ARCHIVE OF MECHANICAL ENGINEERING

Volume 66 2019 Number 1

DOI: 10.24425/ame.2019.126374

Key words: industrial robots, blade measurement, robotic machining

Dariusz Szybicki[1], Andrzej Burghardt[1], Krzysztof Kurc[1], Paulina Pietruś[1]

Calibration and verification of an original module measuring turbojet engine blades geometric parameters

The article presents the issue of calibration and verification of an original module, which is a part of the robotic turbojet engines elements processing station. The task of the module is to measure turbojet engine compressor blades geometric parameters. These type of devices are used in the automotive and the machine industry, but here we present their application in the aviation industry. The article presents the idea of the module, operation algorithm and communication structure with elements of a robot station. The module uses Keyence GT2-A32 contact sensors. The presented information has an application nature. Functioning of the module and the developed algorithm has been tested, the obtained results are satisfactory and ensure sufficient process accuracy. Other station elements include a robot with force control, elements connected to grinding such as electrospindles, and security systems.

1. Introduction

High reliability of current passenger plane engines, exceeding 20,000 hours, results from, among others, engine blades and flow passages shape optimization, using advanced construction materials and cutting-edge technology of subsystems production. More and more frequently, industrial robots are used in turbojet engines elements production. Aerospace industry robotization results from the necessity of ensuring high repeatability and preciseness of element production.

Examples of aerospace industry robotization are presented in papers [1–3]. Robotic processing, using force control in robotic processes, and robotic station elements automatic diagnostics are the subject of publications [4–8]. Measurements of jet engine blades due to the complexity of the shape are quite demanding.

✉ Dariusz Szybicki, e-mail: dszybicki@prz.edu.pl

[1] Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, Department of Applied Mechanics and Robotics, Rzeszów, Poland.

The blade surface is a complex three-dimensional surface, with a strong twist. The blade is expensive to manufacture. Regular blade repair service and testing not only extends the engine life, but also enhances economic efficiency and saves costs. Therefore, blade surface detection is very significant for to the maintenance of engine parts. The blade measurement methods include contact and non-contact measurements. The contact measurement methods include CMM measurements and inductance measurements. CMM measurements can get the point cloud data; however, they do not meet all the needs of obtaining three-dimensional information. The measurement speed of contact measurement methods is very slow. Optical non-contact measurements are widely used methods, and include the triangulation, fringe projection and stereovision methods. Optical methods can be used with 2D or 3D scanners. The use of a 3D scanner for blades geometry measurements in service and repairs is presented in paper [9]. Blades geometry measurements are used in processing to correct the tool motion [10, 11], and to correct robot TCP point using a laser system for more precise grinding [12, 13]. Laser systems based on triangulation used for quick blade measurements is presented in paper [14]. The grinding process may also be improved using laser scanning [15]. 3D laser systems measuring blade geometry and comparing it to a model in order to manage robotic processing is presented in paper [17]. The issue of approximating large amounts of measurement information received during scanning is considered in paper [16].

The article presents an original blade geometric parameters measurement module, its calibration, and the method of width measurement in a specific cross-section. The received measurement data can be used for both quality control and robotic processing using force control.

Summing up, the issues presented in the paper are currently worth considering and are part of the issue of machine parts production and control automatization.

2. Turbojet engine blades geometric parameters

The structure of currently used turbojet engines is very complex. Turbojet engine compressor and turbine blades belong to its most important elements. Depending on their size and usage, the engines differ in the number and type of used blades [18]. In the general case of the turbojet engine, there may be discerned:

- compressor blades – their task is to increase air flow speed,
- turbine blades – they function at high temperatures, used for transferring active power from fumes to a rotor, causing its rotative motion.

Blades are currently produced using advanced technology allowing achieving correct durability and high geometric preciseness. They are crucial elements undergoing numerous control procedures. Blades production cost and time consumption is up to 35% of the cost and time consumption of a whole engine production [18]. In a modern engine, there might be even as much as ca. 3500 blades. A number of blades in the engine necessitates automatization and repeatability of their production and control. Blade shape (Fig. 1) depends on its type. It consists of a part called the aerofoil blade and the roof platform. Aerofoil blades in the cross-section have an aerodynamic profile.

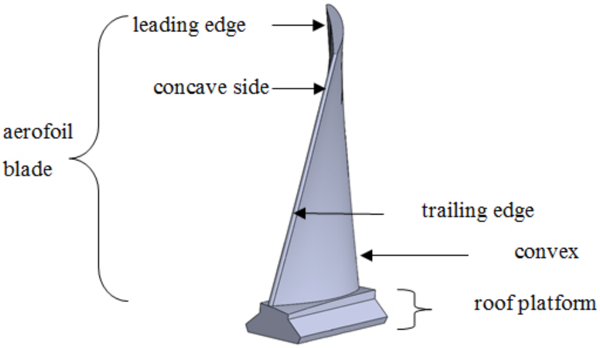


Fig. 1. Blade elements

The blade structure can be divided into the convex part and the concave part. Blade geometric parameters are measured in its specific cross-sections called the profiles (Fig. 2).

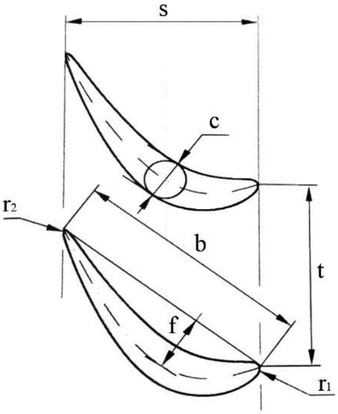


Fig. 2. Blade profile [19]

The blade profile includes the following elements:

- r_1 – leading edge radius,
- r_2 – trailing edge radius,
- b – blade chord,
- c – blade thickness,
- f – section centre line.

Blade profile length is appropriately twisted in relation to its longitudinal axis, which results from conditions in which the blade performs and the stress it undergoes. Blade dimensions are determined through gas dynamic calculations.

Currently, there are several methods of measuring blade geometry and twisting angle of specific profiles. Used methods can be divided into contact and non-contact ones. The article presents an original measurement module using contact sensors for aerofoil blade width measurement in three various points as well as cord size measurement. During measurements, the blade is held by an industrial robot of 0.06 mm repeatability, enabling measurement of any cross-section.

3. Blades geometric parameters' measurement module

Original measurement module is one of the crucial elements of the robotic turbojet engines blades grinding station (Fig. 3).

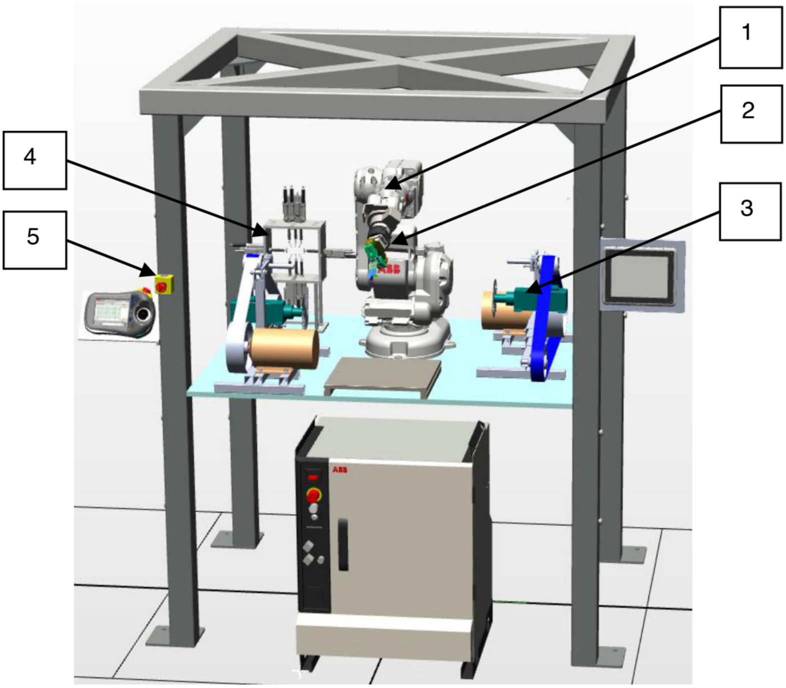


Fig. 3. CAD design of grinding station of turbojet engine blades

The most important elements of the station include:
1. ABB industrial robot equipped with the dedicated gripping device,
2. force control addition used for grinding,
3. electrospindle and belt grinder,
4. blades measurement module,
5. elements of communication with the user and security systems.

Design and manufacturing of the whole station will be presented in further papers, while the following article focuses mainly on the original measurement module, which is based on contact sensors. In the sensor, the absolute value scale, with different slit patterns engraved according to position, is captured at high speed with a high-resolution CMOS sensor. High-intensity illumination from HL-LEDs reliably emits light through the absolute value scale to a high resolution CMOS. Output signals are calculated by the processor, which allows for constant position recognition. The concept of sensor operation is shown in Fig. 4.

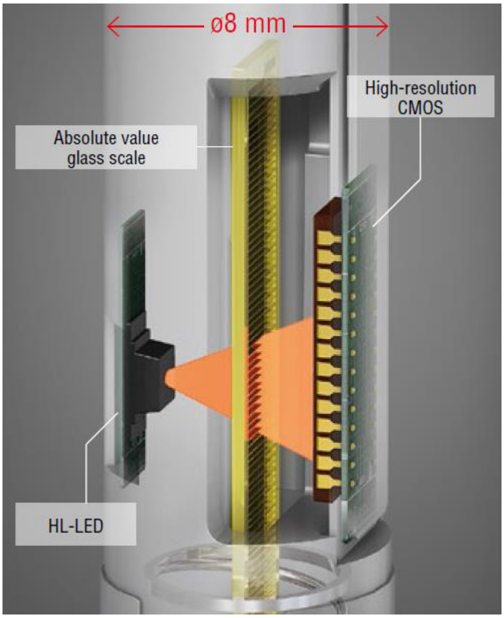


Fig. 4. The conception of sensor working

The module uses Keyence sensors (model GT2-A32) for which the accuracy declared by the manufacturer is 0.003 mm and the range is 32 mm. The use of 8 sensors and their positions relative to the blade result from the technical documentation of the selected blade model. The producer of the blades specifies the quantity and distribution of the measurement points for the selected model of the blade. The designed module allows measurement in 8 points for any number of cross-sections. The sensor resolution specified by the manufacturer is 0.0005 mm. Requirements in the process, established during design, indicate that the accuracy of the measuring module is 0.01 mm. The sensors are equipped with gas spring responsible for the measurement element movement. The contact sensor heads require a compressed air supply.

In the designed solution, a valve block was used as the control system of the compressed air supply manufactured by SMC (Fig. 5). The valve block was controlled by the robot controller over the ProfiBus.

Fig. 6 presents the CAD model and the built prototype of the measurement module.

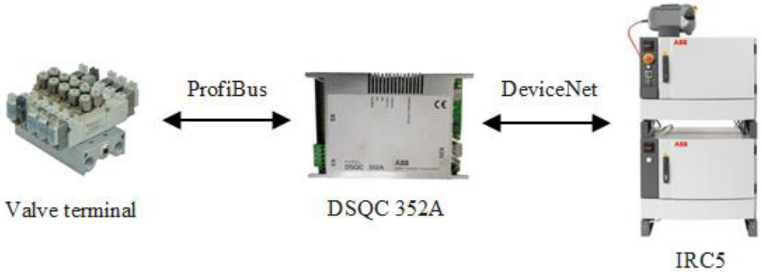


Fig. 5. Connection wiring diagram of the valve block and the robot controller

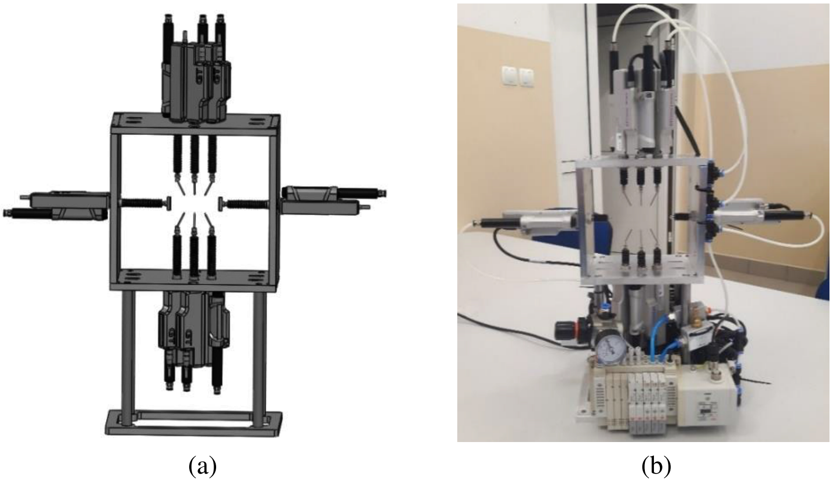


Fig. 6. Measurement module CAD model (a), module prototype picture (b)

The main elements of the module, that is, GT2-A32 sensors, are connected to a GT2-500 amplifier. It powers heads and transforms the electric signal into digital information on heads projection distances. The information is transferred to devices connected to the Ethernet by DL-EN1 module. Fig. 7 presents the communication layout.

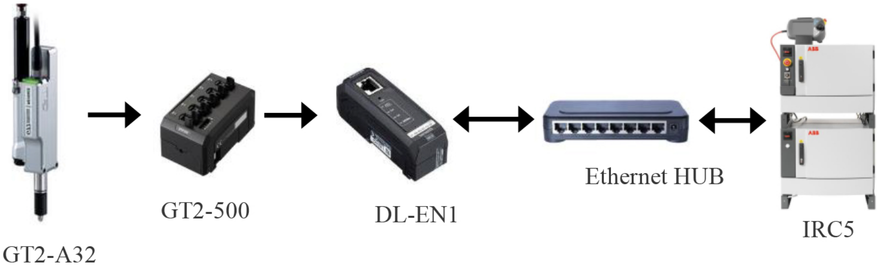


Fig. 7. Layout of connecting Keyence sensors to the robot controller

The module DL-EN1 transfers sensors projection data through TCP/IP protocol. The contact sensor head outputs were read by interrogating the data communication module with an ASCII command. Each command format had a strictly defined content for the interrogation and reply data frames. The frame formats are shown in Fig. 8.

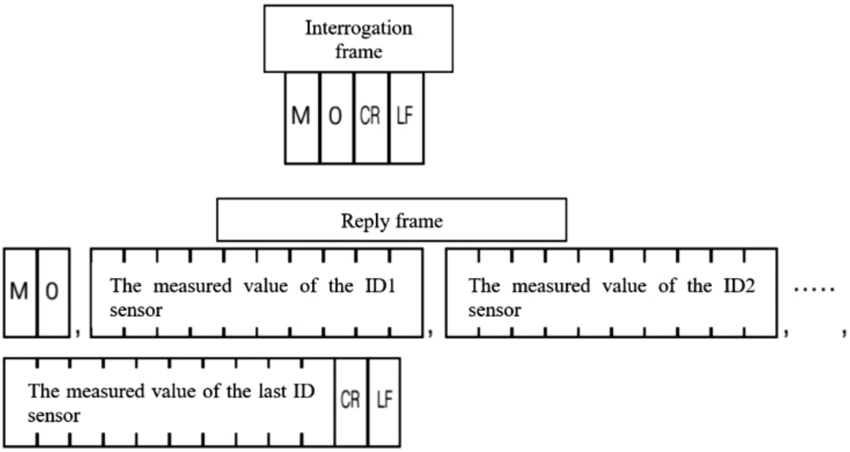


Fig. 8. Formats of the interrogation and reply data frames

Each data frame ended with the control characters: CR (carriage return, ASCII 13) and LF (line feed, ASCII 10).

The received blade geometric parameters are used in the realization of the blades grinding process (Fig. 9).

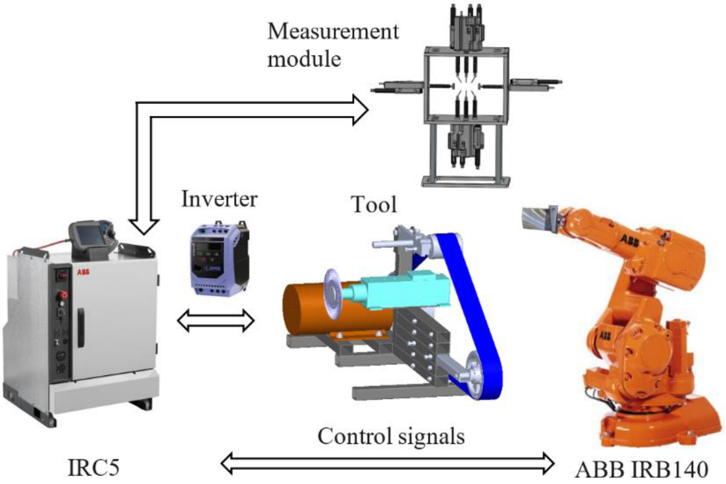


Fig. 9. The layout of turbojet engine blades measuring and grinding station

Testing of selected measurement module functioning confirmed correctness of the assumptions. It became crucial to create an algorithm of blade width measurement on the basis distance measurement and module calibration.

4. Measurement module functioning and calibration

Each of the sensors (marked S_n, where $n = 1 \ldots 8$) of the module shows slightly different value in the non-projected state (0 MPa pressure). It is a numeral value marked as M_{in}, meaning measurement element position, which is close to the maximum sensor range. After complete projection of a gas spring (applying 0.5 MPa pressure), the measured value is close to zero. Fig. 10 presents placement of specific sensors in relation to the selected cross-section. Sensors in the measurement module are divided into pairs and placed opposite to one another. 0.005 mm positioning axiality was achieved by creating gripping holes on CNC machines.

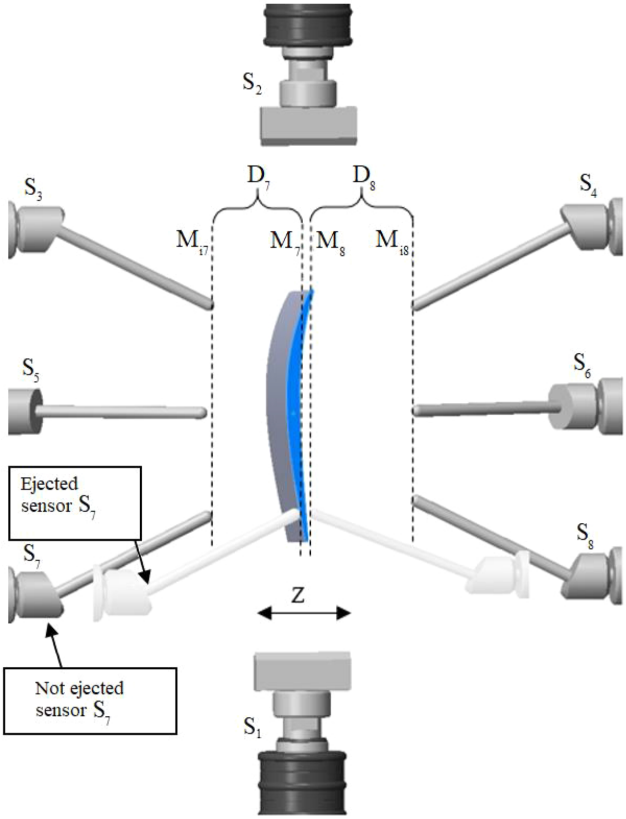


Fig. 10. Positions of specific sensors in the measurement module

After sending an inquiry, the robot IRC5 controller receives current sensor position measurement.

Blade width measurement at the specific point is conducted on the basis of specific sensor pair projection measurement. The algorithm (Fig. 11) in the Rapid language was created for blade width measurement and device calibration.

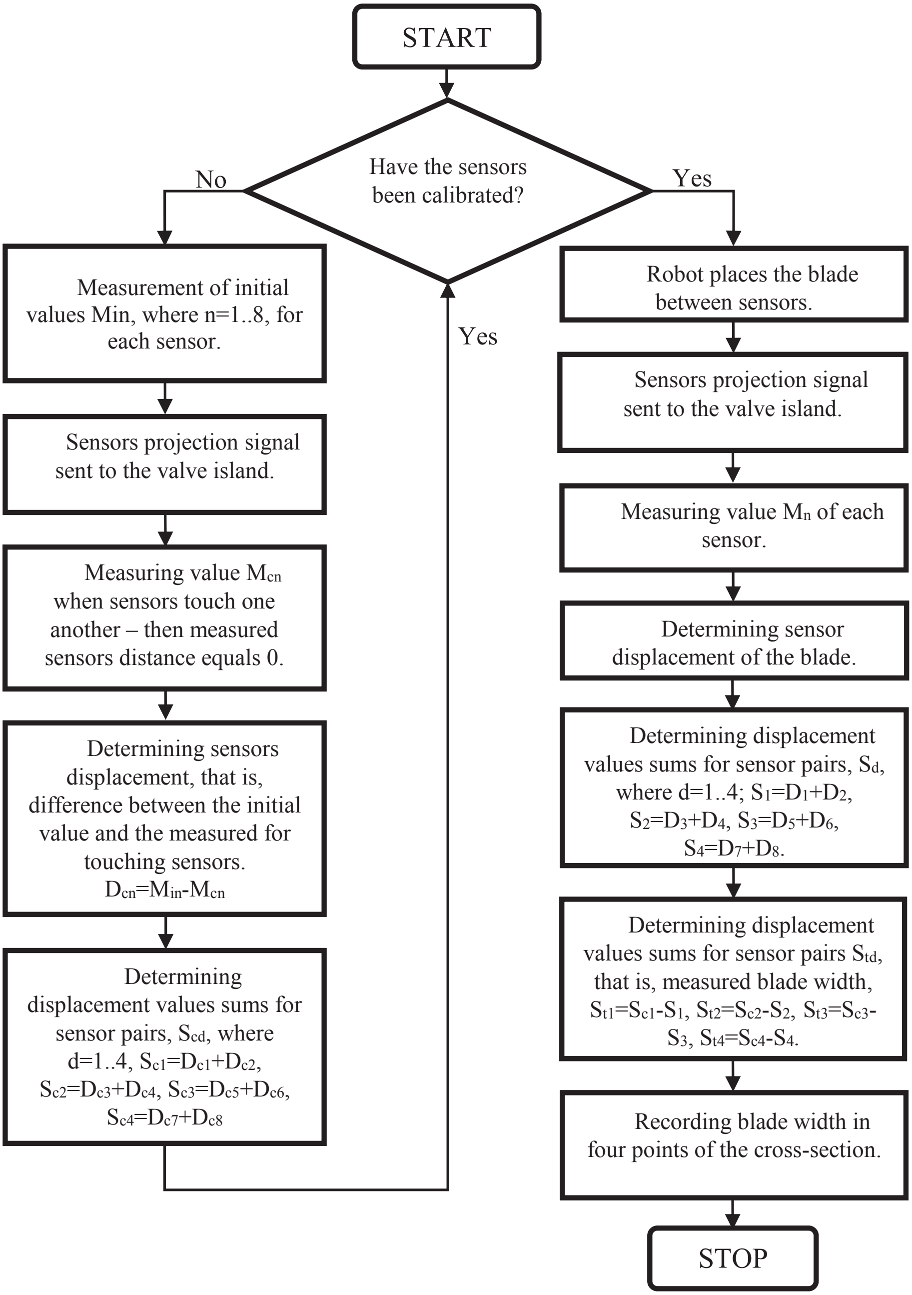
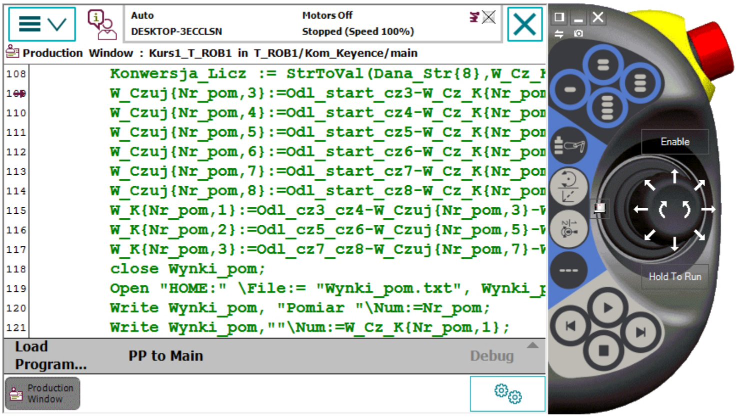


Fig. 11. Module calibration and measurement algorithm

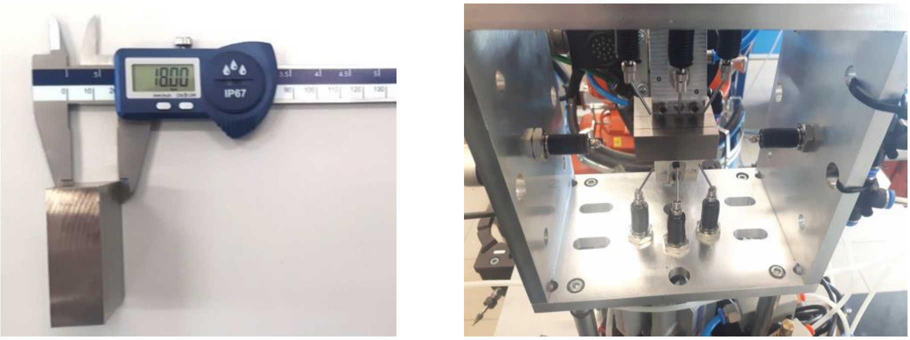
A fragment of the Rapid language code containing the implementation of the calibration algorithm is shown in Fig. 12.



```
        Konwersja_Licz := StrToVal(Dana_Str{8},W_Cz_K
        W_Czuj{Nr_pom,3}:=Odl_start_cz3-W_Cz_K{Nr_pom
        W_Czuj{Nr_pom,4}:=Odl_start_cz4-W_Cz_K{Nr_pom
        W_Czuj{Nr_pom,5}:=Odl_start_cz5-W_Cz_K{Nr_pom
        W_Czuj{Nr_pom,6}:=Odl_start_cz6-W_Cz_K{Nr_pom
        W_Czuj{Nr_pom,7}:=Odl_start_cz7-W_Cz_K{Nr_pom
        W_Czuj{Nr_pom,8}:=Odl_start_cz8-W_Cz_K{Nr_pom
        W_K{Nr_pom,1}:=Odl_cz3_cz4-W_Czuj{Nr_pom,3}-W
        W_K{Nr_pom,2}:=Odl_cz5_cz6-W_Czuj{Nr_pom,5}-W
        W_K{Nr_pom,3}:=Odl_cz7_cz8-W_Czuj{Nr_pom,7}-W
        close Wynki_pom;
        Open "HOME:" \File:= "Wynki_pom.txt", Wynki_p
        Write Wynki_pom, "Pomiar "\Num:=Nr_pom;
        Write Wynki_pom,""\Num:=W_Cz_K{Nr_pom,1};
```

Fig. 12. Implementation of the calibration algorithm in Rapid language

The working of the measurement module and the calibration algorithm has been verified during the tests shown in Fig. 13. For calibration and tests, a 18 mm high cuboid was made on a CNC machine. The cuboid was made with a tolerance of ±0.002 mm. The measurement is made differentially, the algorithm calculates the height of the cuboid, so the errors of the part's position do not affect the accuracy.



(a) (b)

Fig. 13. Verification of the measurement module work

During the tests, a series of 10 measurements was performed, the results of which are shown in Fig. 14.

The maximum measurement error was 0.006 mm, but the accuracy of the workpiece detail of ±0.002 mm should be taken into account. The required module accuracy of 0.01 has been obtained. In the process the algorithm determines blade

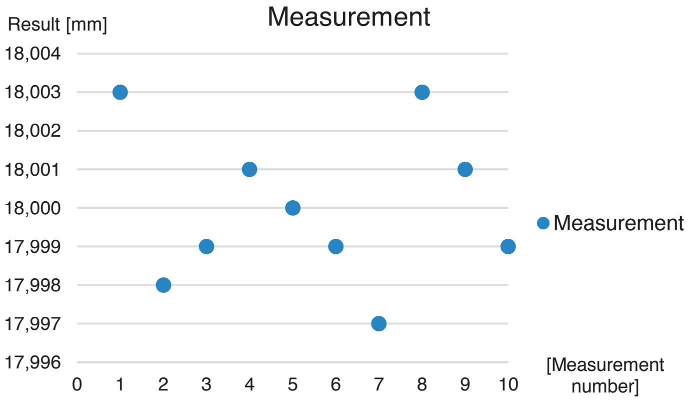


Fig. 14. Test results for the accuracy of the measurement module

width in the specific cross-section in three points of the aerofoil blade, as well as the cord value. The utilized algorithm allows measuring blade cross-section width regardless of its position in the module Z axis. Blade position error in other axes results from the robot repeatability and the error of blade position in the gripping device.

On the basis of the measurement, the original algorithm implemented in the controller is able to point out faulty blades, display measurement report, and adjust grinding process parameters to the set blade geometry. Fig. 15 presents pictures of the module and illustrates taking blade measurement with the use of the module.

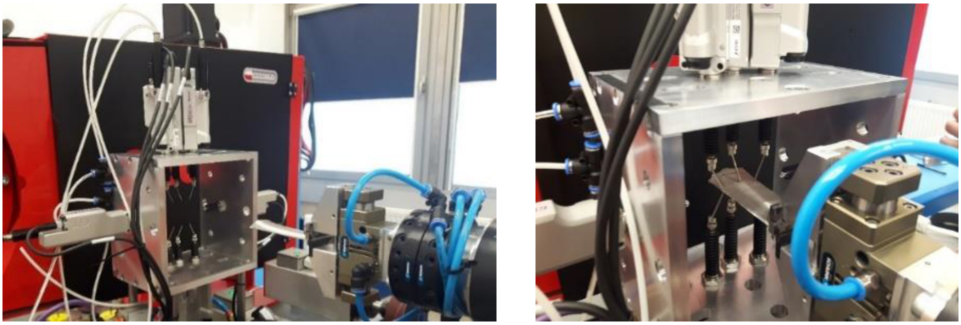

(a) (b)

Fig. 15. Pictures of a built measurement module (a), blade geometry measurement in the selected cross-section (b)

The proposed calibration method is based on measuring projection values of particular sensor pairs while they are touching. It enables automatic calibration before each measurement cycle. Moreover, the prepared algorithm allows making the blade width measurement regardless of its position in the module Z axis.

5. Conclusions

The article presents the structure and functioning of an original module, which is a part of a robotic processing station for turbojet engine elements. Similar measuring devices work in the automotive industry, but here we present their application in the aviation industry. The article presents the construction of the module, the structure of communication and the algorithm of functioning. This information is not available for commercial solutions. A characteristic feature of the device is the differential measurement that eliminates the errors associated with robot repeatability. The paper presents the method of communication of the module with the IRC5 controller. The objective of the module is to automatically measure blade thickness in four points and in any number of cross-sections. A crucial element of the endeavor, also presented in the article, was creating the method of width measurement and the automatic calibration algorithm. The algorithm was implemented in the Rapid language in the controller of IRC5 robot (ABB brand). The working of the module and the developed algorithm has been tested on a properly prepared calibration element. The obtained results are satisfactory and provide sufficient accuracy for the process. The received data may be used for blades grinding process, displayed on operator panel, or used to prepare a measurement report. In further work, the measurement module will be developed. Laser optical sensors will be added, they will measure the position of the part relative to the touch sensors. This will eliminate the error related to robot accuracy. This will allow one to make precise measurements of elements' geometry details.

Manuscript received by Editorial Board, July 20, 2018;
final version, January 09, 2019.

References

[1] A. Burghardt, K. Kurc, D. Szybicki, M. Muszyńska, and J. Nawrocki. Robot-operated quality control station based on the UTT method. *Open Engineering* 7(1):37–42, 2017. doi: 10.1515/eng-2017-0008.

[2] A. Burghardt, K. Kurc, D. Szybicki, M. Muszyńska, and T. Szczęch. Robot-operated inspection of aircraft engine turbine rotor guide vane segment geometry. *Tehnicki Vjesnik –Technical Gazette,* 24(Suppl. 2):345–348, 2017. doi: 10.17559/TV-20160820141242.

[3] A. Burghardt, K. Kurc, D. Szybicki, M. Muszyńska, and J. Nawrocki. Software for the robot-operated inspection station for engine guide vanes taking into consideration the geometric variability of parts. *Tehnicki Vjesnik – Technical Gazette*, 24(Suppl. 2):349–353, 2017. doi: 10.17559/TV-20160820142224.

[4] A. Burghardt, D. Szybicki, K. Kurc, M. Muszyńska, and J. Mucha. Experimental study of Inconel 718 surface treatment by edge robotic deburring with force control. *Strength of Materials*, 49(4):594–604, 2017. doi: 10.1007/s11223-017-9903-3.

[5] A. Burghardt, K. Kurc, D. Szybicki, M. Muszyńska, and T. Szczęch. Monitoring the parameters of the robot-operated quality control process. *Advances in Science and Technology Research Journal*, 11(1):232–236, 2017. doi: 10.12913/22998624/68466.

[6] P. Gierlak and M. Szuster. Adaptive position/force control for robot manipulator in contact with a flexible environment. *Robotics and Autonomous Systems*, 95:80–101, 2017. doi: 10.1016/j.robot.2017.05.015.

[7] P. Gierlak, A. Burghardt, D. Szybicki, M. Szuster, and M. Muszyńska. On-line manipulator tool condition monitoring based on vibration analysis. *Mechanical Systems and Signal Processing*, 89:14–26, 2017. doi: 10.1016/j.ymssp.2016.08.002.

[8] Z. Hendzel, A. Burghardt, P. Gierlak, and M. Szuster. Conventional and fuzzy force control in robotised machining. *Solid State Phenomena*, 210:178–185, 2014. doi: 10.4028/www.scientific.net/SSP.210.178.

[9] O. Yilmaz, N. Gindy, and J. Gao. A repair and overhaul methodology for aeroengine components. *Robotics and Computer-Integrated Manufacturing*, 26(2):190–201, 2010. doi: 10.1016/j.rcim.2009.07.001.

[10] P. Zhao and Y. Shi. Posture adaptive control of the flexible grinding head for blisk manufacturing. *The International Journal of Advanced Manufacturing Technology*, 70(9–12):1989–2001, 2014. doi: 10.1007/s00170-013-5438-3.

[11] P. Zhsao and Y.C. Shi. Composite adaptive control of belt polishing force for aeroengine blade. *Chinese Journal of Mechanical Engineering*, 26(5):988–996, 2013. doi: 10.3901/CJME.2013.05.988.

[12] X. Xu, D. Zhu, H. Zhang, S. Yan, and H. Ding. TCP-based calibration in robot-assisted belt grinding of aero-engine blades using scanner measurements. *The International Journal of Advanced Manufacturing Technology*, 90(1–4):635–647, 2017. doi: 10.1007/s00170-016-9331-8.

[13] W.L. Li., H. Xie, G. Zhang, S.J. Yan, and Z.P. Yin. Hand–eye calibration in visually-guided robot grinding. *IEEE Transactions on Cybernetics*, 46(11):2634–2642, 2016. doi: 10.1109/TCYB.2015.2483740.

[14] B. Sun and B. Li. Laser displacement sensor in the application of aero-engine blade measurement. *IEEE Sensors Journal*, 16(5):1377–1384, 2016. doi: 10.1109/JSEN.2015.2497363.

[15] W. Li, H. Xie, G. Zhang, S.J. Yan, and Z.P. Yin. 3-D shape matching of a blade surface in robotic grinding applications. *IEEE/ASME Transactions on Mechatronics*, 21(5):2634–2642, 2016. doi: 10.1109/TMECH.2016.2574813.

[16] Y. Zhang, Z.T. Chen, and T. Ning. Efficient measurement of aero-engine blade considering uncertainties in adaptive machining. *The International Journal of Advanced Manufacturing Technology*, 86(1–4):387–396, 2016. doi: 10.1007/s00170-015-8155-2.

[17] L. Qi, Z. Gan, C. Yun, and Q. Tang. A novel method for Aero engine blade removed-material measurement based on the robotic 3D scanning system. In *Proceedings of 2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering*, volume 4, pages 72–75, Changchun, China, 24–26 August, 2010. doi: 10.1109/CMCE.2010.5610214.

[18] J. Godzimirski. New technologies of aviation turbine engines. *Transactions of the Institute of Aviation*, 213:22–36, 2011 (in Polish).

[19] G. Budzik. *Geometric accuracy of aircraft engine turbine blades*. Publishing House of Rzeszow University of Technology, 2013 (in Polish).