PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891
E-ISSN 2720-5266

14, 1 (51), 2023, 105-122

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

The Use of Virtual Twins in the Robotic Yoghurt Mixing Process

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Received: August 15, 2022 / Revised: September 10, 2022 / Accepted: December 6, 2022 / Published: March 31, 2023.

DOI 10.5604/01.3001.0016.2962

Abstract. This paper presents the results of computer simulations related to the selection and optimisation of parameters for a robotic yoghurt mixing process. The authors proposed a station configuration using the RobotStudio environment for off-line robot programming and virtual controller technology and determined the performance of the robotised production line. The main component of the study was a computer simulation of the station based on the Picking PowerPac package and Pick Master 3 program. As a result of the simulations, numerical values were obtained informing about the number of handled and rejected products, filled containers and the times of production cycles of the station.
Keywords: virtual twin, robotization, packaging, Industry 4.0

1. INTRODUCTION

Food is one of the fastest growing industries, which is particularly challenging to robotise due to the often irregular shapes of the products and the need for frequent modifications to the production line [1], [2].

Because of the highly competitive market and the need to meet stringent product quality standards, factory strategies have to be constantly changing, so it is necessary to carry out analyses on current production [3]. Due to the large number of technological and hardware parameters, achieving high productivity at the same time is a major challenge to ensure quality [4]. Given the high cost of robotic production lines, it is necessary to develop flexible production systems that allow rapid adaptation to customer requirements. Such a solution is possible through the use of techniques and tools to analyse the process flow with the possibility of predicting its future functionality [5-9]. It is necessary to simultaneously estimate the requirements of the process and create behavioural models of the process itself, as well as the individual machines, so that all possible problems are considered and included in the model to be created.

Given the high cost of running such experiments on the shop floor, it is worthwhile carrying out computer simulations as early as the production design stage to eliminate many problems. It is particularly important to carry out analyses that allow a numerical evaluation of the process flow and to assess the extent of the changes made [10]. Full analyses should take into account maintenance, scheduling and task sequencing, while taking into account the stochasticity of the processes and the uncertainty associated with demand, supply and machine performance [11]. Another approach is a process analysis focusing on the time required to complete each task (operation) and, related to this, the time required to complete the entire contract [12]. Despite the technical feasibility of performing computer simulations before or during production, it remains a difficult task to prepare an accurate model based on the actual process [13]. The new challenges posed by Industry 4.0 have resulted in the dynamic development of simulation environments (e.g. RobotStudio, Robo Guide, KUKA Sim, Delmia, Process Simulate), which allow the conditions existing on real production lines to be accurately reproduced through the mechanism of the virtual controller [14-16].

2. STATE OF KNOWLEDGE

Creating digital twins of production workstations (DTMCs) is possible using off-line robot programming techniques [17-22]. This makes it possible to carry out analyses of the operation of production stations before they are put into operation and (quickly and without stopping the actual machines) to make modifications to the stations during production.

This is especially important in the current trend of production personalization [23]. Production cell digital twins can be used to study collaborative strategies between industrial robots and humans [24]. This approach enhances operator safety related to the hazards of high-speed robotic movements, the enormous forces generated by robots and the need for humans and industrial robots to share a common workspace. Digital twins have another important feature, they allow the development of advanced control applications using most modern tools, i.e. artificial intelligence (AI – *Artificial Intelligence*), virtual reality (VR – *Virtual Reality*), and augmented reality (AR – *Augmented Reality*) [18, 25]. In order to be able to accurately represent reality, it is required that the machine models (among other robots) are complete. This means that for industrial robots it is necessary to develop the exact kinematics of the models and their control systems [26].

3. ROBOTIC YOGHURT MIXING STATION

In the era of Industry 4.0, the preparation of production workstations begins with the development of a virtual twin of a real production workstation [27]. Counter-intuitively, this is a very important stage, and its implementation has an impact (including economic) not only on the launch of the actual cell, but also on the introduction of modifications to the cell in the future. The importance of this step and of modern design tools is confirmed by the fact that all major manufacturers on the global market offer environments for modelling robotic production workstations and robot programming (e.g.: RobotStudio by ABB, RoboGuide by FANUC, RT ToolBox 3 by Mitsubishi Electric, KUKA Sim by KUKA).

Off-line virtual environments for programming industrial robots also allow the computer to interact with the actual robot (fully or partially) online. Environments of this type can also be equipped with tools to transfer the scene to virtual (e.g. using HTC goggles – RobotStudio) and augmented reality (e.g. using Hololens goggles – RobotStudio, or using additional applications installed on a smartphone or tablet – RobotStudio AR).

This paper presents selected issues in the use of the RobotStudio environment with the Picking PowerPac and PickMaster 3 software to model robotic yoghurt mixing stations. The choice of software was dictated by the contracting authority's requirements.

3.1. RobotStudio

ABB's RobotStudio 2022 environment allows the design of robotic production workstations based on ABB robots. It enables off-line simulation, programming and optimisation of robotic production stations in an intuitive way.

The RobotStudio programme is based on Virtual Robot Technology, allowing the creation of digital twins, which is characterised by an accurate reflection of the real software used in robots – RobotStudio can create ready-made configuration files that work with the real robot.

When creating a system for a specific robot(s) and ancillary equipment, it is possible to select the options and functions of the RobotWare operating system. When a virtual workstation is created, all options are available, whereas when a workstation with actual equipment is created, the system is pre-configured to its needs by the manufacturer. Then, it is possible to extend the functionality with the appropriate option keys.

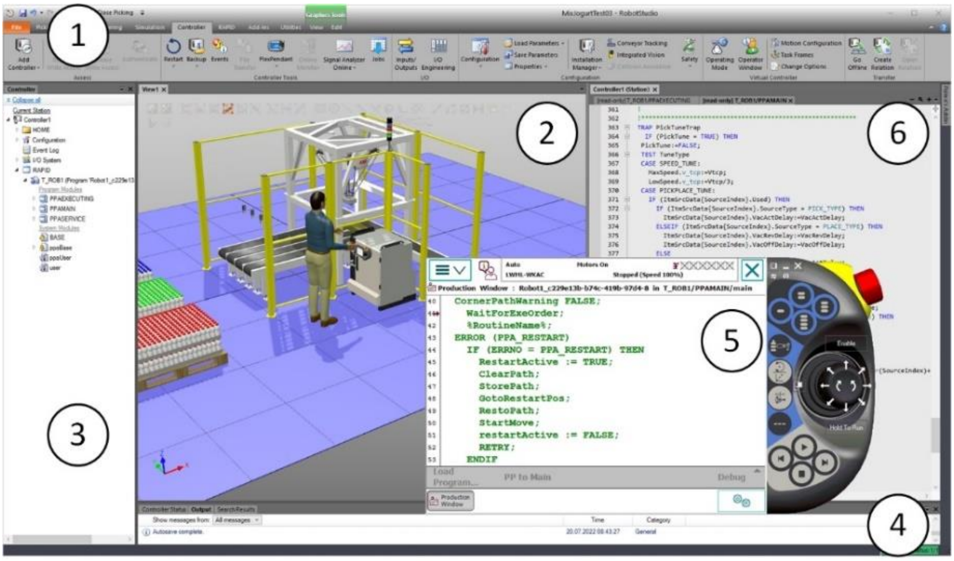

Fig. 3.1. General view of ABB's RobotStudio window:
1 – toolbar, 2 – layout, 3 – project tree, 4 – message window,
5 – virtual FlexPendant, 6 – programme window

The interest in the robotisation of sorting and packaging processes is so great that robot manufacturers offer modules to support the creation of such stations off-line (e.g. ABB offers the Picking PowerPac package for the RobotStudio environment – Fig. 3.2) and programmes to support engineers during the configuration of the sorting/packing process in on-line operation (e.g. PickMaster 3 from ABB – Fig. 3.3). However, it appears that the best results in job modelling can be achieved by supplementing the above-mentioned products with SmartComponent created by engineers for the needs of a specific solution.

3.2. Picking PowerPac

Picking PowerPac supports users in the design of robotic sorting and packaging production workstations and allows the creation of system simulations that can be a complete reflection of the systems installed in real robots. Many components of the add-on are 'configured' rather than programmed, which (according to the manufacturer) saves up to 80% of the programming time compared to traditional methods. This is possible because the manufacturer provides code templates in the RAPID language. Unfortunately, these templates are only fully useful for simple packaging tasks, making deep modification often necessary for custom projects. In such situations, the advanced code editor (available in RobotStudio) is useful.

Picking PowerPac allows the reconfiguration of a prepared stand. In the case of hardware changes ('lines'), it is necessary to calibrate base frames and work areas. If the sorting and packaging algorithms are changed, a software compilation is required.

A very good advantage of the package is the implemented operator interface. It is used to run the simulation, but above all it allows you to monitor and control the simulation. This allows the operator to adjust process parameters in real time (e.g. robot speeds, conveyors, making adjustments to robot trajectory points) without having to stop the simulation. This allows optimum settings to be made for the operation of the individual devices comprising the workstation. The Picking PowerPac toolbar (Fig. 3.2) is used to set up and prepare the workstation rules (fig. 3.2).

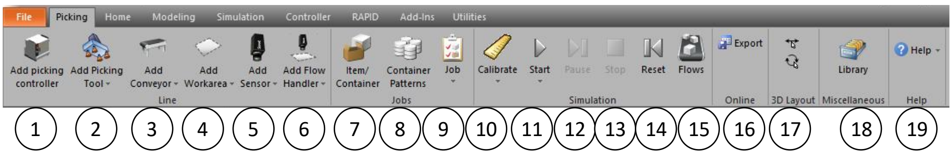

Fig. 3.2. Picking PowerPac – tool bar:
1 – adding virtual controllers, 2 – defining tools and coordinate systems,
3 – configuring conveyors, 4 – configuring picking up and putting down zones,
5 – configuring sensors and vision systems, 6 – configuring product flow managers,
7 – defining products and containers, 8 – defining product putting down patterns,
9 – creating rules for the robot control program, (Jobs), 10 – calibrating lines,
11-14 – simulation control buttons, 15 – defining product and container flows,
16 – exporting jobs, lines and the project to files for PickMaster 3, 17 – defining the scene. (3D Layout), 18 – defining component libraries, 19 – Help.

Picking PowerPac works with PickMaster 3, so that the workstation configurations and robot algorithms prepared with it can be easily exported to the actual robot(s) controller.

This allows for a significant reduction in off-line application preparation time without the need for actual robots, thus reducing the downtime of the actual production station.

3.3. PickMaster 3 application

PickMaster 3 is a modular application for controlling ABB robots in product sorting and packaging applications. It is an application for programming operations for picking up workpieces and placing them in containers (e.g. trays, formats). The vision system is used in PickMaster 3 to find randomly placed products on conveyors.

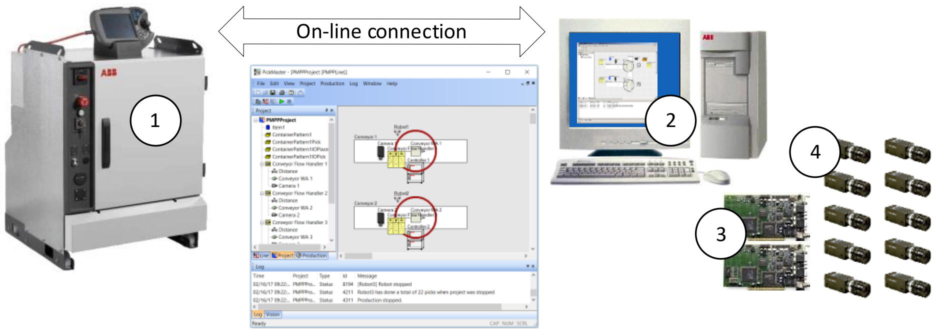

Fig. 3.3. Elements of ABB's PickMaster3 system:
1 – IRC5 controller, 2 – computer with PickMaster3 software, 3 – camera cards, 4 – cameras

PickMaster 3 has graphical interfaces for configuring and running advanced applications where it can control multiple industrial robots, providing full process control. PickMaster 3 can be used:

- for fully randomised operations on moving conveyors and accurate positioning of workpieces on indexable feeders or trays thanks to an integrated vision system,
- as a tool for efficient production with guided product flow on multiple conveyors without the need for vision systems,
- for quality control and product categorisation, also with position and orientation recognition.

The software application for process control in PickMaster 3 consists of two elements: line and project. The line includes all physical objects such as robots, cameras and transporters. The project includes the details to be retrieved and the connections between work zones, products and cameras. Working with the application involves creating and configuring a line (the hardware equivalent of the actual station) once, which is saved in a file on the computer.

Only one line can be opened at a time. The line comprises the following components and configurations:

- cameras,
- robots and controllers,
- conveyors,
- working areas (for conveyors and indexes),
- camera calibration,
- fine-tuning of the base frame and camera.

Each saved line can use multiple projects (job templates). The project includes the following elements and configurations:

- details,
- containers and patterns,
- sources of items specifying the rules for collection and deposition,
- vision models,
- RAPID programme,
- settings and fine-tuning of the work area,
- robot settings.

It is possible to have more than one project open at the same time, but they must all be configured to the same line.

3.4. ABB IRB360 industrial robot

A four-degree-of-freedom delta robot (ABB's IRB360) was used for the prepared stand. Some knowledge of direct kinematics and inverse kinematics is also required to control the manipulator. [2] In most cases, positioning (the robot's primary axes) is decoupled from orientation (the robot's secondary axes) when creating mathematical models. The kinematic relationships to determine the robot's position in Cartesian space (*x*, *y*, *z*) are shown below. The length of the side of the base platform (B) is sB, the length of the side of the mobile platform (P) is sP (Fig. 3.4). The axial variables are:

$$\Theta = \{\theta_1\ \theta_2\ \theta_3\}^T \tag{3.1}$$

where θ_1, θ_2, θ_3 – adjustable angles of the rotary axes

The Cartesian variables are:

$${}^{B}P_{P} = \{x\ y\ z\}^T \tag{3.2}$$

where *x*, *y*, *z* – Cartesian coordinates.

A diagram of the robot is shown in the figure below.

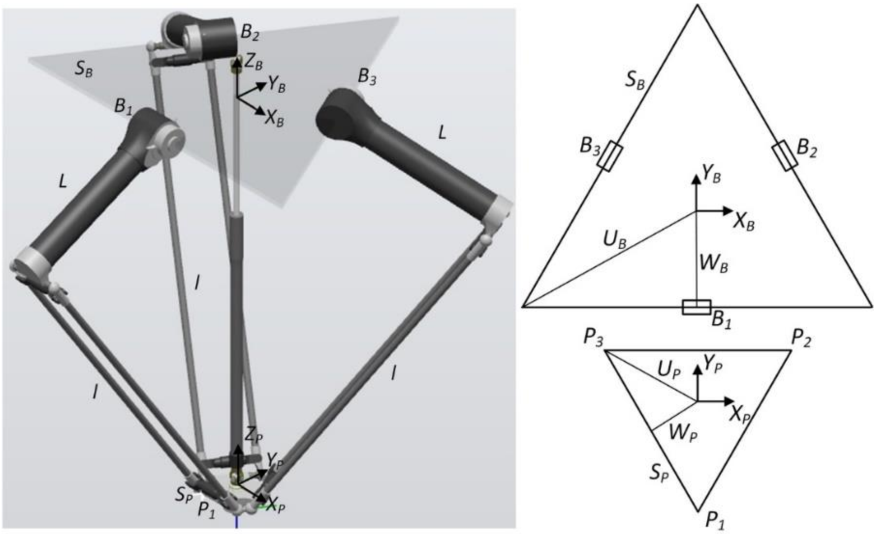

Fig. 3.4. Diagram of a Delta-type manipulator

Simple kinematics are described by the following equations. The three absolute vector nodal points are defined as:

$$ {}^{B}\mathrm{A_i} = {}^{B}\,\mathrm{B_i} + {}^{B}\mathrm{L_i} \quad \mathrm{i} = 1{,}2{,}3 \tag{3.3}$$

where:

$$ {}^{B}B_1 = \begin{Bmatrix} 0 \\ -w_B \\ 0 \end{Bmatrix} 1\, {}^{B}B_2 = \begin{Bmatrix} \frac{\sqrt{3}}{2} w_B \\ \frac{1}{2} w_B \\ 0 \end{Bmatrix} 1\, {}^{B}B_3 = \begin{Bmatrix} -\frac{\sqrt{3}}{2} w_B \\ \frac{1}{2} w_B \\ 0 \end{Bmatrix} \tag{3.4}$$

$$ {}^{B}L_1 = \begin{Bmatrix} 0 \\ -Lcos\theta_1 \\ -Lsin\theta_1 \end{Bmatrix} 1\, {}^{B}L_2 = \begin{Bmatrix} \frac{\sqrt{3}}{2} Lcos\theta_2 \\ \frac{1}{2} Lcos\theta_2 \\ -Lsin\theta_2 \end{Bmatrix} 1\, {}^{B}L_3 = \begin{Bmatrix} -\frac{\sqrt{3}}{2} Lcos\theta_3 \\ \frac{1}{2} Lcos\theta_3 \\ -Lsin\theta_3 \end{Bmatrix} \tag{3.5}$$

The three centres of the virtual spheres are as follows:

$$ {}^{B}A_{i\nu} = {}^{B}\,A_i - {}^{P}P_i \; i = 1, 2, 3 \tag{3.6}$$

where:

$$^{B}A_{1\nu} = \begin{Bmatrix} 0 \\ -w_B - Lcos\theta_1 + u_p \\ -Lsin\theta_1 \end{Bmatrix}$$

$$^{B}A_{2\nu} = \begin{Bmatrix} \frac{\sqrt{3}}{2}(w_B + Lcos\theta_2) - \frac{s_P}{2} \\ \frac{1}{2}(w_B + Lcos\theta_2) - w_P \\ -Lsin\theta_2 \end{Bmatrix} \quad (3.7)$$

$$^{B}A_{3\nu} = \begin{Bmatrix} -\frac{\sqrt{3}}{2}(w_B + Lcos\theta_3) - \frac{s_P}{2} \\ \frac{1}{2}(w_B + Lcos\theta_3) - w_P \\ -Lsin\theta_3 \end{Bmatrix} \quad (3.8)$$

$$^{P}P_1 = \begin{Bmatrix} 0 \\ -u_P \\ 0 \end{Bmatrix} 1\, ^{P}P_2 = \begin{Bmatrix} \frac{s_P}{2} \\ w_P \\ 0 \end{Bmatrix} 1\, ^{P}P_3 = \begin{Bmatrix} -\frac{s_P}{2} \\ w_P \\ 0 \end{Bmatrix}$$

w_B – horizontal distance from {0} to the side closer to the base,
L – length of the upper arms,
u_P – horizontal distance from {P} to the top of the platform,
s_P – side of the platform's equilateral triangle,
w_P – horizontal distance from {P} to the nearest side of the platform.

The Unknown Linear Kinematics Point (BPP) is the intersection of three known spheres:

$$(\{1\, ^{B}A_{1\nu}\}, l)(\{1\, ^{B}A_{2\nu}\}, l)(\{1\, ^{B}A_{1\nu}\}, l) \quad (3.9)$$

where l is the length of the parallelogram of the lower limbs.

Inverse kinematics is described by the following equations:

$$E_i cos\theta_i + F_i sin\theta_i + G_i = 0 \; dla \; i = 1, 2, 3 \quad (3.10)$$

where:

$$E_1 = 2L(y+a); E_2 = -L(\sqrt{3}(x+b)+y+c); E_3 = L(\sqrt{3}(x-b)-y-c) \quad (3.11)$$

$$F_1 = 2zL; F_2 = 2zL; F_3 = 2zL \quad (3.12)$$

$$G_1 = x^2+y^2+z^2+a^2+L^2+2ya-l^2$$
$$G_2 = x^2+y^2+z^2+b^2+c^2+L^2+2(xb+yc)-l^2 \quad (3.13)$$
$$G_3 = x^2+y^2+z^2+b^2+c^2+L^2+2(-xb+yc)-l^2$$

$$a = w_B - u_P; b = \frac{s_P}{2} - \frac{\sqrt{3}}{2}w_B; c = w_P - \frac{w_B}{2} \quad (3.14)$$

The required driven angles of the rotary axes can be calculated from the formula:

$$\theta_i = 2tan^{-1}\left(\frac{-F_i \pm \sqrt{E_i^2+F_i^2-G_i^2}}{G_i-E_i}\right) \quad (3.15)$$

3.5. Construction of a robotic yoghurt mixing station

The main objective in developing the robotic station was to test the ability to mix four types of yoghurt with a single robot and to test the performance of the station. This was dictated partly by the cost of upgrading the existing production line and the available space in the production room. Due to the customer's requirements and preferred hardware, the workstation included an IRB360 delta robot with an ABB IRC5 controller. The main features of the robot are:

- four degrees of freedom,
- load capacity – 3 kg,
- working range – 1130 mm,
- repeatability – 0.06 mm,
- speed – 10 m/s,
- acceleration – 100 m/s^2.

Due to the requirement for an ABB robot, the bench was prepared in the RobotStudio environment using the Picking PowerPac package (Figs. 3.5-3.6). The models used in the project were imported from the RobotStudio library or prepared in SOLIDWORKS.

Four infeed conveyors are responsible for delivering cartons filled with products of a particular type (the weight of one bottle is 400 g). It was assumed that the packages would be placed on the conveyors manually and the empty trays would be directed to the chute (Fig. 3.7). The robot picks three bottles of yoghurt at a time (the load weight is 1.2 kg).

The exit conveyor is used to transport the mixed yoghurt packets out of the station. It was assumed that the mixed packages would be picked up from the conveyor manually. The robot was suspended from a standard frame and a fence equipped with safety curtains and a signal column was proposed as a safety system.

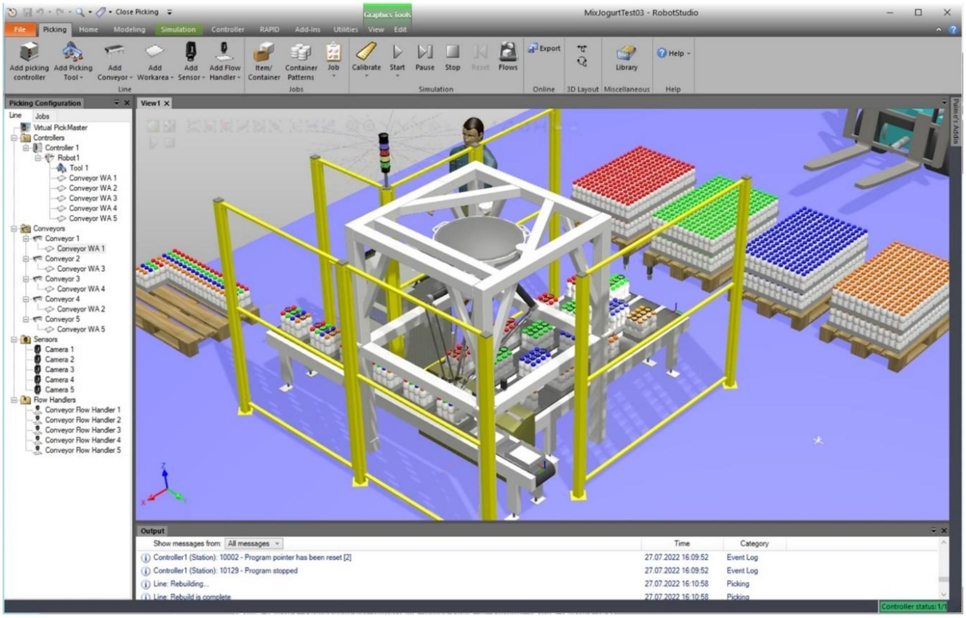

Fig. 3.5. General view of the site

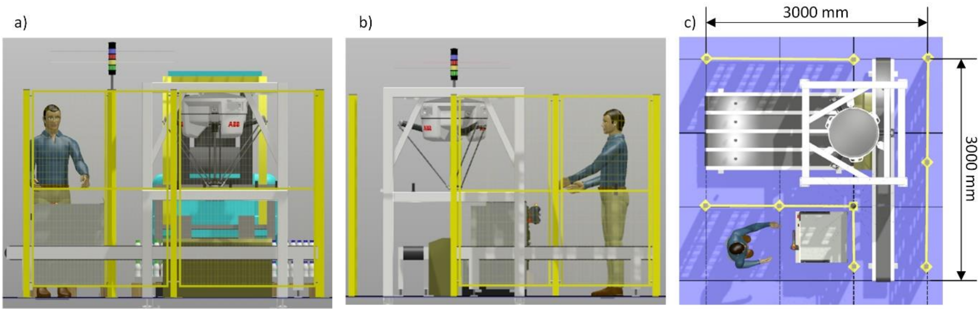

Fig. 3.6. Views of the site:
(a) – from the front, (b) – from the side, (c) – from above

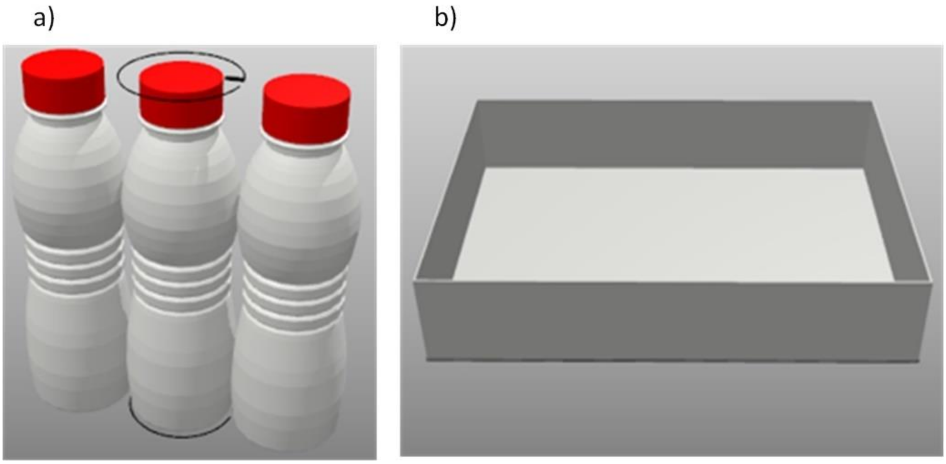

Fig. 3.7. General views of: a) – products and b) – packaging

During the task, the robot operating system version 6.13 (RobotWare OS) was prepared, creating a virtual twin. Additional system modules responsible for communication and the packaging process were attached to the created system:

- 709-1 DeviceNet Master/Slave,
- 606-1 PC Interface,
- 642-1 PickMaster 3 with work zone configuration.

For the prepared position model, the following was defined:

- Tool Centre Point (TCP) with coordinates x = 0 mm, y = 0 mm, z = 80 mm,
- control signals for on-the-fly product retrieval,
- conveyor control signals.

A control application has been developed to track the infeed and outfeed conveyors, allowing the robot to pick up and put down products without having to stop the conveyors. When defining the work zones for the robot (product picking and depositing zones), the use of vision systems were proposed (these can be replaced by optical or mechanical sensors to reduce the cost of the workstation). The field of view of the cameras was assumed to be 400 × 400 mm, and image triggering was set every 150 mm of conveyor movement. It was also assumed that all mixing packs can be recognised and would be handled by the robot. This was achieved by queuing all detected products and packaging and controlling their presence in the picking and putting away areas.

The following robot operating parameters were adopted in the picking and depositing zones:

- picking ramp height – 220 mm (product height 200 mm),
- gripping action time – 0.20 s,
- gripper activation – 0.025 s after reaching the pick-up/drop-off point,

The Start/Stop function used in the programme allows all products supplied by the transporters to be 'handled', i.e. all yoghurts are repacked into new packs according to a prepared working algorithm. This required defining the limits of the robot's work, measured from its centre:

- input limit, from which the robot starts to carry out the picking process,
- output limit, from which the product is removed from the download queue,
- Start border – informing the robot to start the conveyor if another carton is in front of the border,
- Stop limit – informs the robot to stop the conveyor if the carton moving on it reaches the stop limit.

The prepared control application is modular, to which further system and software modules and Smart Component objects can be attached (Fig. 3.8).

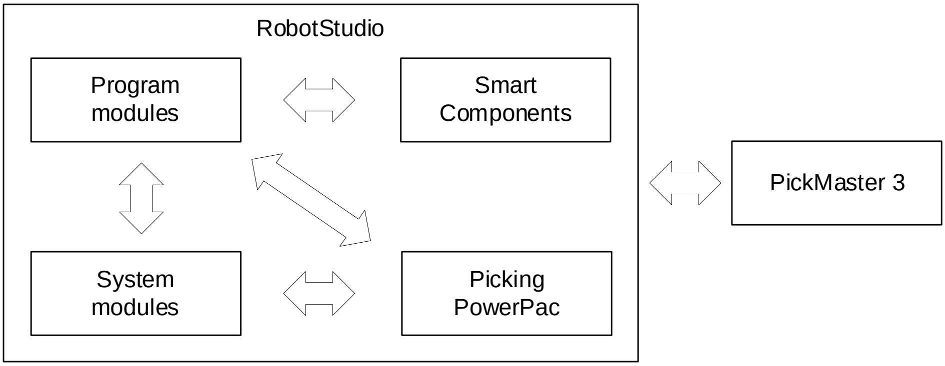

Fig. 3.8. Software architecture

Running simulations is possible by combining the functionality of the RobotStudio environment, Picking PowerPac and PickMaster 3.

RobotStudio enabled the graphical development of the workstation, including the programmable Smart Component objects (Fig. 3.9), which are responsible for the graphical representation of the process execution and the signal connection of all components to the robot controller (Fig. 3.10) and the development of the control programme.

Picking PowerPac and PickMaster were used to create the operating logic for the individual station elements (e.g. picking zones) and to assign specific tasks to them.

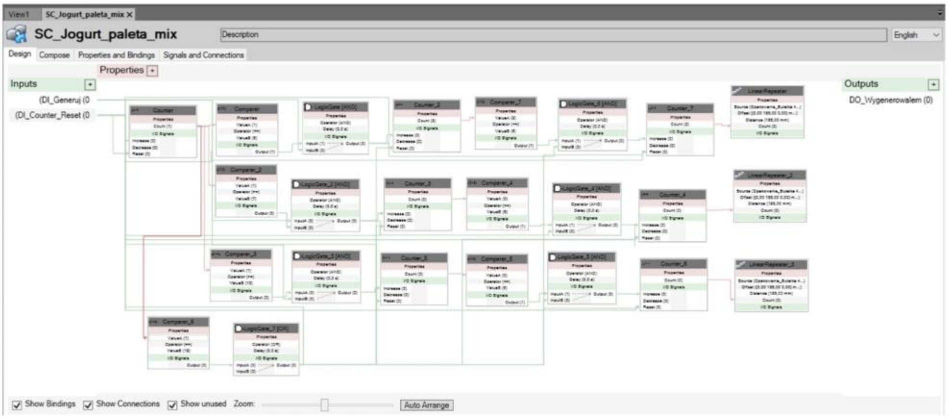

Fig. 3.9. Smart Component object architecture responsible for stacking packages of mixed products on a pallet

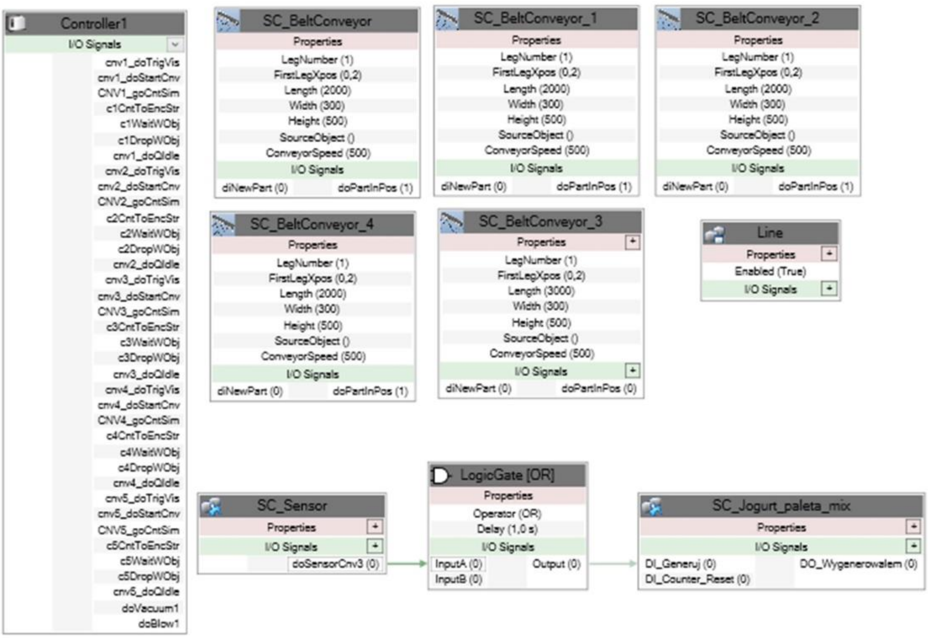

Fig. 3.10. View of the station's logical components

3.6. Tests

As part of the computer simulations, a number of tests were carried out to determine package completeness (Table 3.1) and bench performance. The tests carried out made it possible to select the optimum parameters for the workstation. In order to make full use of the industrial robot on the production bench, its speed was set to 10 m/s (maximum robot speed).

Taking into account the robot's cycle time, the speeds of all conveyors were selected to be 150 mm/s, ensuring smooth operation of the station with no conveyor downtime. Table 3.1 shows selected results from the tests carried out (the duration of a single test was 30 minutes). For the selected parameters of the robot and conveyors, the productivity of the station was determined, which is 12 mixed yoghurt packs per minute.

Table 3.1 Number of products per work area

	Transporter 1	**Transporter 2**	**Transporter 3**	**Transporter 4**	**Transporter 5**	**%**
Completion	-	-	-	-	360	100%
Downloaded	361	361	362	361	-	
Omitted	0	0	0	0	-	-

4. CONCLUSIONS

The use of virtual environments and tools by engineers provides new opportunities in the design and testing of advanced robotic systems. Researchers and engineers have noted that realistic virtual models reflecting the real world are essential to bridge the gap between design and manufacturing. Increasing customer demands on products and frequently changing production conditions (e.g.: due to short production runs) make it necessary to test multiple concepts and processes simultaneously during the design phase. This is made possible by creating digital twins that mirror the actual robotic workstations. When creating the twin, if a backup of the actual robot is used, the prepared station should be equipped with virtual controllers which, according to the robot manufacturers, should allow a 99% replication of the actual robot cycle times. This allows the performance of the proposed station to be tested, analysed and optimised off-line, without the use of an actual workstation. The creation of a virtual station reduces software development costs and the implementation time of the proposed solution. It also reduces the cost of the entire project due to the possibility of making detailed investment decisions before implementation work begins.

In the example shown, the prepared stand allowed the determination of package completions and stand efficiency. Starting from the robot's cycle time, it was possible to select the speed of the conveyors in such a way that the entire station ran smoothly and without downtime. For the selected parameters of the robot and conveyors, the productivity of the station was 12 mixed yoghurt packs per minute.

The work carried out demonstrated that, with the latest version of the RobotStudio environment, combining the available components (RobotStudio, Picking PowerPac, PickMaster3 and SmartComponent objects), results in complex simulations.

FUNDING

This work was co-financed by Military University of Technology (Warsaw, Poland) under research project UGB 776/2022.

REFERENCES

[1] International Federation of Robotics. 2019. *World Robotics 2019 Industrial Robots*. Germany: VDMA Services GmbH.

[2] Iqbal, Jamshed, Zeashan H. Khan, and Azfar Khalid. 2017. „Prospects of robotics in food industry". *Food Science and Technology* 37 (2) : 159-165.

[3] Barabady, Javad, Tore Markeset, and Uday Kumar. 2010. „A framework for improvement of production plant performance using production assurance programs". *International Journal of Systems Assurance Engineering and Management* 1 (1) : 59-65.

[4] Bect, Pierre, Zineb Simeu-Abazi, and Pierre-Loic Maisonneuve. 2015. „Identification of abnormal events by data monitoring: Application to complex systems". *Computers in Industry* 68 : 78-88.

[5] van der Aalst, Wil. 2016. Process Mining. Berlin,: Heidelberg: Springer.

[6] Vera-Baquero, Alejandro, Ricardo Colomo-Palacios, and Owen Molloy. 2014. „Towards a Process to Guide Big Data Based Decision Support Systems for Business Processes". *Procedia Technology* 16 : 11-21.

[7] Kaczmarek, Wojciech, Bartłomiej Lotys, Szymon Borys, Dariusz Laskowski, and Piotr Lubkowski. 2021. „Controlling an industrial robot using a graphic tablet in offline and online mode". *Sensors* 21 (7) : 2439-1-20.

[8] Borys, Szymon, Wojciech Kaczmarek, and Dariusz Laskowski. 2020. „Selection and optimization of the parameters of the robotized packaging process of one type of product". *Sensors* 20 (18) : 5378-1-21.

[9] Panasiuk, Jarosław, Wojciech Kaczmarek, Michał Siwek, and Szymon Borys. 2022. „Test Bench Concept for Testing of Gripper Properties in a Robotic Palletizing Process". *Problemy mechatroniki. Uzbrojenie, lotnictwo, inżynieria bezpieczeństwa / Problems of Mechatronics. Armament, Aviation, Safety Engineering* 13 (2) : 51-64.

[10] Ruschel, Edson, Eduardo Alves Portela Santos, and Eduardo de Freitas Rocha Loures. 2017. „Industrial maintenance decision-making: A systematic literature review". *Journal of Manufacturing Systems* 45 : 180-194.

[11] Purohit, S. Bhushan, and Bhupesh Kumar Lad. 2016. „Production and maintenance planning: an integrated approach under uncertainties". *The International Journal of Advanced Manufacturing Technology* 86 (9-12) : 3179-3191.

[12] van der Aalst, M.P. Wil. 2011. *Process Mining: Discovery, Conformance and Enhancement of Business Processes*. Springer Berlin, Heidelberg.

[13] Ayo, Emmanuel Femi, Olusegun Folorunso, and Friday Thomas Ibharalu. 2017. „A probabilistic approach to event log completeness”. *Expert Systems with Applications* 80 (C) : 263-272.

[14] Kaczmarek, Wojciech, Jarosław Panasiuk, and Szymon Borys. 2017. *Środowiska programowania robotów*. Warszawa: Wydawnictwo Naukowe PWN.

[15] Damic, Vjekoslav, Maida Cohodar, and Nedzma Kobilica. 2019. Development of Dynamic Model of Robot with Parallel Structure Based on 3D CAD Model, In *Proceedings of the 30th DAAAM International Symposium on Intelligent Manufacturing and Automation* pp. 0155-0160.

[16] Sam, Rosidah, Kamarul Arrifin, and Norlida Buniyamin. 2012. Simulation of pick and place robotics system using Solidworks Softmotion. In *Proceedings of the 2012 International Conference on System Engineering and Technology (ICSET),* 6 pages.

[17] Kaczmarek, Wojciech, and Jarosław Panasiuk. 2017. *Robotization of Production Processes Introduction*. Warsaw: Wydawnictwo Naukowe PWN.

[18] Zhang, Chao, Guanghui Zhou, Jun He, Zhi Li, and Wei Cheng. 2019. „A data- and knowledge-driven framework for digital twin manufacturing cell”. *Procedia CIRP* 83 : 345-350.

[19] Pires, Flavia, A. Cachada, J. Barbosa, A. P. Moreira, and P. Leitao. 2019. Digital Twin in Industry 4.0: Technologies, Applications and Challenges. In *Proceedings of the 2019 IEEE 17th International Conference on Industrial Informatics (INDIN)* pp. 721-726.

[20] Jinsong, Bao, Dongsheng Guo, Jie Li, and Jie Zhang. 2019. „The modelling and operations for the digital twin in the context of manufacturing”. *Enterprise Information Systems* 13 (4) : 534-556.

[21] Damic, Vjekoslav, Maida Cohodar, and Avdo Voloder. 2018. Modelling and Path Planning of Delta Parallel Robot in Virtual Environment., In *Proceedings of the International DAAAM Symposium* pp. 0149-0156.

[22] Fera, Marcella, Alessandro Greco, Mario Caterino, Salvatore Gerbino, Francesco Caputo, Roberto Macchiaroli, and Egidio D'Amato. 2019. „Towards Digital Twin Implementation for Assessing Production Line Performance and Balancing”. *Sensors* 20 (1) : 97-1-18.

[23] Kousi, Niki, Christos Gkournelos, Sotiris Aivaliotis, Christos Giannoulis, George Michalos, and Sotiris Makris. 2019. „Digital twin for adaptation of robots’ behavior in flexible robotic assembly lines”. *Procedia Manufacturing* 28 : 121-126.

[24] Oyekan, O. John, Windo Hutabarat, Ashutosh Tiwari, Raphael Grech, Min H. Aung, Maria P. Mariani, Laura Lopez-Davalos, Timothe Ricaud, Sumit Singh, and Charlene Dupuis. 2019. „The effectiveness of virtual environments in developing collaborative strategies between industrial robots and humans". *Robotics and Computer - Integrated Manufacturing* 55 (A) : 41-54.
[25] Araiza Illan, Dejanira, Alberto De San Bernabé Clemente, Hongchao Fang, and Yong Shin Leong. 2019. Augmented Reality for Quick and Intuitive Robotic Packing Re-Programming. In *Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)* pp. 664-664.
[26] Camacho, Guillermo, Cesar Hernán Rodriguez Garavito, and David Alvarez Martinez. 2018. Modelling the Kinematic Properties of an Industrial Manipulator in Packing Applications. In *Proceedings of th 14th International Conference on Control and Automation (ICCA)* pp. 1028-1033.
[27] Kaczmarek, Wojciech, Jarosław Panasiuk, Szymon Borys, Michał Siwek, and Robert Dyczkowski. 2022. *Robotyzacja i automatyzacja. Przemysł 4.0*. Warszawa: Wydawnictwo Naukowe PWN.

Wykorzystanie wirtualnych bliźniaków w procesie zrobotyzowanego miksowania jogurtów

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Streszczenie. W artykule przedstawiono wyniki przeprowadzonych symulacji komputerowych związanych z doborem i optymalizacją parametrów zrobotyzowanego procesu miksowania jogurtów. Autorzy zaproponowali konfigurację stacji przy użyciu środowiska RobotStudio do programowania robotów w trybie off-line oraz w technologii wirtualnego kontrolera i wyznaczyli wydajność zrobotyzowanej linii produkcyjnej. Głównym elementem badań była symulacja komputerowa stanowiska w oparciu o pakiet Picking PowerPac oraz Pick Master 3. W wyniku przeprowadzonych symulacji uzyskano liczbowe wartości informujące m. in. o liczbie obsłużonych i odrzuconych produktów, zapełnionych kontenerów oraz czasach cykli produkcyjnych stacji.
Słowa kluczowe: wirtualny bliźniak, robotyzacja, pakowanie, Przemysł 4.0