APPLIED COMPUTER SCIENCE

*Applied Computer Science, vol. 18, no. 1, pp. 37–44*
*doi: 10.35784/acs-2022-3*

*Submitted: 2021-12-08 | Revised: 2022-02-09 | Accepted: 2022-03-21*

*Keywords: computer applications, robot safety, virtual reality*

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# A METHOD OF VERIFYING THE ROBOT'S TRAJECTORY FOR GOALS WITH A SHARED WORKSPACE

**Abstract**

*The latest market research (Fanuc Polska 2019) shows that the robotization of the Polish industry is accelerating. More and more companies are investing in robotic production lines, which enable greater efficiency of implemented processes and reduce labour costs. The article presents the possibilities of using virtual reality (VR) for behavioural analysis in open robotic systems with a shared workspace. The aim of the article is to develop a method of verification of programmed movements of an industrial robot in terms of safety and efficiency in systems with a shared workspace. The method of the robot program verification on the digital model of the working cell made in VR will be checked. The obtained research results indicate a great potential of this method in industrial applications as well as for educational purposes.*

## 1. INTRODUCTION

Virtual reality (VR) is used by many spheres of human activity. Until recently, most people associated VR with the entertainment sphere, mainly for computer games, while for many years it has been used in scientific research (Klarak et al., 2021; Kuts, Otto, Tahemaa & Bondarenko, 2019; Sobaszek, Gola & Świć, 2022) and for educational purposes (Ji, Yin & Wang, 2018). For example, it can be used in architecture or design, where people can firstly try their projects in a digital environment before going to real projects (Kuts, Otto, Tahemaa & Bondarenko, 2019). This way can prevent dozens of mistakes and errors without any loss (Kuts, Otto, Tahemaa & Bondarenko, 2019). VR simulation could also be used in manufacturing, robotics and control systems (Chen et al., 2018; Covaciu et al., 2018; Kot, Novak & Bajak, 2018; Oyekan et al., 2019) by simulating different algorithms and control methods. Another application is audio – to use VR as a sound visualization tool for artists or the blind (Kose et al., 2018). Moreover, smart racks and simulations are done with force feedback (Burdea, 1999) for a better haptic feeling of tested in VR joysticks, devices or manipulators (Kuts, Otto, Tahemaa & Bondarenko, 2019). Fedorko (2021), investigated an application possibilities of the VR within the failure analysis of the rubber-textile

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conveyor belts. Other studies concern the use of VR for robotic assembly works. Through VR proposed setup a typical robotic cell that performs assembly operations could rapidly be reprogramed to handle different assembly variations (Togias, Gkournelos, Angelakis, Michalos & Makris, 2021). The energetic and economic aspects of VR implantation in robotized technology systems are the subject of research Klačková et al. (Klačková, Kuric, Zajacko & Tucki, 2020). Economic aspects of manufacturing systems design e.g. capacity planning, system configuration and their effect on financial and operation costs are presented in (Gola, 2014).

The development of manufacturing processes is related to the growing quality and cost requirements of products (Bogucki, Stączek & Płaska, 2003; Cechowicz, 2003; Stączek, Bogucki & Płaska, 2003; Świć & Gola, 2013) as well as the development of automation and robotics systems. Automation is a process of replacing man's control function by operation of various machines and devices (Blatnicky, Dižo & Timošcuk, 2016). The highly visible development of robotic systems is also noticeable in the automotive industry, as evidenced by the following scientific works (Blatnicky, Dižo, Barta & Droździel, 2020; Blatnicky et al., 2020; Gola, Plinta & Grznar, 2021; Heydaryan, Suaza Bedolla & Belingardi, 2018; Jenis, Hrcek, Drumercik & Bastovansky, 2021) and aviation industry (Bistak et al., 2017; Vosniakos, Ouillon & Matsas, 2019). Handling with materials and products in the automotive industry is an activity, which requires the use of suitable operations methods for the transportation of a given quantity of material to a specified location in as short a time as possible (Blatnicky et al., 2020). Vosniakos et al. (Vosniakos, Ouillon & Matsas, 2019) analyzes the application of VR to the safety strategy of robots cooperating in the technological line of composite materials. In (Wang, Chen, Jiao, Johnson & Zhang, 2019) a human-robot collaborative welding system in virtual reality was proposed, which allows them to collaborate with each other in order to carry out welding tasks. The welding experiments show that the welded workpiece from human-robot collaboration has better performance compared with that from either humans or robots separately and demonstrated the effectiveness of the proposed virtual reality human-robot collaborative welding system (Wang, Chen, Jiao, Johnson & Zhang, 2019). The VR technique is already widely used to analyze robotic systems and verify the technological correctness of programs (Ehmanna & Wittenberg, 2018; Heydaryan, Suaza Bedolla & Belingardi, 2018; Kuts, Otto, Tahemaa & Bondarenko, 2019; Shen, 2020).

The latest market research (Wpływ robotyzacji na konkurencyjność polskich przedsiębiorstw III edycja, 2019) shows that the robotisation of the Polish industry is accelerating. There are new security systems on the market that allow industrial robots to work in open spaces (without fencing) and to share space between a machine and a human (e.g. FreeMove, – Veo Robotics, 2020; Collaborative Robot Safety Made Simple, 2020). Preparing an industrial robot to work in such conditions requires taking into account additional requirements (e.g. traffic predictability, traffic range, relation to the shared area) and carrying out an extended safety analysis. It is also important to program the robot in such a way that the presence of a human in the shared zone does not cause an excessive decrease in system efficiency.

The main aim of the article is to develop a method to verify the programmed movements of an industrial robot in terms of safety and performance in systems with a shared workspace. The method of verifying the robot program on a digital model of the working cell made in VR will be checked. We propose to expand the field of application of this method with behavioural analysis in open robotic systems with a shared workspace.

## 2. RESEARCH METHODOLOGY

The simulation tests were carried out in the ABB RobotStudio offline simulation and programming environment. VR goggles were used to verify the complete installation of the robot's trajectory in a virtual environment.

The verification of the robot path and safety features of a robotic cell, a digital model was created. A simple palletizing cell (Fig. 1) was chosen for the experiment. The access to the cell was open at one side. The open side of the cell was protected by a simulated safety system that would react (decrease the speed of the robot or stop the robot completely) if a presence of a human operator or a transport vehicle was detected.

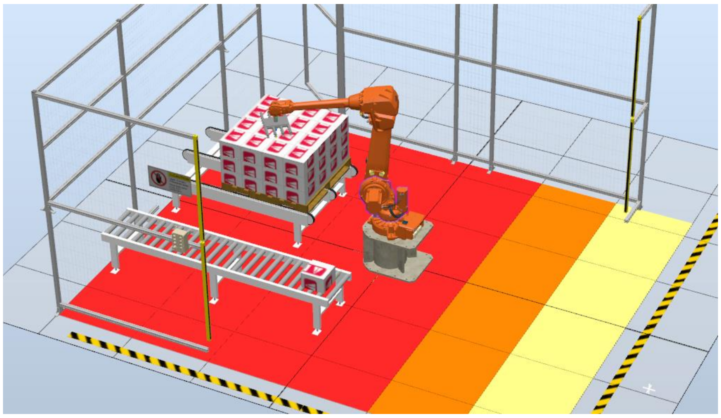

**Fig. 1. Robot cell used in the experiment**

The cell was equipped with a SSM (Speed and Safety Monitoring) safety system. The dimensions of the safety zones (marked with red, orange and yellow) were calculated according to the requirements specified in ISO/TS 15066 and discussed in (Szabo et al. 2012). The required separation distance $S$ can be obtained from formula:

$$S = K_H\,(T_R + T_B) + K_R\,(T_R) + B + C \tag{1}$$

where: $K_H$ is the approach speed of human operator – assumed 1.6 m/s as suggested in TS15066, $K_R$ is the maximum robot speed obtained from kinematic calculations (full speed: 3 m/s, reduced speeds: 1.5 m/s in with operator in the yellow zone and 0.3 m/s with operator in the orange zone), $T_R$ – system reaction time (assumed 0.21 s), $T_B$ – time to full stop (braking time; obtained from simulation), $B$ – stop distance (obtained from simulation), $C$ – minimum separation distance (assumed 1.08 m after ISO 13855).

The calculated separation distances for each zone are presented in table 1. The zones used in the model (Fig. 1) are slightly oversized for clarity.

The main purpose of the experiment was to verify the safety of the human operator during ad-hoc maintenance actions:

– making adjustments to the box on the infeeder,
– adjusting the position of the box in the pallet,
– stopping the robot at the picking position.

Furthermore, the reaction of the system to short-term safety zone intrusion (like people passing) was tested.

**Tab. 1. Stop times and separation distances obtained from calculations**

| Area | Outside yellow zone | Yellow zone | Orange zone |
|---|---|---|---|
| **Robot tool speed** | 3 m/s | 1.5 m/s | 0.3 m/s |
| **Robot stop time ($T_B$)** | 0.5 s | 0.2 s | 0.04 s |
| **Robot stop distance (including the reaction time delay)** | 0.95 m | 0.4 m | 0.06 m |
| **Separation distance ($S$)** | 2.8 m | 2.0 m | 1.5 m |

## 3. RESULTS OF THE EXPERIMENT

This chapter presents the results of the experiment obtained from the simulation of the states of human-robot cooperation depending on the situation in the palletizing cell. The area in front of the robot is divided into 3 zones, after the operator enters the restricted area, the robot slows down (first to 50% in the first, yellow zone, then to 10% in the second, orange zone). After the employee enters the last, third zone, the robot stops all movements.

Fig. 2 shows the situation in which the robot works in the presence of a human being in the second safety zone. The safety zones in the robot cell are color-coded as follows: 1st zone – yellow, 2nd zone – orange, 3rd zone – red.

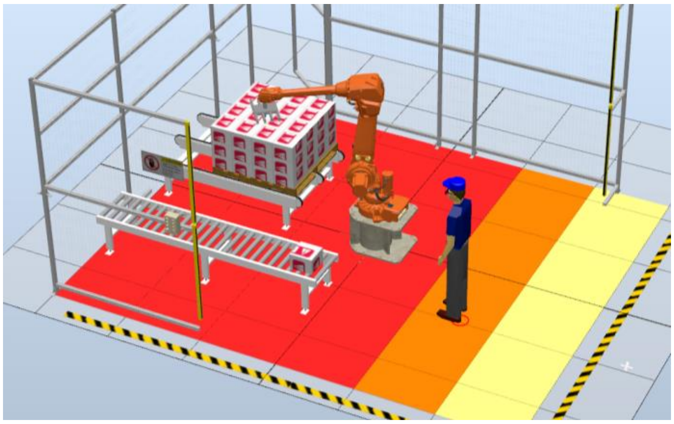

**Fig. 2. Human operator in the 2nd safety zone**

The power of robot motors and the resulting TCP (tool) speed are shown in Fig. 3. Limiting the speed of the robot helps to accomplish two objectives:

1) to decrease the distance at which the robot stops to safe values,
2) to reduce the stress level (or increase psychological comfort) of the person approaching the robot.

To find out how people would react, some volunteers were requested to enter the robot cell and perform one of the maintenance actions in a virtual reality setting (like verifying the sealing on of the box in the in-feed conveyor). The tests have shown that people felt greater comfort and confidence when they saw robots reacting to their actions by slowing down and then stopping completely. When the safety system was disengaged and the robot did not react to the presence of humans, they had shown stressful reactions and tried to escape from the cell quickly.


**Fig. 3. Signals recorded during simulation: speed of manipulator and motor power – colours of the zones in the graph correspond with the safety zones defined in the robot cell**

The approximated category 1 (normal stop) stop distances were computed for each robot axis using the functions built into the RobotStudio and are shown in Fig. 4. The computations confirmed the feelings of the volunteers, that the robot speed in the second (orange) zone allowed them to stop the robot almost immediately (computed distance is less than 10 mm in each axis). The volunteers felt "at control" of the situation and felt confident to approach the box on the conveyor or the pallet. The experiment has shown that volunteers quickly gained confidence in the requested tasks and soon were performing them almost without any consideration of the actual robot position and speed. This overconfidence could create dangerous situations in the real world and should be addressed in further research. These findings show, that all the personnel working near the open robot cells should at least have appropriate training and that the safety procedures should be strictly imposed in such environments.

The experiment has also shown that the recovery time of the open cell was shorter that the estimated re-starting time of a traditional, fenced cell. This in normal working conditions, that is assuming no intrusions in the safety zones except for the process servicing, would result in greater productivity of the cell.

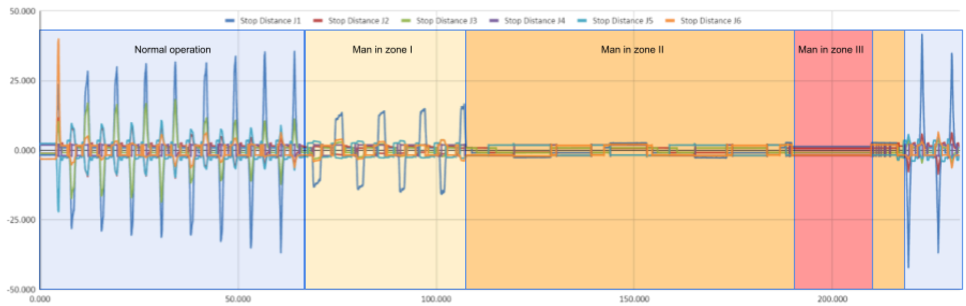


**Fig. 4. Signals recorded during simulation concern the stop distance – colours of the zones in the graph correspond with the safety zones defined in the robot cell**

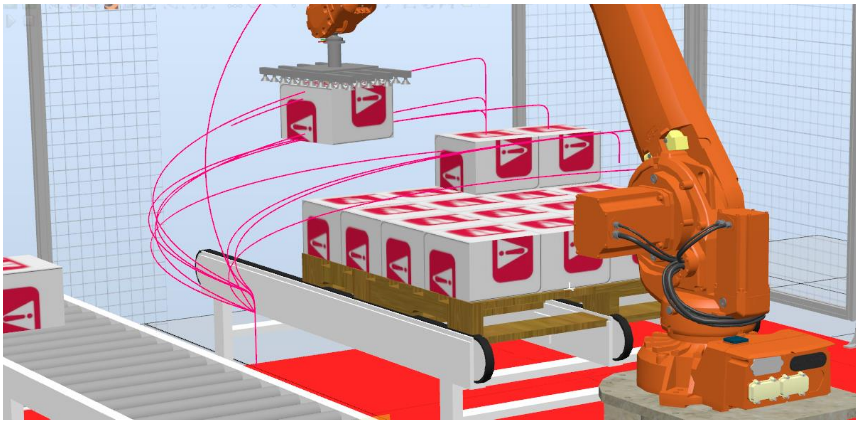

**Fig. 5. Determining the trajectory of the robot's work on the palletizing station**

Virtual simulation environment also provided a powerful tool for analysing and optimisation of robot trajectories (Fig. 5). The programmers with little robot experience could make better decisions when they saw the robot path in 3D. This applied especially to assessing the approach and depart distances and to the choice of joint or linear (circular) movements.

## 4. CONCLUSIONS

The article describes the design and implementation example of a VR-based system to provide the user with a good understanding of the current production environment, as well as the possibility of reprogramming the existing robotic cell. The benefits of using VR consist in increasing the flexibility of the currently installed robotic cell in a cost-effective manner and based on minimal hardware changes.

On the basis of the conducted analyses, a clear division into safety zones can be noticed, depending on the presence of a human-operator in the robot cell. There are clearly noticeable drops in the value of the manipulator speed and the engine power values in individual safety zones. Conducted simulations with volunteers using VR goggles show human behaviour in a robot cell with a shared work space. The main conclusion is that a person quickly gets used to working in such a system, and seeing that the robot changes its operating parameters depending on the place occupied by the operator, it gains confidence. Overconfidence can create dangerous situations in the real world and should be the subject of further research.

Thanks to the use of the VR technique, it is possible to obtain better results of robot programming and reduce errors in the actual adjustment of the cell with an industrial robot to work in a shared area. In addition, the VR technique is a very good educational tool that allows young engineers and operators of industrial machines, including robots and internal transport devices to understand the processes taking place in the production space more easily.

## Funding

*The project was financed in the framework of the project Lublin University of Technology – Regional Excellence Initiative, funded by the Polish Ministry of Science and Higher Education (contract no. 030/RID/2018/19).*

## Conflicts of Interest

*The authors declare no conflict of interest.*

**REFERENCES**

Bistak, M., Medvecky, S., Gajdosova, E., Dzimko, M., Gramblicka, S., Kohar, R., Stopka, M., Steininger, J., Hrcek, S., Tropp, M., & Brumercik, F. (2017). Applications of modern technologies in the production of aircraft propeller prototype. *Communications - Scientific Letters of the University of Zilina, 19*(2), 54–59. https://doi.org/10.26552/com.C.2017.2A.54-59

Blatnický, M., Dižo, J., Barta, D., & Droździel, P. (2020). FEM analysis of main parts of a manipulator for mountig a compressor to a car equipped with a pneumatic suspension system. *Diagnostyka, 21*(2), 87–94. https://doi.org/10.29354/diag/122549

Blatnický, M., Dižo, J., Gerlici, J., Sága, M., Lack, T., & Kuba, E. (2020). Design of a robotic manipulator for handling products of automotive industry. *International Journal of Advanced Robotic Systems, 17*(1), 1–11. https://doi.org/10.1177/1729881420906290

Blatnický, M., Dižo, J., & Timošcuk, M. (2016). Design of a three-finger robot manipulator. *Manufacturing Technology, 16*(3), 485–489.

Bogucki, M., Stączek, P., & Płaska, S. (2003). Methods of improving quality product and process using experimental techniques. *Second International CAMT Conference (Centre for Advanced Manufacturing Technologies), Modern Trends in Manufacturing* (pp. 15–20).

Burdea, G. C. (1999). Invited review: the synergy between virtual reality and robotics. *IEEE Transactions on Robotics and Automation, 15*(3), 400–410. https://doi.org/10.1109/70.768174.

Cechowicz, R. (2003). An approach to flexible scheduling in job shop manufacturing system. *Second International CAMT Conference (Centre for Advanced Manufacturing Technologies), Modern Trends in Manufacturing* (pp. 27–35).

Chen, C., Su, B., Guo, M., Zhong, Y., Yang, Y., & Kuo, H. L. (2018). Applying virtual reality to control of logical control mechanism system. IEEE International Conference on Applied System Invention (ICASI) (pp. 520–523). IEEE. https://doi.org/10.1109/ICASI.2018.8394302

Collaborative Robot Safety Made Simple. (2020). https://sickusablog.com/collaborative-robot-safety-made-simple

Covaciu, F., Pisla, A., Carbone, G., Puskas, F., Vaida, C., & Pisla, D. (2018). VR interface for cooperative robots applied in dynamic environments. *IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR)* (pp. 1–6). IEEE. https://doi.org/10.1109/AQTR.2018.8402734

Ehmanna, D., & Wittenberg, C. (2018). The idea of Virtual Teach-In in the field of industrial robotics. *2018 IEEE 14th International Conference on Control and Automation (ICCA)* (pp. 680–685). IEEE. http://dx.doi.org/10.1109/ICCA.2018.8444250

Fedorko, G. (2021). Application possibilities of virtual reality in failure analysis of conveyor belts. *Engineering Failure Analysis, 128*, 105615. https://doi.org/10.1016/j.engfailanal.2021.105615

FreeMove — Veo Robotics. (2020). https://www.veobot.com/freemove

Gola, A. (2014). Economic aspects of manufacturing systems design. *Actual Problems of Economics, 156*(6), 205–212.

Gola, A., Plinta, D., & Grznar, P. (2021). Modelling and simulation of reconfigurable manufacturing system for machining of casing-class parts. *Engineering for Rural Development, 20*, 1563–1568.

Heydaryan, S., Suaza Bedolla, J., & Belingardi, G. (2018). Safety Design and Development of a Human-Robot Collaboration Assembly Process in the Automotive Industry. *Applied Sciences, 8*(3), 344. https://doi.org/10.3390/app8030344

Ji, W., Yin, S., & Wang, L. (2018). A virtual training based programming-free automatic assembly approach for future industry. *IEEE Access, 6*, 43865–43873. https://doi.org/10.1109/ACCESS.2018.2863697

Jenis, J., Hrcek, S., Brumercik, F., & Bastovansky, R. (2021). Design of automatic assembly station for industrial vehicles parts. *LOGI – Scientific Journal on Transport and Logistics, 12,* 1, 204–213. https://doi.org/10.2478/logi-2021-0019

Klačková, I., Kuric, I., Zajacko, I., & Tucki, K. (2020). Energy and economical aspects of implementation of virtual reality in robotized technology systems. *ICETA 2020 – 18th IEEE International Conference on Emerging eLearning Technologies and Applications, Proceedings* (pp. 318–322). IEEE. https://doi.org/10.1109/ICETA51985.2020.9379176

Klarak, J., Kuric, I., Cisar, M., Stanček, J., Hajducik, A., & Tucki, K. (2021). Processing 3D data from laser sensor into visual content using pattern recognition. *2021 IEEE 8th International Conference on Industrial Engineering and Applications (ICIEA)* (pp. 543–549). IEEE. https://doi.org/10.1109/ICIEA52957.2021.9436712

Kose, A., Tepljakov, A., Astapov, S., Draheim, D., Petlenkov, E. K., & Vassiljeva, K. (2018). Towards a synesthesia laboratory: real-time localization and visualization of a sound source for Virtual Reality applications. *Journal of Communications Software and Systems, 14*(1), 112–120. http://dx.doi.org/10.24138/jcomss.v14i1.410

Kot, T., Novák, P., & Bajak, J. (2018). Using HoloLens to Create a Virtual Operator Station for Mobile Robots. *19th International Carpathian Control Conference (ICCC)* (pp. 422–427). IEEE. https://doi.org/10.1109/CarpathianCC.2018.8399667

Kuts, V, Otto, T., Tähemaa, T., & Bondarenko, Y. (2019). Digital Twin based synchronised control and simulation of the industrial robotic cell using Virtual Reality. *Journal of Machine Engineering, 19*(1), 128–144. https://doi.org/10.5604/01.3001.0013.0464

Oyekan, J. O., Hutabarat, W., Tiwari, A., Grech, R., Aung, M. H., Mariani, M. P., López-Dávalos, L., Ricaud, T., Singh, S., & Dupuis, C. (2019). The effectiveness of virtual environments in developing collaborative strategies between industrial robots and humans. *Robotics and Computer-Integrated Manufacturing, 55*, 41–54. https://doi.org/10.1016/j.rcim.2018.07.006

Shen, W. (2020). Research on virtual simulation design of ABB robot welding operation based on Robotstudio. *IEEE International Conference on Artificial Intelligence and Computer Applications (ICAICA)* (pp. 894–897). IEEE. http://dx.doi.org/10.1109/ICAICA50127.2020.9182551

Sobaszek, Ł., Gola, A., & Świć, A. (2022). The algorithms for robust scheduling of production jobs under machine failure and variable technological operation times. *Lecture Notes in Mechanical Engineering,* (pp. 56–67). Springer. https://doi.org/10.1007/978-3-030-78170-5_6

Stączek, P., Bogucki, M., & Płaska, S. (2003). Fuzzy logic in supervising of complex technological processes. Second International CAMT Conference (Centre for Advanced Manufacturing Technologies), Modern Trends in Manufacturing (pp. 351–360).

Świć, A., & Gola, A. (2013). Economic analysis of casing parts production in a flexible manufacturing system. *Actual Problems of Economics, 141*(3), 526–533.

Szabo, S., Shackleford, W., Norcross, R., & Marvel, J. (2012). A testbed for evaluation of speed and separation monitoring in a human robot collaborative environment. NIST Interagency/Internal Report (NISTIR), National Institute of Standards and Technology, Gaithersburg, MD, https://doi.org/10.6028/NIST.IR.7851

Togias, T., Gkournelos, C., Angelakis, P., Michalos, G., & Makris, S. (2021). Virtual reality environment for industrial robot control and path design. *Procedia CIRP, 100,* 133–138. https://doi.org/10.1016/j.procir.2021.05.021

Vosniakos, G. C., Ouillon, L., & Matsas, E. (2019). Exploration of two safety strategies in human-robot collaborative manufacturing using Virtual Reality. *Procedia Manufacturing, 38*, 524–531. https://doi.org/10.1016/j.promfg.2020.01.066

Wang, Q., Cheng, Y., Jiao, W., Johnson, M. T., & Zhang, Y. M. (2019). Virtual reality human-robot collaborative welding: a case study of weaving gas tungsten arc welding. *Journal of Manufacturing Processes, 48,* 210–217. https://doi.org/10.1016/j.jmapro.2019.10.016

Wpływ robotyzacji na konkurencyjność polskich przedsiębiorstw III edycja. (2019). *Instytut Prognoz i Analiz Gospodarczych*. Fanuc Polska Sp z o.o.