OPTIMIZATION OF A ROBOTIC CELL IN THE ROBOGUIDE ENVIRONMENT

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DOI: 10.17973/MMSJ.2025_06_2025021

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The article deals with the issues of modification and optimization of the manipulation process using a collaborative robot Fanuc in the RobotGuide environment. The collaborative robot is equipped with a combined effector containing two double-jaw pneumatic grippers and a vacuum effector. The robot performs the manipulation process based on the selection via the operating touch panel, where it is possible to choose from eight options. The workplace uses a working area of 1500x1300 mm. By implementing the optimization of the robotic cell, a reduction in working time by more than 20% was achieved.

KEYWORDS

collaborative robot, robotic cell, modification, offline environment, optimization

1 INTRODUCTION

Optimization of robot trajectory allows to increase the productivity of a robotized workplace while maintaining the required quality parameters, such as positioning accuracy and cycle time [Bozek 2021]. The robot trajectory is defined as the robot position as a function of time, which can be described as a combination of path scaling and time scaling. While path scaling is described as a geometric description of the end effector locations, time scaling specifies the time required to move from one position to another [Akbari 2023]. Several approaches have been proposed to optimize robot trajectory. The goal of optimization approaches is to minimize or maximize at least one of the following objective functions: minimum time trajectory planning; minimum energy trajectory planning; minimum jerk trajectory planning [Benotsmane 2020]. When planning a minimum time trajectory, we proceed from the requirement of reducing production time and increasing productivity. Minimizing the energy of the robot leads to a reduction in the mechanical stress of the actuators and energy costs [Trojanova 2021]. The trajectory planning is based on minimizing jerk, the third derivative of the position in time, reducing the joint positioning errors and vibration of the robot [Devi 2021]. These objectives can be considered simultaneously to achieve better results [Wu 2022].

Robot trajectory planning is usually performed in Cartesian or joint space [Chen 2018]. Joint space trajectory planning involves mapping the path points in Cartesian space to joint space based on a kinematic model, and then describing the joint motion using functional correlations between joint angle, angular velocity, angular acceleration, and time [Segota 2021]. This method has reasonable computational cost and can be used to achieve smooth motion [Stilman 2020]. However, joint space trajectory planning cannot ensure that the robot effector accurately follows the desired trajectory. Cartesian space trajectory planning is usually used to solve this problem. The most commonly used methods in this direction are polynomial interpolation, B-spline interpolation, Lame curves, and PH curves [Gauthier 2008, Yuhang 2018, Su 2018].

With the development of intelligent optimization algorithms in recent decades, many algorithms such as particle swarm algorithms [Han 2021], ant colony algorithms [Perez-Carabaza 2018], gray wolf algorithms [Zhang 2019], and convex optimization algorithms [Zhang 2016] have been proposed to optimize the robot trajectory. During further research, it was found that such algorithms offer an efficient scheme for solving the objective function optimization problem, but the accuracy and efficiency of the solution often depend on the convergence rate of the algorithm. For example, conventional intelligent optimization algorithms have a long search time and are easy to reach a local optimum [Xiuli 2022]. In order to solve these difficulties, many modified methods have been proposed. For example, Yu [Yu 2018] used a 4-3-4 polynomial function to adapt the running track and combined genetic algorithm and particle swarm optimization algorithms to optimize the running time of the robot. Based on the fifth NURBS curve, an improved harmony search algorithm was proposed and obtained a smooth and time-optimal running trajectory of the robot [Chen 2013]. Taking the running time as the constraint, a smooth trajectory is obtained by optimizing the five-step and three-step B-spline trajectories using the HS algorithm. However, only the single-objective running time optimization is analyzed. In another research, [Wang 2020] used an improved cuckoo search algorithm to optimize the running time of the trajectory adapted by the 3-5-3 polynomial function.

In terms of optimizing the running time, reducing jerking, and reducing energy consumption during robot operation, it is very important to optimize the robot trajectory. Thus, the aim of the presented research is to optimize the manipulation process consisting of adjustments to individual robot trajectories.

2 FORMULATION OF THE PROBLEM

The robotic cell equipped with a collaborative robot Fanuc CRX-10iA and an R-30iB control system is used for presentation and educational tasks. As part of educational tasks, a work table is attached to the rear of the structure, on which are placed fixtures enabling training, while it is also possible to assign individual tasks according to the student's knowledge. In the case of using the robotic cell for presentation tasks (for example, at exhibitions, conferences, workshops), the need was defined to ensure the delivery of a coffee drink to the customer in the shortest possible time frame [Hajduk 2018]. This means that the customer chooses from several options on the touch screen according to their preferences.

- The first choice is the volume of coffee. The smaller volume is “Espresso” whose volume of the drink is 50 ml. The larger volume is “Coffee” which is 100 ml.
- The second choice is the option to have coffee with or without sugar.
- The third choice is the option to have coffee with or without milk.

The same cup is used to prepare both sizes of drinks. These are environmentally friendly, biodegradable paper cups with a volume of 200 ml. The volume of the cup used is based on the need to subsequently transport it to the event venue. It was necessary to minimize spilled drinks and at the same time ensure that it was possible to hold the cup by its top, which is not hot. The Jura WE6 coffee maker is used to prepare the drinks automatically, which has containers for preparing 25 drinks.

At the same time, the workplace also contains four storage bins with feeders:

1. Cup dispenser SETR GSC5250C18.
2. Sugar hopper and feeder – allows you to dispense hygienically packaged "TUBE" shaped sugar weighing 4 (25x100mm) and 5g (25x125mm).
3. Milk container and feeder weighing 10 g (9.8 ml).
4. Tray and feeder for beverage stirrer, intended for mixing a drink with a size of 1x5x140 mm.

In addition to the mentioned storage units, the workplace is equipped with a pair of storage positions:

5. A place for storing glasses after they have been removed from the tray.
6. A place for storing a technological pallet with dimensions of 74x115x210 mm.

The layout of individual components at the workplace is shown in Figure 1.

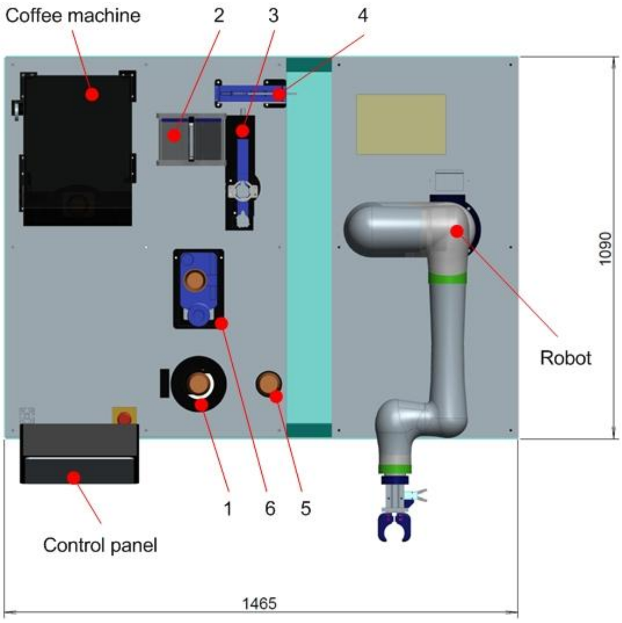

Figure 1. Workplace floor plan with component layout

The supporting structure of the robotic cell is made of closed square steel profiles measuring 40x40x3 mm. The collaborative robot is also mounted on this structure to ensure sufficient rigidity. The auxiliary frame used to place the coffee maker, four containers, a place for transferring cups, and to attach the control panel is constructed of ITEM 40x40 mm system aluminum profiles to reduce the total weight of the cell. Two stainless steel cover plates with a thickness of 2 mm are placed on the structure. The workplace is designed to be independent after being connected to the electrical network (230V, 50Hz), which means that it is also equipped with a silent compressor (Silent MiniAJ30-6RM) for controlling the effectors and containers.

The design of the tanks was based on the requirement of maximum use of 3D printing from PETG material. Pneumatic components from SMC were used to drive the tanks. A 3D view of the workplace is shown in Figure 2.

A combined end effector was designed to implement the manipulation process. The combined effector, Figure 3 consists of a suction cup (1) SMC: ZPT32BU-B5, a double-acting gripper (2) SMC: MHZL2-25D1-M9PL and a single-acting gripper (3) SMC: MHC2-10S-M9PL. The combined effector has the task of gripping a total of five different objects, namely: a paper coffee cup with a volume of 200 ml; sugar packed in a bag weighing 4 or 5 g; a disposable cream package of 10 g, a wooden beverage stirrer for stirring the drink and a technological pallet. A suction cup (1) is used to grip a paper cup from the cup magazine by the bottom of the cup, which then places the cup on the transfer location. The suction cup is also used to hold a disposable cream package. The outer surface of the cup is used to grip and then turn the cup using the fingers of the effector (2). The effector (2) is also used to hold the technological pallet and, using the protrusions shown (highlighted by a solid red line), also to hold a wooden beverage stirrer. The effector (3) serves to hold the packaged sugar from the collection point and is also used to start the selected program on the coffee machine (highlighted by a solid green line).

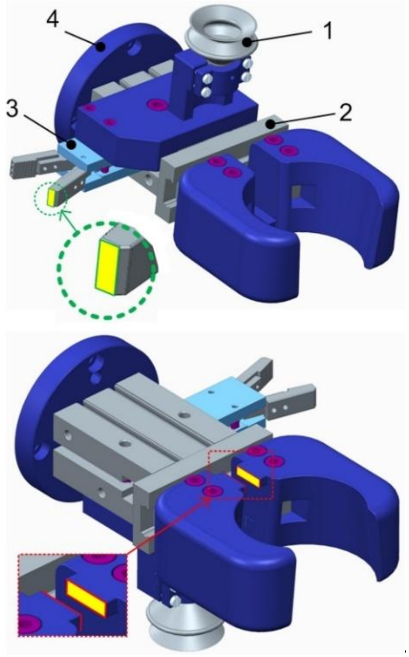

Figure 2. Combined effector in a 3D environment

Figure 3 shows a 3D view of the workplace, where the robot holds a technological pallet in its gripper, which contains a cup of coffee, packaged sugar, and packaged milk.

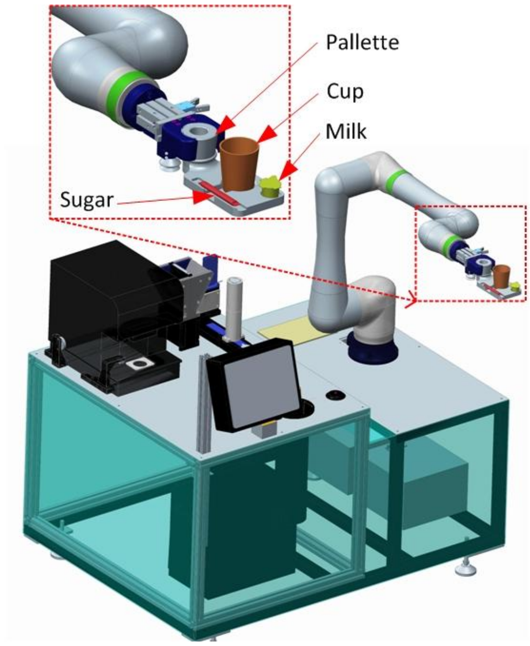

Figure 3. View of the robotized workplace in 3D view

The aim of the presented research was to optimize the manipulation process consisting of adjustments to individual robot trajectories. At the same time, adjustments were made to improve the smoothness of the robot's movement, as well as to maximally prevent the last axis of the robot from spinning. The majority of the optimization process was carried out in the offline Roboguide environment. Verification of the created paths and control of surface-guided compressed air and signal distributions was verified online at the robotized workplace.

3 MATHEMATICAL MODEL OF THE ROBOT

Accurate analysis and control of the FANUC CRX-10iA robot motion requires a complete kinematic model, Fig. 4 that describes the position and orientation of the end effector as a function of time. This model also defines the position progression of the individual links of the mechanism [Marcinko 2024].

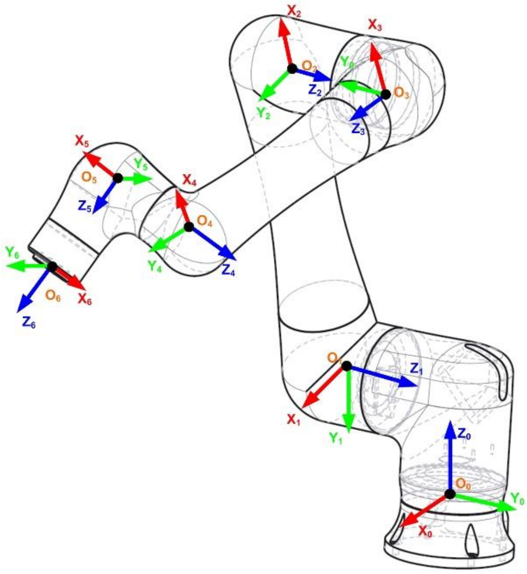

Figure 4. Fanuc CRX-10iA collaborative robot

Since the FANUC CRX-10iA has a serial RRR kinematic structure, the robot kinematics are described using the Denavit-Hartenberg parameters Table 1, which allows for accurate modeling of its motion over time.

Table 1. DH parameters of the Fanuc CRX-10iA robot

Link	$\alpha_i[rad]$	$a_i[mm]$	$d_i[mm]$	$d_i[rad]$
1	-π/2	218	q_1	159
2	0	540	q_2	0
3	-π/2	0	q_3	218
4	π/2	0	q_4	540
5	-π/2	0	q_5	150
6	0	0	q_6	160

Optimizing the robot trajectory is crucial for increasing the efficiency of movements, minimizing cycle time and reducing the load on the drives. By inverse transformation, it is possible to determine the position and rotation curves of individual drives, while the last member of the robot moves at a constant speed with linear approximation. The speed and acceleration of individual drives are calculated by deriving:

$$\dot{q}(t), \ddot{q}(t) \tag{1}$$

To determine the speed of each material point of the part in its local coordinate system, the following equation applies:

$$\omega_i(t) = \omega_{i-1}(t) + \omega_{i-1}^{i} \tag{2}$$

where ω_i is the angular velocity of the coordinate system, ω_{i-1} is the angular velocity of the previous system, and ω_{i-1}^{i} represents the relative angular velocity between two neighbouring systems.
Similarly, the translational velocity can be expressed by the derivative of the position vector:

$$\omega_{i-1}^{i} \begin{cases} k_{i-1}\dot{q} & R \\ 0 & T \end{cases} \tag{3}$$

Dynamic analysis, performed in the Roboguide environment, allowed for the simulation of the position, velocity and acceleration of individual actuators during the measurement. The results show that all joints of the robot contribute to the movement, with the largest change recorded at the 6th joint (J6).
When planning a trajectory, calculations are performed with a sampling period that is determined by the speed of solving the inverse kinematic problem. Sudden changes in motion are eliminated so that the permissible speeds and accelerations of individual drives are not exceeded. The resulting trajectory thus slightly differs from the ideal one due to various factors, such as the positioning accuracy of the drives, the rigidity of the robot and other dynamic influences. Measurements allow identifying actual deviations from the theoretically calculated trajectory.
Homogeneous transformation matrices are used to describe the position and orientation of the members, which are important in the kinematic and dynamic analysis of the robot. The resulting transformation matrix between adjacent coordinate systems is obtained by successive multiplication of partial transformation matrices, thus defining the exact position of the points of the measurement cycle.
Optimization of the motion of the FANUC CRX-10iA robot is necessary to reduce wear of mechanical components, minimize energy consumption and improve the accuracy of work operations. Trajectory control with an emphasis on smoothness and efficiency ensures higher productivity and reliability of industrial processes.

4 RESULTS AND DISCUSSION

The optimization process was carried out primarily in offline simulation using the RoboGuide software, where the dynamics of the robot's movements were analyzed and key problem areas were identified. Based on these analyses, modifications were proposed to improve the robot's trajectory and increase the efficiency of the movements. The following subsections compare the main parameters of the original and optimized versions of the manipulation process, while evaluating critical factors such as cycle time, utilization of individual robot axes and overall smoothness of movement. The goal of the manipulation process optimization was to improve the robot's trajectory in such a way as to minimize redundant movements, increase the overall smoothness of operations and reduce the mechanical load on individual joints [Kelemenova 2022]. A key aspect of the optimization was to eliminate unnecessary overshooting of the last robot axis (J6), thereby achieving a more efficient load distribution and eliminating sudden changes in speed that could negatively affect the wear of mechanical components.
For a better analysis of the optimization, in the first step we focused on comparing the individual times of the subroutines in the overall cycle. The individual times were recorded and compared in Table 2.

Table 2. Comparison of individual subroutine times

Program	Before Optimization [s]	After Optimization [s]	Difference [s]/(%)
Coffee	19.50	14.8	4.51/(23.22)
Milk	6.16	4.62	1.54/(25)
Sugar	6.36	3.04	3.32/(52.20)
Coffee withdrawal	10.84	7.17	3.67/(33.86)
Pallete	13.57	13.38	0.19/(1.40)
Beverage stirrer	11.52	6.89	4.63/(40.19)

The most significant time reduction was observed in the "Beverage stirrer" subroutine, where the time was reduced by 4.63 seconds (40.19%). This subroutine was evaluated as critical because it had the largest share in the total cycle time.

In the original version, the program was structured so that the robot performed individual operations through predefined end positions before moving on to the next step. This caused unnecessary delays, as the robot always had to return to the starting position before starting the next operation. Optimization eliminated these redundant movements, thereby achieving significant time savings and reduced wear on mechanical components. Another important step in the optimization was to adjust the robot path approximations, which increased the smoothness of the movement and reduced the load on individual axes. In the original program, many movements were programmed so that the robot reached a specific point exactly (FINE). While this method of control ensured accuracy, it also caused unnecessary stops between movements, which increased the overall cycle time.

In the optimized version, we therefore used CNT (Continuous Path) values in the range of 50 to 70 where possible. This approach allowed the robot to move smoothly between positions without stopping completely, eliminating the need to reach a precise point. The result of these changes was not only a reduction in subroutine time, but also a significant energy saving and reduction of inefficient movements. This effect can also be seen in the analysis of the speed response of axis 6 in the RoboGuide Profiler, where the optimized version shows lower maximum speed values (22–23 rpm compared to the original 29 rpm) and a significant reduction in oscillations. The change can be seen in Fig. 5 and Fig. 6, where the final part of the program shows the largest differences between the optimized and non-optimized versions.

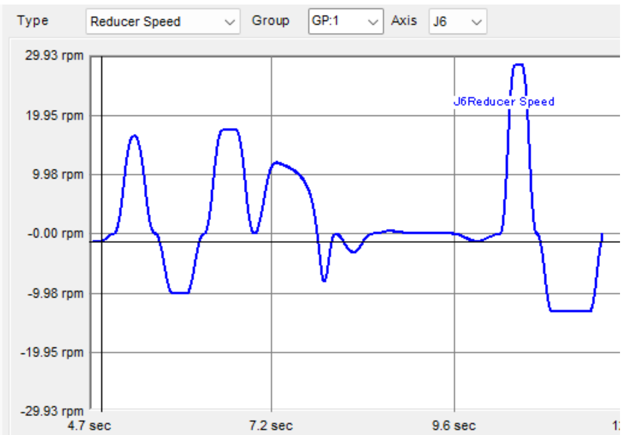

Figure 5. Optimized oscillations on the J6 axis

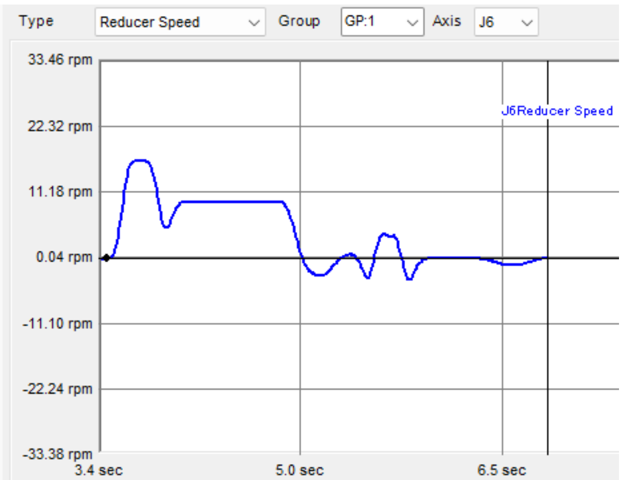

Figure 6. Optimized oscillations on the J6 axis

The optimized version shows a smoother curve, which means smoother speed control and faster stabilization of the movement, which improves the overall stabilization of the robot trajectory.

The last step in optimizing the "Beverage stirrer" program was a visual comparison of the tool orientation course in the robot path. In the first Fig. 7 (non-optimized version), we see that the trajectory contains several points with significant changes in angular velocity, with the maximum value reaching up to 220.63°/s. Such sharp changes cause higher mechanical loads on the robot joints, increase vibrations and can lead to lower accuracy of the operations performed. The colors on the trajectory indicate the rate of changes in speed and orientation, with more intense shades representing more dynamic movements.

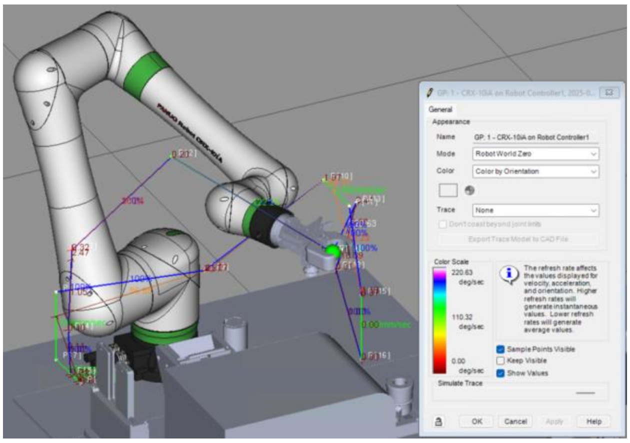

Figure 7. Not optimized robot trajectory

In contrast, Fig. 8 (optimized version) shows a significantly smoother trajectory. It has been modified to minimize abrupt changes in tool orientation. This optimization was achieved in several steps:

- Trajectory smoothing – minimizing sharp changes in joint orientation, resulting in a smoother trajectory.
- Angular velocity reduction – the maximum value has been reduced to 100.45°/s, eliminating extreme speed jumps.
- Better motion distribution – movements are more evenly distributed, preventing sudden accelerations and decelerations.
- Dynamic load reduction – less aggressive movements mean less resistance and less mechanical stress on the robot structure.

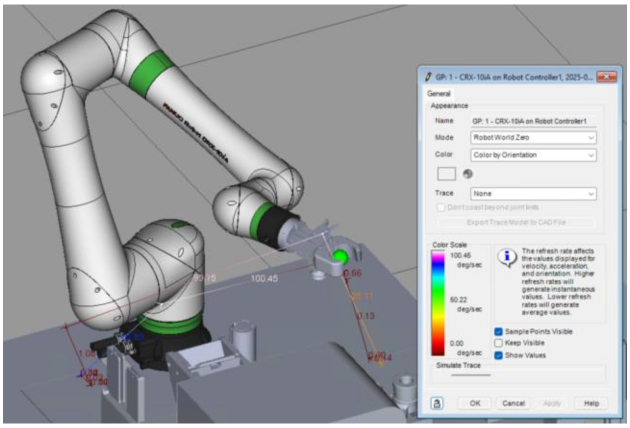

Figure 8. Optimized robot trajectory

Based on the analysis of individual subroutines and subsequent implementation of optimization adjustments, a significant reduction in the total cycle time was achieved. In the original version, the complete cycle was performed in 148.97 seconds, while after optimization this time was reduced to 123.34 s, which represents an improvement of -25.66 seconds (20.75%), Table 3. It should be emphasized that the main cycle runs at only 40% of the robot speed. This speed was chosen intentionally because a higher speed is not necessary for the given type of task, thus ensuring a smooth and safe operation in accordance with the principles of collaborative robotics. The lower speed also contributes to reducing wear on mechanical parts and allows safe work in a shared space with a person without the need for additional protective elements.

Table 3. Comparison of total cycle times

Program	Before Optimization [s]	After Optimization [s]	Difference [s] / (%)
Total time [s]	148.97	123.34	- 25.66/ (- 20.75)
Motion time [s]	140.57	113.13	- 27.45/ (- 19.47)
Delay time [s]	8.38	9.67	1.29/ (15.39)

This reduction was achieved mainly thanks to:

- Streamlining trajectories and eliminating redundant movements, thereby reducing downtime between individual operations.
- Using CNT (Continuous Path) in critical locations, thus ensuring a smoother transition between positions and eliminating unnecessary stops.
- Improving movement speed control, which led to more stable trajectories and less dynamic load on individual robot axes.

Overall, the optimized cycle shows smoother progress, lower maximum speeds and more stable movement dynamics, which positively affected not only the task execution time, but also the overall energy consumption of the system.

In addition to shortening the cycle time, another important aspect was the evaluation of the energy efficiency of the optimized solution.

When analyzing the load on the individual robot axes, it was found that the original version had unnecessarily high peak performances, especially at moments of sharp speed changes and non-smooth transitions between trajectory points, Figure 9.

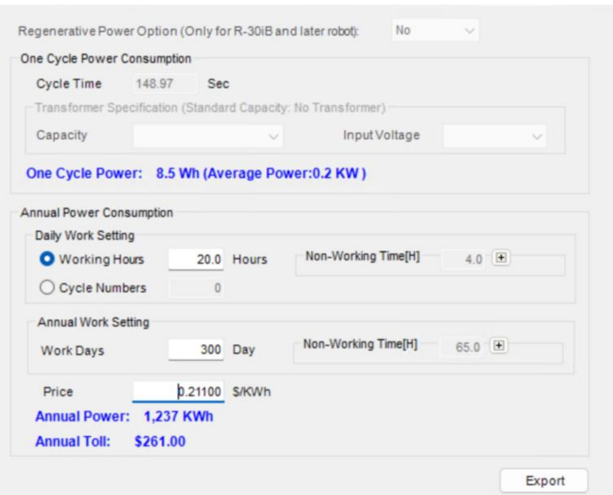

Figure 9. Overview of energy consumption before optimization

Although the optimization of trajectories and the elimination of unnecessary movements led to a reduction in energy per cycle, the overall annual deviation was minimal. This is due to the higher number of cycles performed in the optimized mode, which compensates for the savings at the individual cycle level. The result is more efficient handling with less dynamic load and smoother transitions between movements, while the overall energy impact remains comparable, Figure 10.

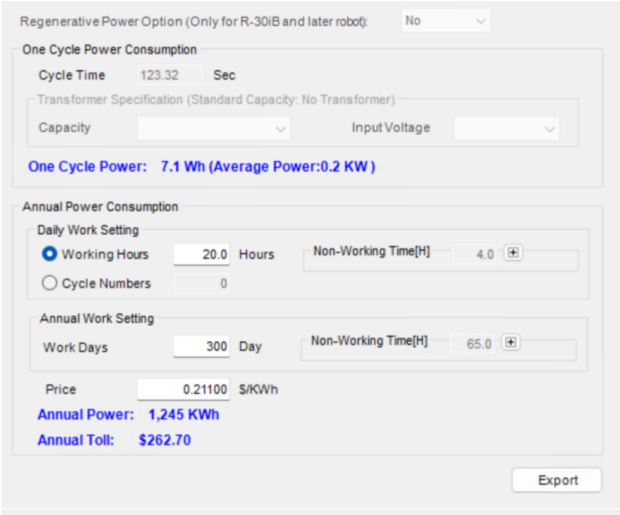

Figure 10. Overview of energy consumption after optimization

These results confirm that motion optimization can have a positive impact not only on robot performance and lifespan, but also on energy efficiency, which is a key factor in the long-term operation of industrial robots [Lekomtsev 2020].

CONCLUSIONS

Based on the implemented optimization of the entire work cycle of a robotic cell equipped with a collaborative robot, it is possible to state a significant improvement in the resulting cycle time. By focusing primarily on the critical operation (subroutine "Beverage stirrer"), it was possible to significantly reduce the working time at the workplace. Optimization focused on smoothing the transitions between individual points of the trajectory (Continuous Path) achieved smoother robot operation, which leads to smoother robot movements and a reduction in its load. The total savings achieved in the cycle time of the robotic cell after the optimization represents a value of 25.66 seconds.

ACKNOWLEDGMENTS

This research was supported by the project IVG-24-01 EspressoBot: Innovative coffee brewing system with collaborative robot FANUC CRX 10iA; the research was supported also within projects: VEGA 1/0215/23 - Research and development of robotic workplaces equipped with industrial and collaborative robots; KEGA 043TUKE-4/2024 - Creation of prospective educational tools for the field of additive manufacturing with the implementation of progressive elements of virtual reality; and, this work was supported also by the Slovak Research and Development Agency under the Contract No. APVV-18-0413.

REFERENCES

[Akbari 2023] Akbari, A., et al. Movement Optimization of Robotic Arms for Energy and Time Reduction using Evolutionary Algorithms. 0.48550/arXiv.2306.05329.

[Benotsmane 2020] Benotsmane, R., et al. Trajectory Optimization of Industrial Robot Arms Using a Newly Elaborated "Whip-Lashing" Method. Applied Sciences, 2020, Vol. 10, 8666. doi.org/10.3390/app10238666.

[Bozek 2021] Bozek, P., Krenicky, T., Nikitin, Y. Editorial for Special Issue "Automation and Robotics: Latest

Achievements, Challenges and Prospects". Appl. Sci., 2021, Vol. 11, 12039. https://doi.org/10.3390/app112412039.

[Chen 2013] Chen, Y., et al. Optimal trajectory planning for industrial robots using harmony search algorithm. Industrial Robot: An International Journal, 2013, Vol. 40, No. 5, pp. 502-512.

[Chen 2018] Chen, Y. and Li, L. Predictable Trajectory Planning of Industrial Robots with Constraints. Applied Sciences, 2018, Vol. 8, 2648. doi.org/10.3390/app8122648.

[Devi 2021] Devi, M., et al. Minimum Jerk Trajectory Planning of PUMA560 with Intelligent Computation using ANN. In: 6th Int. Conf. on Inventive Computation Technologies (ICICT 2021), 2021, pp. 544-550. 10.1109/ICICT50816.2021.9358674.

[Gauthier 2008] Gauthier, J.F., et al. Optimization of a Test Trajectory for SCARA Systems. Advances in Robot Kinematics: Analysis and Design. Springer: Dordrecht. doi.org/10.1007/978-1-4020-8600-7_24.

[Hajduk 2018] Hajduk, M., et al. Principles of Formation of Flexible Manufacturing Systems. Tehnicki vjesnik, 2018, Vol. 25, No. 3, pp. 649-654. doi.org/10.17559/TV-20161012132937.

[Han 2021] Han, S., et al. Industrial robot trajectory planning based on improved PSO algorithm. Journal of Physics: Conference Series, 2021, p. 012185.

[Kelemenova 2022] Kelemenova, T., et al. Verification of the torque gauges. MM Science Journal, 2022, pp. 5533-5538. DOI: 10.17973/MMSJ.2022_03_2022014.

[Lekomtsev 2020] Lekomtsev, P.V. Prediction of residual life of complex electromechanical systems based on small training samples. IOP Conference Series: Materials Science and Engineering, 2020, Vol. 971. DOI: 10.1088/1757-899X/971/5/052019.

[Marcinko 2024] Marcinko, P., et al. Analysis of the Methodology for Experimental Measuring of the Performance Criteria of the Laser-Using Collaborative Robot's Path Accuracy. Applied Sciences, 2024, Vol. 14, 1414. doi.org/10.3390/app14041414.

[Perez-Carabaza 2018] Perez-Carabaza, S., et al. Ant colony optimization for multi-UAV minimum time search in uncertain domains. Applied Soft Computing, 2018, Vol. 62, pp. 789-806.

[Segota 2021] Segota, S.B., et al. Utilization of multilayer perceptron for determining the inverse kinematics of an industrial robotic manipulator. Int. J. of Adv. Robotic Systems, 2021, Vol. 18, Iss. 4. DOI: 10.1177/1729881420925283.

[Stilman 2020] Stilman, M. Global Manipulation Planning in Robot Joint Space with Task Constraints. IEEE Transactions on Robotics, 2010, Vol. 26, No. 3, pp. 576-584. DOI: 10.1109/TRO.2010.2044949.

[Su 2018] Su, T., et al. Time-Optimal Trajectory Planning for Delta Robot Based on Quintic Pythagorean-Hodograph Curves. IEEE Access, 2018, Vol. 6, pp. 28530-28539. DOI: 10.1109/ACCESS.2018.2831663.

[Trojanova 2021] Trojanova, M., et al. Estimation of Grey-Box Dynamic Model of 2-DOF Pneumatic Actuator Robotic Arm Using Gravity Tests. Applied Sciences, 2021, Vol. 11, No. 10, Art. No. 4490.

[Wang 2020] Wang, W., et al. Robot Time-Optimal Trajectory Planning Based on Improved Cuckoo Search Algorithm. IEEE Access, 2020, Vol. 8, pp. 86923-86933. DOI: 10.1109/ACCESS.2020.2992640.

[Wu 2022] Wu, P., et al. Optimal Time–Jerk Trajectory Planning for Delta Parallel Robot Based on Improved Butterfly Optimization Algorithm. Applied Sciences, 2022, Vol. 12, 8145. doi.org/10.3390/app12168145.

[Xiuli 2022] Xiuli Y., et al. Time-optimal trajectory planning of manipulator with simultaneously searching the optimal path. Computer Communications, 2022, Vol. 181. doi.org/10.1016/j.comcom.2021.10.005.

[Yu 2018] Yu, R., et al. Time-optimal trajectory planning of robot based on breed algorithm. Mech. Drive, 2018, Vol. 42, pp. 55-59.

[Yuhang 2018] Yuhang L., et al. An approach for smooth trajectory planning of high-speed pick-and-place parallel robots using quintic B-splines. Mechanism and Machine Theory, 2018, Vol. 126. doi.org/10.1016/j.mechmachtheory.2018.04.026.

[Zhang 2016] Zhang, Q., et al. Time-optimal path tracking for robots under dynamics constraints based on convex optimization. Robotica, 2016, Vol. 34, No. 9, pp. 2116-2139. DOI: 10.1017/S0263574715000247.

[Zhang 2019] Zhang, X.Q., et al. Trajectory Planning and Optimization for a Par4 Parallel Robot Based on Energy Consumption. Applied Sciences, 2019, Vol. 9, 2770. doi.org/10.3390/app9132770.

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