3 – precision rotary module, 4 – precision linear manipulator (transverse/vertical), 5 – adjustment linear module (longitudinal), 6 – head with measurement base, 7 – force sensor, 8 – precision linear module, 9 – optical measurement scale, 10 – granite body of the inspection device, 11 – camera

2.1. 3D model of the inspection device

Figure 3 presents a 3D model of the mechanical structure of the device developed based on the assumed concept. The dial indicator to be tested (1) is mounted in a clamping holder (2) by inserting it into an 8 mm diameter hole and tightening it with a screw. The clamping holder is equipped with slide guides (6) to which a support plate is attached. By adjusting the position of the sliding cover within the plate, pressure can be applied to the measuring tip of the indicator, causing it to move. The slide guides (6) and the support plate are moved relative to the clamping holder (2) using a screw with a manual knob (7). Thus, it is possible to mount the dial indicator (1) in the clamping holder (2) and move its measuring tip to a desired position of the hand. The clamping holder (2), along with the slide guides (6), support plate, and screw (7), forms a compact assembly mounted on a movable part of a rotary positioner (3) and can be rotated around the horizontal axis by any angle. This allows the implementation of a standard inspection procedure consisting in the verification whether the readings are not dependent on the dial indicator's position.

The described assembly is installed on the movable component of a cross-positioner consisting of two linear drives (4), which can move the sensor perpendicularly to its main measurement axis, and on the movable component of the linear module (5), which moves the entire assembly along the device in the direction of the main measurement axis of the sensor positioned as shown in Figure 1. The linear module (5), which is a precision screw linear drive with a servo motor, serves to position the tested dial indicator or bore gauge so that its measuring tip rests against the frontal surface of the measuring head (8).

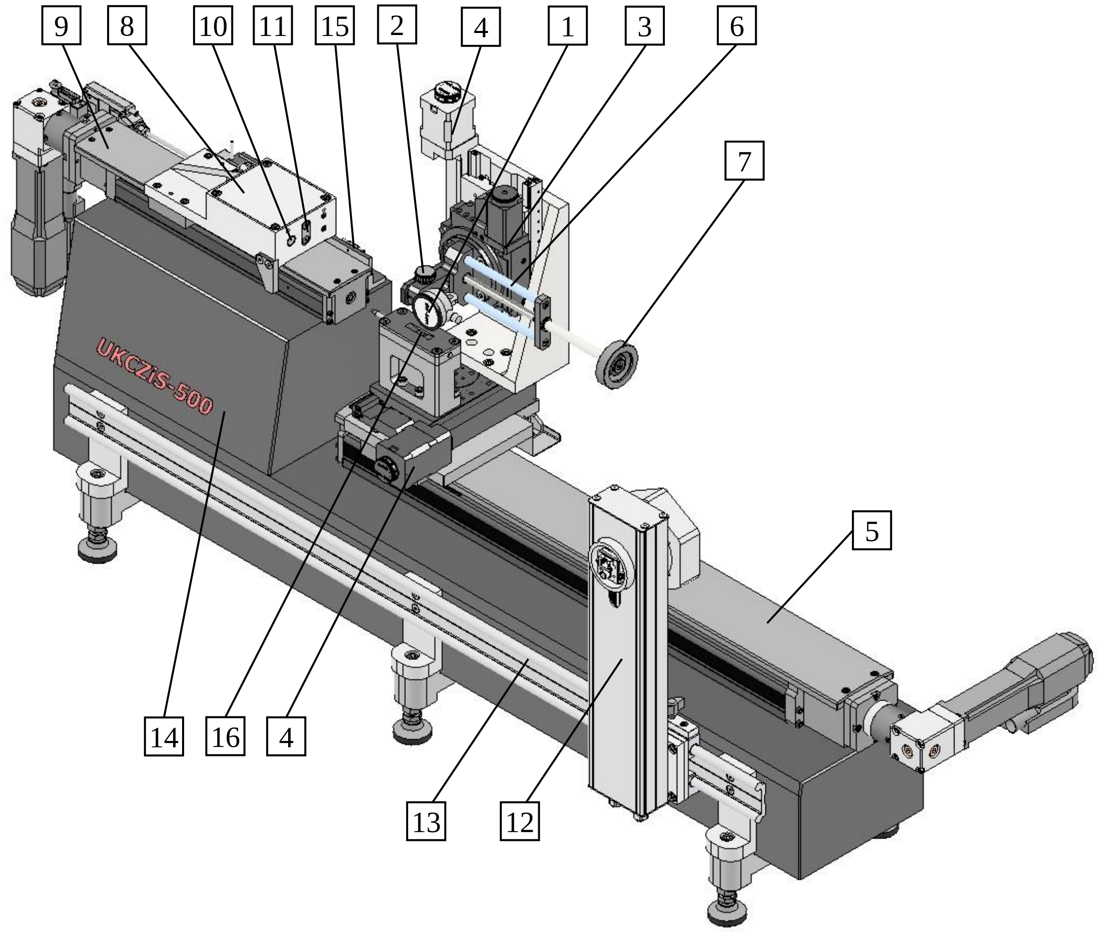

Fig. 3. Concept of the device for automatic accuracy inspection of dial indicator readings (3D model): 1 – tested dial indicator; 2 – indicator holder; 3 – rotary positioner; 4 – linear positioner; 5 – linear module with servo motor; 6 – support plate guide rails; 7 – adjustment screw; 8 – measuring head; 9 – linear module with servo motor; 10 – force transducer; 11 – contact surface; 12 – camera with illuminator; 13 – camera guide rail; 14 – granite body; 15 – precision measuring scale; 16 – sliding reference plate

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The measuring head (8) is equipped with the following elements enabling the execution of standard inspection procedures:

- Strain gauge force sensor (10): Its surface, intended for applying the measured force, coincides with the frontal surface of the head and is used to measure the pressure force of the measuring tip of the tested instrument across the entire measurement range.
- Hardened steel insert with a smooth contact surface (11): This serves to support the measuring tip of the tested instrument (1) during inspection and its movement resulting from the change in the distance between the holder (2) and the measuring head (8).

The contact of these elements with the measuring tip of the tested measuring instrument is achieved by appropriately adjusting the positioner (4), which guides the tip to the selected element. The measuring head (8) is mounted on the movable component of the precision axis (9) and can move, deflecting the measuring tip of the tested instrument. The position of the head (8) is determined with an accuracy of 0.5 μm using the optical measuring scale (15) connected to the device body (14), cooperating with a reader connected to the head. To verify the correctness of the indication, the relative readings of the tested instrument (analogue or electronic) (1) and the readings of the scale (15) are compared. Inspection of the full-range measurement is possible thanks to appropriate ranges of movement of the precision axis (9) and scale (15). The sliding reference plate (16), moved by the head (8), is used to verify the effect of lateral force acting on the measuring tip resting on it on the change in the indicator's readings.

A digital camera (12) with an illuminator is used to read and graphically record the readings of the tested instrument (1). The camera, mounted on a bracket and slide guide (13), can be moved along the device and positioned so that the tested instrument is within its field of view. Electronic inspection of the device operation allows synchronization of the readings of the measuring scale (15) with the image recorded by the camera. This enables precise selection of measurement points of the tested instrument when performing the standard hysteresis testing procedure.

The functional modules of the device determining its accuracy and stability, i.e., the precision axes (5 and 9) along with the assemblies mounted on them, and the optical scale (15), are fixed to a monolithic granite body (14), ensuring the constancy of their mutual positioning and resistance to mechanical vibrations. The body, equipped with adjustable feet, can be mounted and levelled on the flat surface of a laboratory table.

Additionally, optional equipment enabling the accuracy inspection of two-point bore gauges with dial indicators was developed for the device. Figure 4 shows the method for setting the bore gauge in the device for automatic accuracy inspection of dial indicator readings.

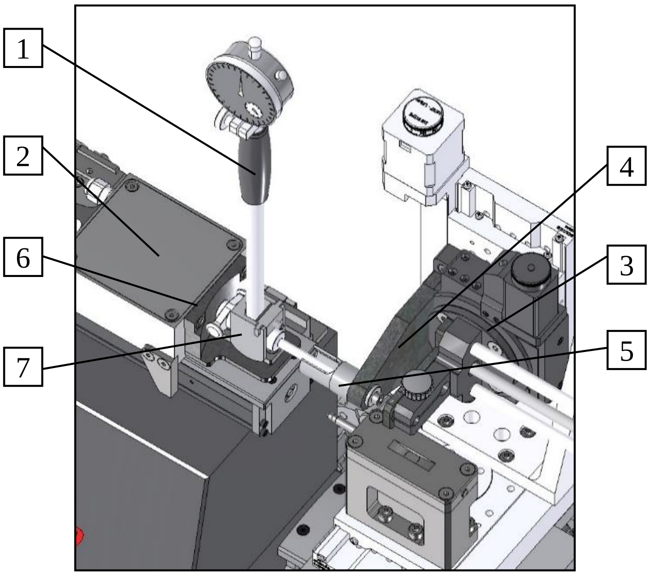

Fig. 4. Method for setting a two–point bore gauge with a dial indicator in the device for automatic accuracy inspection of dial indicator readings: 1 – tested bore gauge; 2 – head of the inspection device; 3 – setting module of the inspection device; 4 – bracket; 5 – fixed support element; 6 – movable support element; 7 – bore gauge holder

The tested bore gauge (1) is placed between the head of the inspection device (2) and the setting module of the inspection device (3). The setting module (3) is rigidly attached to the bracket (4) with the fixed support element (5) with a smooth, flat and hardened support surface perpendicular to the direction of movement of the module (3), against which the anvil of the bore gauge rests. On the frontal surface of the head (2), the movable support element (6) is mounted, whose smooth and hardened support surface has the shape of a cylinder with a vertical geometric axis. Against the cylindrical surface of the support element (6), the contact anvil of the bore gauge (1) and its guide rest. The bore gauge is held in the holder (7) ensuring its stable position, in which its measurement axis is parallel to the direction of movement of the measuring head (2). Precise movement of the head (2) and its individual positions indicated in the inspection computer or read on the monitor can be compared with the readings of the dial indicator of the bore gauge.

2.2. Control system for the operation of the inspection system and software

The authors developed a structure of the inspection system for the device used to verify dial indicators (Figure 5), which consists of the following five functional modules:

The travel module composed of two EMMS-AS-40 servo motors controlled by drivers and a CPX PLC. The PLC communicates with the motor drivers via a CanOpen network and with a PC via Ethernet using the Modbus/TCP protocol. The current position of the travel module is read from an absolute encoder located in the servo motor, and the position of the measurement module is read from an optical encoder.

The indicator stem position measurement module composed of a linear scale, an LIP 481R optical linear encoder mechanically connected to the measurement module, and an EIB 741 processing module. Data from the EIB 741 module is transmitted to the measurement module controller via Ethernet.

The pressure force measurement module consisting of a force sensor with a measurement range of 20 N, a signal amplifier, and an RS485/RS232 converter. The current force value is read by the PC via the RS232 port using the Modbus protocol.

The lateral load module for the indicator stem including linear and rotary positioners, a 3-axis controller, and a power supply. The positioners are controlled and managed by the PC through a USB port using manufacturer's STANDA protocol.

The CCD camera, which takes photos of the dial face when the measurement scale confirms the programmed position has been reached by the linear actuator in the measurement module.

The software developed on the Delphi7 Enterprise platform, allowing control and management of the inspection system modules and the execution of tests.

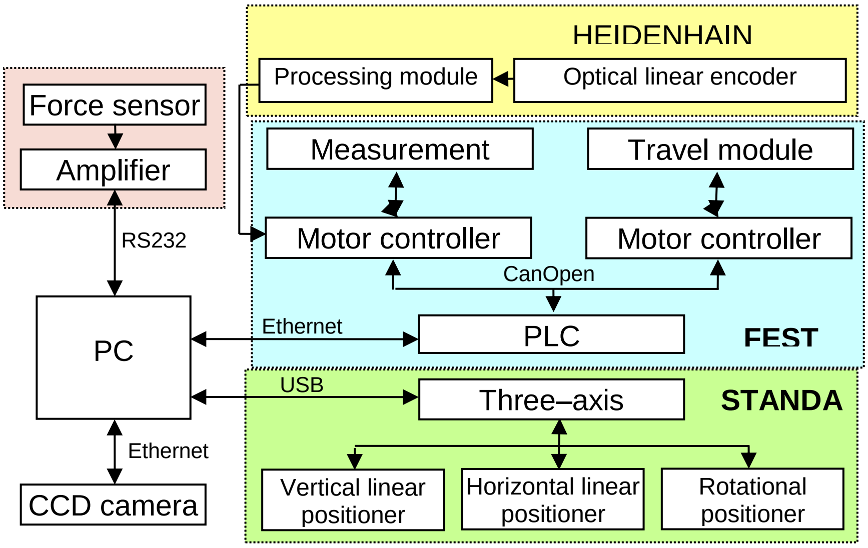

Fig. 5. Diagram of the inspection system structure

The developed software of the inspection system automatically executes inspection procedures, generates test reports, and archives measurement results. The developed operator interface (Figure 6) allows for the following:

- System performance verification.
- Selection of the tested object and its data, description of the conducted test.
- Automatic execution of standard or custom test procedures.
- Measurement result archiving and verification and inspection over their output format.

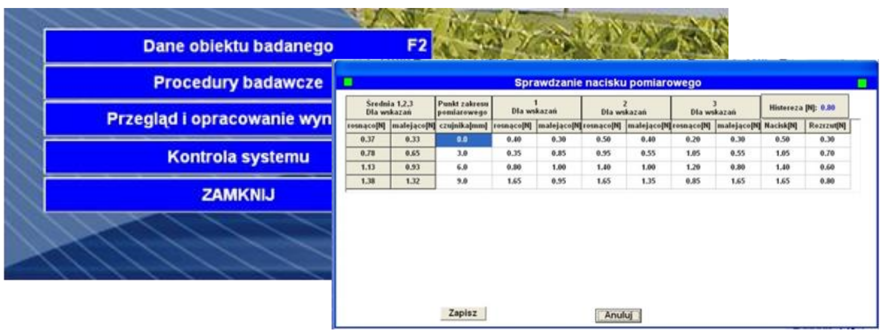

Fig. 6. Sample screens of the control software of the device for monitoring dial indicators (main menu screen and the pressure force check procedure screen)

The software allows the following: testing a measuring instrument recorded in the system; recording a new instrument in the system; removing an instrument from the system; editing the description of an instrument recorded in the system; editing the information about the tests performed; and editing the measurement results obtained.

After entering the data concerning the tested instrument and identifying the test, the operator initiates the selected inspection procedures. Depending on the procedure type, it may be necessary to enter detailed execution conditions, confirm subsequent stages, and approve the results. The software screens also inform the operator about the statuses of individual actuators to monitor and assess the correctness of the instrument test execution.

3. Results of verification tests of the inspection device prototype

The authors constructed a prototype of a device for the automatic accuracy inspection of manual measuring instruments, based on the developed virtual 3D model and verified technical documentation (Figure 7).

A computer inspection system responsible for powering and controlling the modules with electrically controlled drives, as well as software for the automatic execution of inspection procedures, were activated. Tests were conducted on the working and setting movements performed by linear rolling modules and movements of the tested instrument's positioner. Systems measuring the deflection of the moving measuring element of the tested instrument, and the force of the measuring tip, as well as a vision system with a camera recording indicator's readings with a mechanical hand were also activated (Figure 8).

a) b)

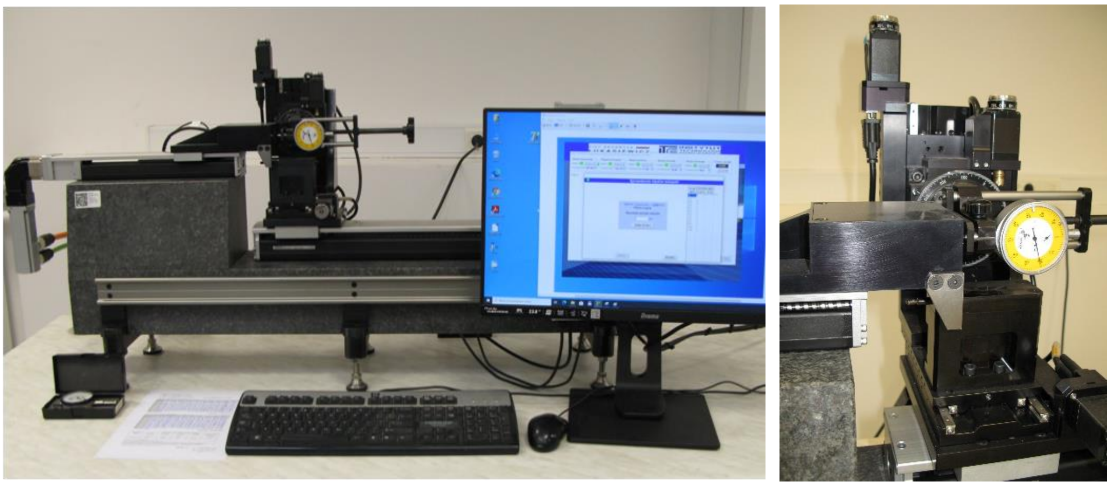

Fig. 7. Prototype of the inspection device with a laptop: a) general view of the measuring station, b) measuring head and positioner of the tested instrument with the controlled dial indicator

Fig. 8. Prototype of the inspection device – use of the camera to ensure precision of dial indicator's readings

Verification tests involved a series of inspection tests on 8 dial indicators selected out of 35 such measuring instruments used at the Łukasiewicz–ITEE Prototyping Centre. Proof tests of each of them were performed five times to verify the repeatability of the results of the measurements obtained. A month prior to verification tests, the selected indicators had passed manual inspection at the Quality Control Laboratory. Due to limited equipment resources, manual inspection was restricted to determining indication errors and measurement hysteresis.

Table 1 presents sample inspection results for the ETALON indicator with a measuring range of 0–10 mm and a resolution of 0.01 mm. The indicator with identification number NP/001-00, was approved in 2000 and since then it has been sporadically used at the Quality Control Laboratory. Cells marked in blue show the inspection measurement results obtained using the described device, while those marked in green the results of measurements performed manually. From the table it follows that manual and automatic measurements are sufficiently consistent, and the results of the automated inspection cover the full metrological characteristics required by the Central Office of Measures (Regulation no. 50; Regulation no. 53).

Table 1. Inspection measurement results for the ETALON indicator with a measuring range of 0–10 mm and a resolution of 0.01 mm obtained using the described device (*blue*) and through manual measurements (*green*)

<table>
<tr><th colspan="5">Measuring force</th></tr>
<tr><td>required</td><td colspan="2">measured automatically (average value)</td><td colspan="2">standard deviation</td></tr>
<tr><td>0.4 ÷ 1.5 N</td><td colspan="2">1.05 N</td><td colspan="2">0.0122</td></tr>
<tr><th colspan="5">Measuring force dispersion</th></tr>
<tr><td>permitted</td><td colspan="2">measured automatically (average value)</td><td colspan="2">standard deviation</td></tr>
<tr><td>0.7 N</td><td colspan="2">0.56 N</td><td colspan="2">0.0292</td></tr>
<tr><th colspan="5">Measuring force hysteresis</th></tr>
<tr><td>permitted</td><td colspan="2">measured automatically (average value)</td><td colspan="2">standard deviation</td></tr>
<tr><td>0.6 N</td><td colspan="2">0.23 N</td><td colspan="2">0.0122</td></tr>
<tr><th colspan="5">Change in indication due to lateral force</th></tr>
<tr><td>permitted</td><td colspan="2">measured automatically (average value)</td><td colspan="2">standard deviation</td></tr>
<tr><td>0.005 mm</td><td colspan="2">0.003 mm</td><td colspan="2">0.0007</td></tr>
<tr><th colspan="5">Indication errors</th></tr>
<tr><td></td><td>permitted</td><td>measured manually</td><td>measured automatically (average value)</td><td>standard deviation</td></tr>
<tr><td>for 1/10 rotation</td><td>±0.005 mm</td><td>0.005 mm</td><td>0.005 mm</td><td>0.0007</td></tr>
<tr><td>for 1/2 rotation</td><td>±0.008 mm</td><td>0.008 mm</td><td>0.007 mm</td><td>0.0010</td></tr>
<tr><td>for 1 rotation</td><td>±0.010 mm</td><td>0.008 mm</td><td>0.008 mm</td><td>0.0010</td></tr>
<tr><td>for 2 rotations</td><td>±0.015 mm</td><td>0.013 mm</td><td>0.012 mm</td><td>0.0013</td></tr>
<tr><td>for the entire measuring range</td><td>±0.020 mm</td><td>0.015 mm</td><td>0.013 mm</td><td>0.0019</td></tr>
<tr><th colspan="5">Measuring hysteresis</th></tr>
<tr><td>permitted</td><td colspan="2">measured manually</td><td>measured automatically (average value)</td><td>standard deviation</td></tr>
<tr><td>0.003 mm</td><td colspan="2">0.003 mm</td><td>0.003 mm</td><td>0.0004</td></tr>
</table>

Tests of the prototype of the device and the developed software, conducted using measuring instruments employed at the Łukasiewicz–ITEE Prototyping Centre, confirmed the possibility of executing complete, standard verification procedures as part of periodic measuring instrument inspection

4. Summary

The authors constructed and developed a prototype of a mechatronic device for the automatic accuracy inspection of manual measuring instrument readings. This device enables dial indicators and two-point bore gauges with dial indicators to be fully tested automatically, during periodic inspection, in accordance with the regulations of the Central Office of Measures (Regulation no. 50 and Regulation no. 53). The solution significantly accelerates the inspection process and eliminates potential human errors. It carries out an automatic test programme analogous to the advanced sensor calibrators offered by Steinmeier (https://www.feinmess-suhl.com) and allows for a much broader control of measuring tools compared to the instrument offered by Mitutoyo (https://shop.mitutoyo.eu). The precision and scope of the tests performed correspond to the standard needs of the engineering industry and to the metrology regulations in force (Order No. 50; Order No. 53).

The device has been verified and implemented to test measuring instruments used at the Łukasiewicz–ITEE Prototyping Centre, in both laboratory measurements and experimental production. It is intended mainly for the machine industry, where dial indicators and bore gauges are employed in production processes and quality control, and difficult working conditions necessitate more frequent inspections.

The original structural solutions developed at Łukasiewicz–ITEE, are patented (patents no. PL239823 and PL243868).

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