Robot-Assisted Quality Inspection of Turbojet Engine Blades

Dariusz Szybicki(✉), Andrzej Burghardt, Piotr Gierlak, and Krzysztof Kurc

Rzeszow University of Technology,
Al. Powstancow Warszawy 12, 35-959 Rzeszow, Poland
{dszybicki,andrzejb,pgierlak,kkurc}@prz.edu.pl

Abstract. This paper presents the design and construction of a module for measuring the geometry and orientation of turbojet engine blades. The measurement module forms a component of a robotic processing station for grinding of turbojet engine blades. The robotic processing station comprises an industrial robot manipulator with a dedicated gripper, the measurement module with proximity sensors, and blade grinding tooling components. The measurement outputs were transferred by TCP from the measurement module to the controller of the robot manipulator. The measurement outputs could be applied in blade grinding, displayed on a control panel, or processed into a measurement test report.

Keywords: Robotic measurement · Blade inspection · Turbojet engine blades

1 Introduction

The development of industrial robotics focuses mainly on applications which require a high level of process-robot interaction. This includes turbojet engine blade measurement and grinding processes, where varying allowances must be removed. The processes include the robotic-assisted quality control of jet engine components presented in [1–3].

This paper proposes an alternative solution to the measurement module used for robot-assisted geometry measurement of turbojet engine blades. The measurement data output by the solution can be used for quality control or for the execution of or assistance in robotic machining. Aerospace robotic machining and the diagnostics of robotic processing station components are discussed in [4–8]. An application of a 3D scanner manufactured by GOM for the measurement of blade geometry during servicing and overhaul is presented in [9]. Blade geometry is measured in machining processes for cutting tool motion correction, for example by measurements made with machining head sensors, [10, 11] or the correction of a robot's TCP with a laser measurement system to improve grinding processes, [12, 13]. A grinding process can also be improved by laser scanning [14]. Laser triangulation systems for fast blade geometry measurements are presented in [15], with a mathematical description of the measurement method. The problems of approximation of the high volumes of

© Springer Nature Switzerland AG 2019
R. Hanus et al. (Eds.): MSM 2018, LNEE 548, pp. 337–350, 2019.
https://doi.org/10.1007/978-3-030-11187-8_28

measurement output information obtained by scanning are considered in [16]. 3D laser systems which measure blade geometry and compare the measurement outputs to geometric masters (models) in robotic machining control applications are discussed in [17]. The problem of measurement uncertainty in vision systems is discussed in the paper [18].

To recapitulate, the problems of constructing a module dedicated to robot-assisted blade geometry verification remain valid and a part of the automation of machinery component fabrication and control processes.

2 Blade Characteristics

Blades are among the basic components of turbojet engines. The design of any modern turbojet engine is very complex, and the engines vary in the number and application types of blades [15]. A general classification of turbojet engine blades is as follows:

- compressor blades: these compress the air stream passing through the compressor; they are prone to foreign object damage (FOD), such as bird strikes,
- turbine blades: these transfer the active energy from the jet fuel combustion gas to the turbine rotor to propel it; they operate at high temperatures and in aggressive conditions.

Turbojet engine blades have to be manufactured using state of the art technologies to achieve the required high geometric accuracy and strength parameters. Turbojet engine blades are qualified as flight safety critical components, and are subject to many control procedures. The blade control procedures focus on the quality of castings and forgings, material structure, and fabricated geometric features. Turbojet engine blades are subject to torsion and bending by the aerodynamic forces and tension by the centrifugal forces. These mean that the blades the most stressed components in a turbojet engine, and require replacement at short intervals. The time and cost of blade production can be as much as 35% of the total time and cost of production of an entire turbojet engine [19]. A modern turbojet engine may have around 3000 blades. This sheer number of blades makes their durability a crucial criterion of the strength of the entire turbojet engine. The number of blades per turbojet engine means their manufacturing and quality control have become mass, automatic and repeatable processes.

The blade design (Fig. 1) depends on the blade type. A blade comprises an airfoil (the working part of the blade) and a blade locking piece. The crosssections of a blade airfoil are aerodynamically profiled and fabricated down to a geometric tolerance of 0.1 mm, at roughness levels (Ra) between 0.08 and 0.63 mm in the case of turbine blades. The blade locking piece fastens the blade to a component, and is fabricated to a geometric tolerance of 0.01 mm and Ra = 1.25 mm [20].

The concave portion of a blade is the high pressure surface while the convex portion is the low pressure surface. A blade features different edges: the leading edge (LE) is oriented towards the incoming gas flow, while the opposite edge is the trailing edge (TE). The quality control of these features involve geometry measurements of the blade by reference to the blade section, as shown in Fig. 2.

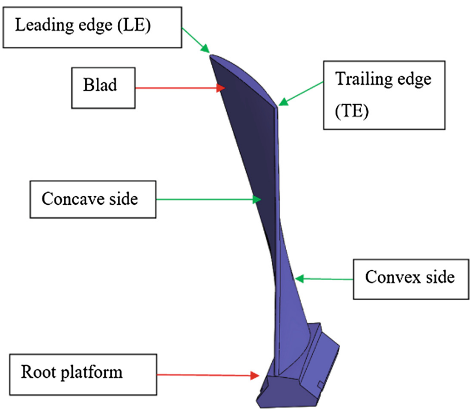

Fig. 1. Blade design.

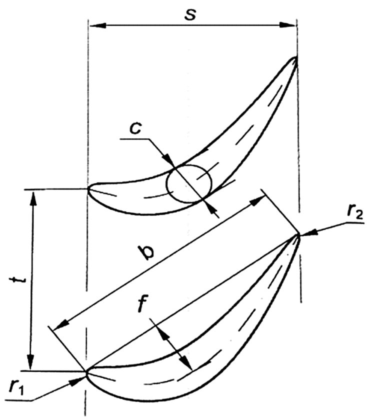

Fig. 2. Blade section [20].

The blade section has the following features:

- b – blade chord,
- c – blade thickness,
- f – section centre line,
- r1 – LE radius,
- r2 – TE radius.

The blade section is specifically twisted along its length and relative to the longitudinal axis of the blade; this twist is defined by the operating conditions of the blade and the stress it must withstand. Blades are dimensioned according to gas dynamic calculations. However, several general relationships can be defined for blade dimensioning, including the relationship of the blade thickness to the blade length (Fig. 3).

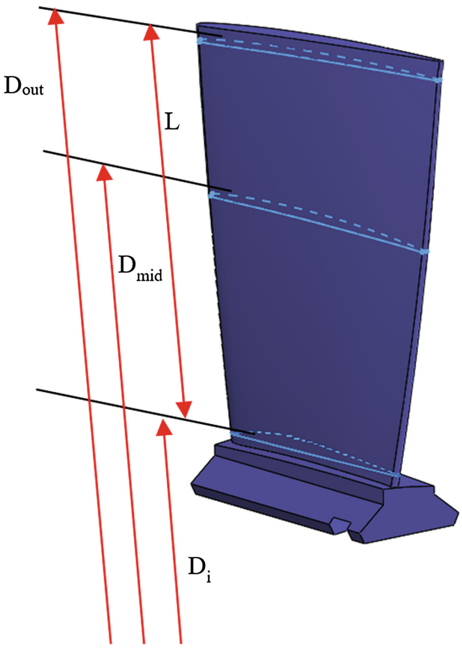

Fig. 3. Blade geometry vs. blade length.

The blade section thickness cmax for a turbine generator blade is within the following limits:

- root diameter (Din), c1 = 0.2 − 0.3b,
- middle diameter (Dmid), c2 = 0.10 − 0.15b,
- tip diameter (Dout), c3 = 0.04 − 0.06b.

3 Blade Geometry Measurement Methods

Several methods are available today by which the geometry and the twist angle of blades at individual blade sections can be measured. Geometry measurement methods generally include contact and non-contact methods.

Traditional geometry measurements rely on contact methods. The blade is measured by specifically designed instruments. The blade to be measured is aligned and secured in a fixture, following which contact sensors are used to measure the geometry. The measurement is made by bringing the measurement instrument's contact sensor head to the blade surface; if the measurement is done on both sides of the blade, the blade thickness can be determined. Legacy contact measurement solutions relied on a few specifically chosen measurement points, due to the immobility of the contact sensors. Commercially available, dedicated measurement modules exist which enable automatic geometric measurements. One example is a module manufactured by Renishaw (Fig. 4).

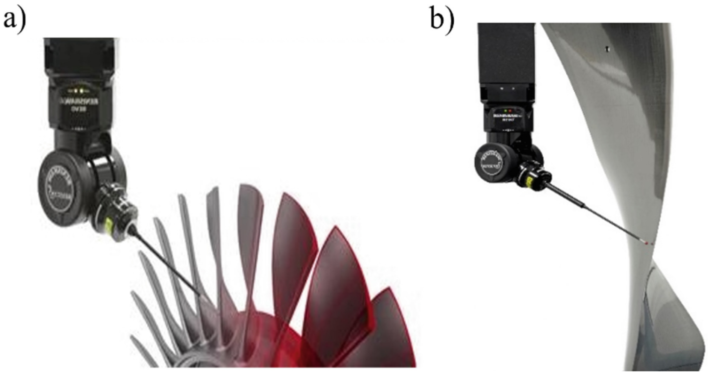

Fig. 4. REVO 5-axis contact sensor head applied in a blade geometry scan, (a) measurement of the rotor, (b) zoom.

In the solution proposed here, the REVO contact sensor head was installed in a coordinate measurement machine. The contact sensor head's paths of motion were generated by a dedicated software suite, APEXBlade. A drawback of this geometry measurement method was the need for manual fixing of the blades, the time required for the process, and the restricted data connectivity between the measurement system and other processing equipment. The overall solution was expensive due to the necessary cost of purchasing a CMM.

Non-contact geometry measurement methods can be based on laser proximity sensors, 2D and 3D laser scanners, and other types of 3D scanners.

Geometric measurement with laser triangulation sensors is a non-contact method. Laser triangulation sensors provide 2D scanning, by which the successive measurement points are offset by a fixed distance defined by the sensor resolution. Each measurement sensor has the distance to the laser sensor specified. The blade geometry is determined from the measurement outputs by a dedicated software suite.

The advantages of laser sensors include high accuracy, short measurement times and larger mounting distances from the test object than is possible with other types of non-contact sensors. Their weakness is that the LOS (line of sight) between the laser sensor and the test object must be clear and unobstructed at all times. Test results can be disturbed by suspended airborne dust or smoke, or a high gloss level of the blade being measured. However, the primary drawback of laser sensors is an accuracy level lower than available with contact geometry measurement methods. The application of laser sensors requires a precise definition of the blade basic surface location to enable the geometric measurement by a known distance.

Measurements of the blade geometry are often made by structural light 3D scanning. There are many commercial manufacturers of devices based on this method. One of these is the ATOS Core optical 3D scanner, manufactured by GOM (Fig. 5).

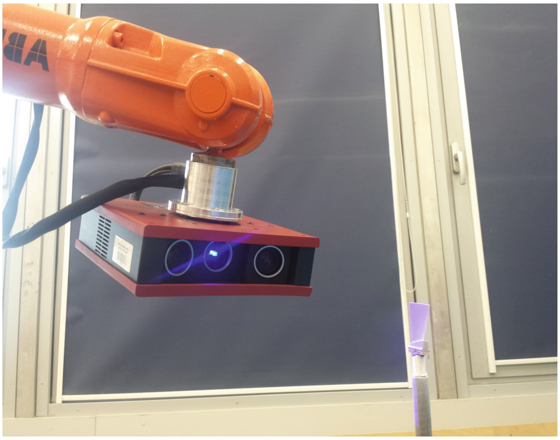

Fig. 5. Actual geometric measurement of a blade with the optical 3D scanner.

The ATOS Core optical 3D scanner features two stereo cameras, which work by the principle of triangulation, and one projector. The projector casts bands on the surface of the test object for the stereo cameras to capture. GOM uses blue LED projectors for scanning; this projected light emission spectrum enables precise geometric measurements under different lighting conditions.

The ATOS Core optical 3D scanner has the advantage of scanning small and moderately-sized objects at significantly reduced measurement and inspection times. This geometric measurement method produces a cloud of points, where the geometric data is compared to the CAD model (master) of the test object. Next, the dedicated software suite determines what differences, if any, exist between the actual test object and its CAD model. Optical 3D scanning has been gaining popularity in real-life applications; however, its use in the large-scale manufacturing of engine blades is difficult due to the high gloss levels of the product. To facilitate the geometric measurement of blades (Fig. 5) with this method, the high-gloss surfaces of each blade must be dimmed by applying a special powder. The powder reduces the measurement accuracy and makes the geometric measurement difficult in large-scale manufacturing. Another drawback of optical 3D scanners is the time required for measurement and subsequent polygonal digitization; it is longer than for laser sensor-based geometry measurements.

4 Measurement Module Design

The measurement module formed a component of a robotic processing station for grinding of turbojet engine blades (Fig. 6). The robotic processing station comprised an ABB industrial robot manipulator with a dedicated gripper, the measurement module, the ForceControl expansion for grinding, electrospindles, and a suite of other machining tools.

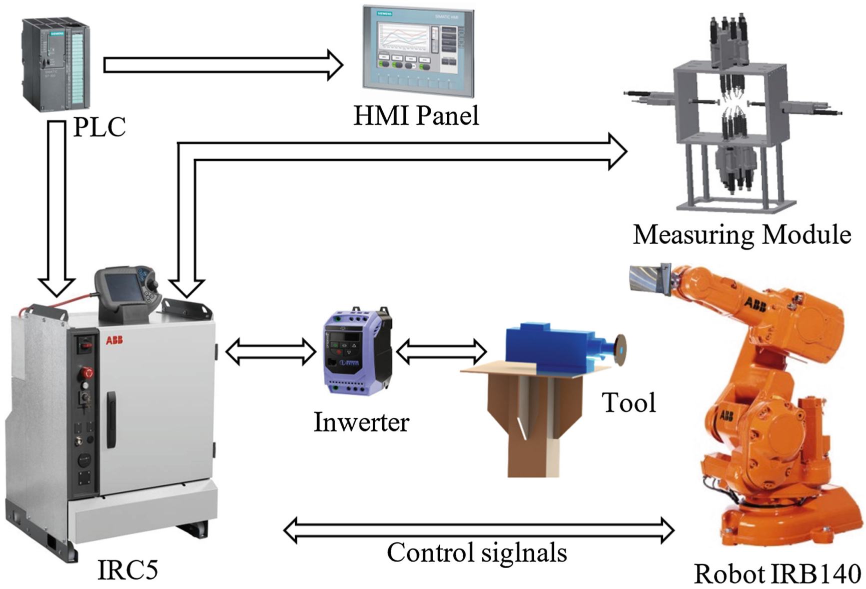

Fig. 6. Schematic diagram of the robotic processing station for grinding of turbojet engine blades.

A review of the available solutions for the quality control of turbojet engine blades and their deficiencies prompted the decision to develop a proprietary measurement module. Three measurement module concepts were prepared, and one of these was implemented. Each of the concepts had an accurate 3D-CAD model developed with a simulation of its functioning in RobotStudio, a software suite for offline robot programming. At the concept development stage it was assumed that the quality control of blades would be made by measuring the thickness at three blade sections (Figs. 2 and 3) and the chord at each blade section. The measurement sensors, the key elements of each of the three concepts, were functionally tested on a selection of blade types. The selection criteria of the final solution of the measurement module were: measurement accuracy, feasibility of communication with the robot controller over Ethernet TCP/IP, and price.

The first measurement model concept was based on 2D distance laser scanners and six laser spot sensors (Fig. 7). The measurement module with the 2D distance laser scanners was stationary. A blade was fastened in the gripper of an industrial robot manipulator with a repeatability rating of 0.06 mm. The position of the gripper with the blade was determined by measuring the distance with the laser spot sensors. The blade geometry, based on the measured distance, was determined with an algorithm implemented in the robot controller. This solution was tested with Keyence LJ-G080 series 2D scanners from Keyence.

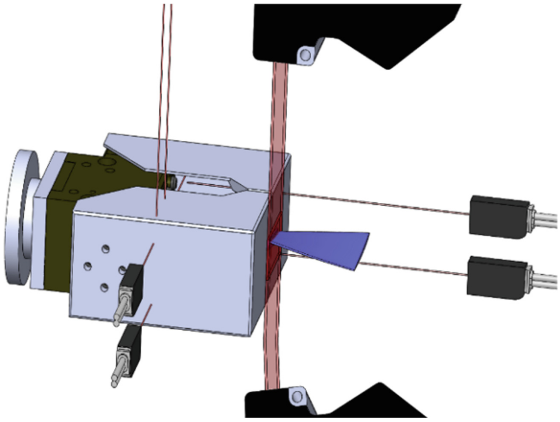

Fig. 7. Measurement module concept with 2D scanners.

The measurements with the sensors were based on a system of triangulation. The laser beam formed a series of points on the surface of the test object. The reflected laser light was picked up by a detector, which measured the reflected laser light's angle of incidence. The determined angle of incidence defined the distance from the surface of the test object. The main specifications of the Keyence LJ-G080 sensor were:

- Measurement distance: 80 ± 23 mm,
- Laser beam width: 32 ± 7 mm,
- Measurement accuracy: 0.05 mm.

The exact position of the gripper holding the blade was determined with 6 laser spot sensors installed in a linear arrangement on three walls of the measurement module. The laser spot sensors were a part of the determination of blade position within the measurement module. The test object positional data was sent to the robot controller, which enabled the correction of positioning errors imposed by the accuracy and repeatability of the robot manipulator. The laser spot sensors chosen were Keyence LV-S61.

The measurement model concept with the 2D scanners was tested. An example of the tests is shown in the photograph in Fig. 8a. The measured value master was the measurements made with a GOM 3D scanner and processed in ATOS Professional (Fig. 8(b)).

The tests demonstrated the feasibility of the measurement module concept with the 2D scanners. However, a number of problems were observed, which consisted of light reflections from the blades after grinding, which disturbed the measurement output data. The price of the solution was twice that of the finished solution.

The second measurement module concept (Fig. 9) was also based on 2D scanners, with the measurement module in motion relative to a stationary blade held by the robot manipulator gripper. The mobile measurement module solution was intended to eliminate the measurement errors imposed by the repeatability of the robot manipulator.

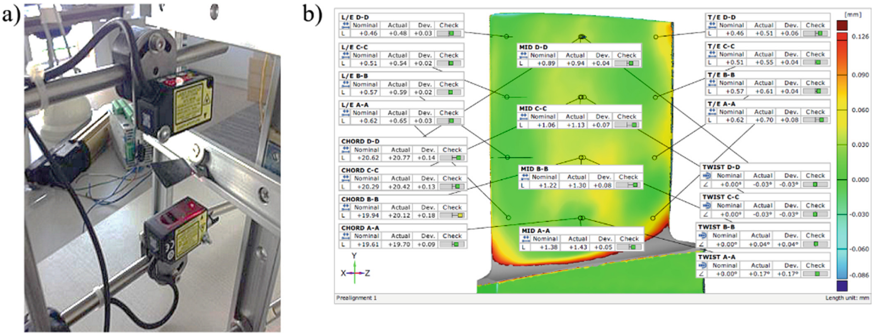

Fig. 8. (a) Testing of the solution with the 2D scanners, (b) Measurement results obtained with the GOM 3D scanner.

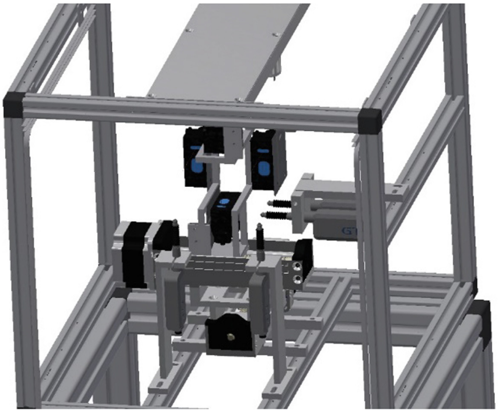

Fig. 9. The mobile measurement module concept.

The motion of the 2D scanners in this concept was made by a linear motion module, comprising aluminium sections, guides, and ball screws. The ball screws were driven by 57BYGH series stepper motors manufactured by WObit.

A CAD model, detailed engineering drawings and RobotStudio simulations were prepared for this measurement module concept. The concept was not implemented due to the issues with precision manufacturing and calibration of the linear motion modules. The price was higher than the price of the first measurement module concept.

The third measurement module concept was based on contact sensors. The concept featured a stationary measurement module with the blade (test object) moved by a robot manipulator. The repeatability error of 0.06 mm by the robot manipulator was deemed acceptable. The contact sensors chosen were GT2-A32 manufactured by Keyence, with the rated accuracy and travel of 0.003 mm and 32 mm, respectively. Figure 10 shows a photograph from the preliminary testing of this solution.

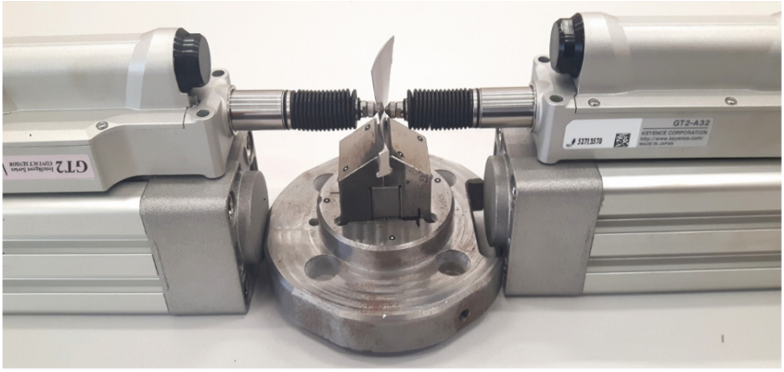

Fig. 10. The mobile measurement module concept. Geometry measurement with Keyence contact sensors.

The positive results of testing the solution with the contact sensors provided the foundation required for further development of the measurement module design (Fig. 11(b)). The contact sensor mounts were designed and fabricated as the casing of the measurement sensor, as shown in Fig. 11(a).

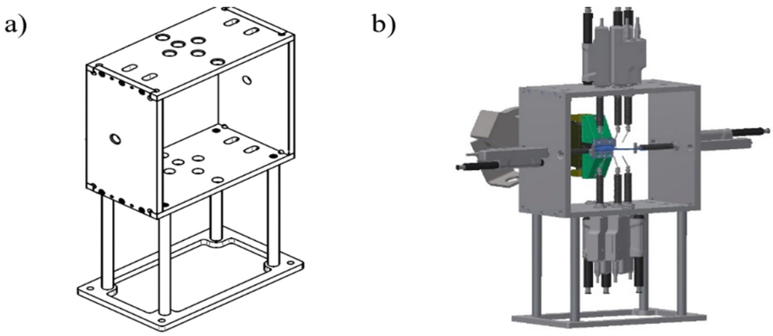

Fig. 11. (a) Part of the assembly drawing of the measurement casing, (b) CAD model of the measurement module.

The Keyence contact sensors were connected to a GT2-500 amplifier module, which could process signals from a maximum of five contact sensor heads. The amplifier model powered the contact sensor heads and processed the analogue electrical outputs from the contact sensor heads into the digital data required for the extension distance of each head. The digital data of the extension length of each head was then relayed to other devices connected to an Ethernet network via a DL-EN1 module. The data communication diagram is shown in Fig. 12.

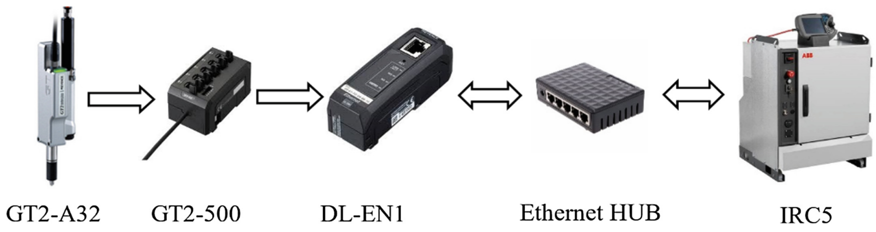

Fig. 12. Connection wiring diagram of the Keyence sensors and the robot controller.

The measured distance data was relayed over TCP/IP. The contact sensor head outputs were read by interrogating the data communication module with an ASCII command. Four command formats were available:

- command M0: read the measurement values from all connected sensors,
- command MS: read the measurement values and the output status of all connected sensors,
- command SR: read the operating parameters of a specific sensor,
- command SW: write the operating parameters of a specific sensor,
- command FR: read the decimal place count of the parameter of a specific sensor.

Each command format had a strictly defined content for the interrogation and reply data frames. The frame formats are shown in Fig. 13.

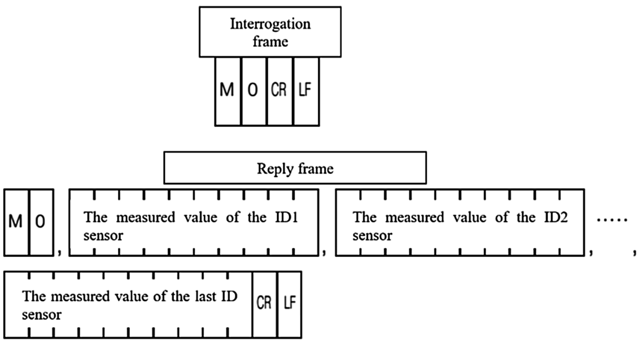

Fig. 13. Formats of the interrogation and reply data frames.

Each data frame ended with the control characters: CR (carriage return, ASCII 13) and LF (line feed, ASCII 10). Each applied GT2-A32 contact sensor featured a gas spring to control the motion of the contact sensing probe. The contact sensor heads required a compressed air supply, as shown in the diagram in Fig. 14.

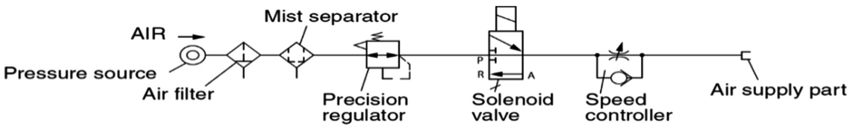

Fig. 14. GT2-A32 compressed air supply system.

The compressed air supply was controlled in this solution with a valve block manufactured by SMC (Fig. 15). The valve block was controlled by the robot controller over ProfiBus.

Fig. 15. Connection wiring diagram of the valve block and the robot controller.

The designed and fabricated measurement module is shown in Fig. 16(a). The measurement of a blade with the module is shown in Fig. 16(b).

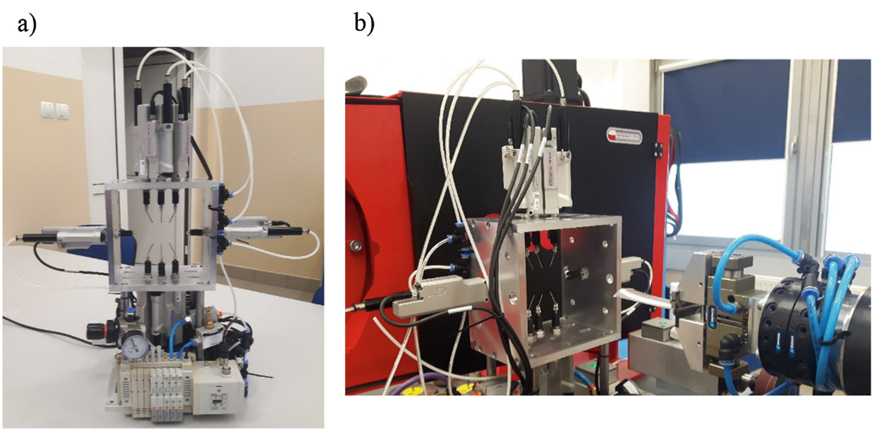

Fig. 16. Photographs of the fabricated measurement module, (a) Photographic overview of the module, (b) A blade introduced into the measurement module by the industrial robot manipulator.

The functional tests of the fabricated measurement module proved that the conceptual assumptions were valid. Once calibrated, the measurement module correctly measured the geometry of the blades by the distance detected by the contact sensor heads. The distance data output was transmitted to the robot controller. A proprietary algorithm implemented in the robot controller could identify defective blades according to the measurements made by the contact sensor heads, display a measurement report and adjust the robot-assisted grinding process parameters to suit the measured geometric features.

5 Conclusion

This paper presents the process of designing and constructing a module for geometry and orientation measurement of turbojet engine blades. An overview of existing solutions was made and directed the authors to the deficiencies in commercially available measurement instruments. The authors proposed, modelled and preliminarily tested three measurement module concepts. Suboptimal solution selection criteria were adopted to qualify and fabricate the final concept for the measurement module. The designed and fabricated measurement module was intended for a robotic processing station for grinding of turbojet engine blades. The algorithm implemented in the robot controller to determine the blade geometry features based on contact sensor head measurements is a topic for future research papers. The functioning of the designed and fabricated robotic processing station for grinding of turbojet engine blades will be demonstrated to the public with the application of measurement feedback.

References

1. Burghardt, A., Kurc, K., Szybicki, D., Muszyńska, M., Szczęch, T.: Robot-operated inspection of aircraft engine turbine rotor guide vane segment geometry. Tehnicki Vjesn.-Tech. Gaz. **24**(Supplement 2), 345–348 (2017)
2. Burghardt, A., Kurc, K., Szybicki, D., Muszyńska, M., Nawrocki, J.: Software for the robot-operated inspection station for engine guide vanes taking into consideration the geometric variability of parts. Tehnicki Vjesn.-Tech. Gaz. **24**(Supplement 2), 349–353 (2017)
3. Burghardt, A., Kurc, K., Szybicki, D., Muszyńska, M., Nawrocki, J.: Robot-operated quality control station based on the UTT method. Open Eng. **7**(1), 37–42 (2017)
4. Gierlak, P., Burghardt, A., Szybicki, D., Szuster, M., Muszyńska, M.: On-line manipulator tool condition monitoring based on vibration analysis. Mech. Syst. Signal Process. **89**, 14–26 (2017)
5. Gierlak, P.: Hybrid position/force control in robotised machining. Solid State Phenom. **210**, 192–199 (2014)
6. Burghardt, A., Kurc, K., Szybicki, D., Muszyńska, M., Szczęch, T.: Monitoring the parameters of the robot-operated quality control process. Adv. Sci. Technol. Res. J. **11**(1), 232–236 (2017)
7. Burghardt, A., Szybicki, D., Kurc, K., Muszyńska, M., Mucha, J.: Experimental study of Inconel 718 surface treatment by edge robotic deburring with force control. Strength Mater. **49**(4), 594–604 (2017)
8. Hendzel, Z., Burghardt, A., Gierlak, P., Szuster, M.: Conventional and fuzzy force control in robotised machining. Solid State Phenom. **210**, 178–185 (2014)
9. Yilmaz, O., Gindy, N., Gao, J.: A repair and overhaul methodology for aeroengine components. Robot. Comput.-Integr. Manuf. **26**(2), 190–201 (2010)

10. Zhao, P., Shi, Y.: Posture adaptive control of the flexible grinding head for blisk manufacturing. Int. J. Adv. Manuf. Technol. **70**(9–12), 1989–2001 (2014)
11. Zhsao, P., Shi, Y.: Composite adaptive control of belt polishing force for aero-engine blade. Chin. J. Mech. Eng. **26**(5), 988–996 (2013)
12. Xu, X., Zhu, D., Zhang, H., Yan, S., Ding, H.: TCP-based calibration in robot-assisted belt grinding of aero-engine blades using scanner measurements. Int. J. Adv. Manuf. Technol. **90** (1–4), 635–647 (2017)
13. Li, W.L., Xie, H., Zhang, G., Yan, S.J., Yin, Z.: P: hand-eye calibration in visually-guided robot grinding. IEEE Trans. Cybern. **46**(11), 2634–2642 (2016)
14. Li, W.L., Xie, H., Zhang, G., Yan, S.J., Yin, Z.P.: 3-D shape matching of a blade surface in robotic grinding applications. IEEE/ASME Trans. Mechatron. **21**(5), 2294–2306 (2016)
15. Sun, B., Li, B.: Laser displacement sensor in the application of aero-engine blade measurement. IEEE Sens. J. **16**(5), 1377–1384 (2016)
16. Qi, L., Gan, Z., Yun, C., Tang, Q.: A novel method for aero engine blade removed-material measurement based on the robotic 3D scanning system. In: 2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering (CMCE), vol. 4, pp. 72–75 (2010)
17. Zhang, Y., Chen, Z. T., Ning, T.: Efficient measurement of aero-engine blade considering uncertainties in adaptive machining. Int. J. Adv. Manuf. Technol. **86**(1–4), 387–396 (2016)
18. Kohut, P., Holak, K., Martowicz, A.: An uncertainty propagation in developed vision based measurement system aided by numerical and experimental tests. J. Theor. Appl. Mech. **50** (4), 1049–1061 (2012)
19. Godzimirski, J.: New technologies of aviation turbine engines. Works of the Institute of Aviation (in Polish) (4 (213)), 22–36 (2011)
20. Budzik, G.: Geometric accuracy of aircraft engine turbine blades. Rzeszow University of Technology Publisher (in Polish), 22–34 (2013)