The influence of computer-generated path on the robot’s effector stability of motion

K Foit\textsuperscript{1}, W Bana\textsuperscript{ś}\textsubscript{2}, A Gwiazda\textsuperscript{3}, G Ćwikła\textsuperscript{4}

\textsuperscript{1,2,3,4}Silesian University of Technology, Faculty of Mechanical Engineering, Institute of Engineering Processes Automation and Integrated Manufacturing Systems, Konarskiego 18A, 44-100 Gliwice, Poland

E-mail: krzysztof.foit@polsl.pl

Abstract. The off-line trajectory planning is often carried out due to economical and practical reasons: the robot is not excluded from the production process and the operator could benefit from testing programs in the virtual environment. On the other hand, the dedicated off-line programming and simulation software is often limited in features and is intended to roughly check the program. It should be expected that the arm of the real robot’s manipulator will realize the trajectory in different manner: the acceleration and deceleration phases may trigger the vibrations of the kinematic chain that could affect the precision of effector positioning and degrade the quality of process realized by the robot. The purpose of this work is the analysis of the selected cases, when the robot’s effector has been moved along the programmed path. The off-line generated, test trajectories have different arrangement of points: such approach has allowed evaluating the time needed to complete the each of the tasks, as well as measuring the level of the vibration of the robot’s wrist. All tests were performed without the load. The conclusions of the experiment may be useful during the trajectory planning in order to avoid the critical configuration of points.

1. Introduction

The industrial robots play a key role in the automation of manufacturing systems. Because they are universal machines that are controlled by a program, the field of their possible applications is constantly growing. The most important factor of the nowadays manufacturing is the continuity of the production process. It is required that all machines will work without the break, but pauses may be necessary to provide the process of reprogramming. In such situation, the objective is to make the break as short as possible, what could be fulfilled by preparing the program in the virtual environment, using the off-line programming application.

The off-line programming involves writing the code, without the physical presence of the machine, for which the program is intended. This may cause several problems with accuracy, because there may be physical differences (in the meaning of tolerances) between the particular units. What is more, the specificity of the drives may cause different effects on different machines. Such problems should be considered also in the case of robots’ manipulators.

The process of the off-line programming of the robot is closely tied to the computer simulation of the performance of the robot’s program. However the detailed information about the dynamics of robot’s manipulator could be available only in the specialized application, dedicated to the particular
type of the robot or as a result of measurements carried out on the real object [1]. Other, especially the self-developed applications, does not take into account dynamic parameters [2-4]. Speaking generally, the programmer has the information if the path is properly programmed, but has no information about the behaviour of robot’s kinematic chain (vibrations, accelerations etc.). Such data may be important during planning the complicated paths where many points are arranged at different distances between them. The off-line programming of the robot has also strong link with the accuracy. Nubiola et al. point out that “in offline programming, accuracy becomes important, since positions are defined in a virtual space with respect to an absolute or relative coordinate system” [5].

The aim of this paper is to consider the influence of the distribution of points along the path that is realized by the robot. This work should give the preliminary conclusions about the behaviour of the kinematic chain of the particular industrial robot. As the consequence, the initial findings may be used in the further work, in order to define the outlines for optimal distribution of the points along the path.

2. Justification for the experiment
The robot’s manipulator can realize the trajectory in two different manners. The first one is less precise, because the consecutive points may be roughly reached by the tool – this mode is often used during manipulation tasks, providing the fast realization of the task (fast motion of the tool) and minimizing the consumption of electrical energy. The price for efficiency is that the tool may not reach every point exactly (as it is written in program) but passes nearby the point. Such approach cannot be accepted if the task requires the proper level of precision, like grinding, cutting, sealing mass application etc. In the cases that require high precision, the other method of the trajectory realization is used, where all of the defined points are reached accurately. The considerable disadvantage of this method results from the way in which the manipulator is moved – because each point must be reached precisely, the robot’s controller stops the manipulator for the moment in this point. Regarding the manner in which the manipulator moves, the move from one point to another involve three phases: acceleration, uniform motion and deceleration (figure 1). Repeating the phases of motion for each point of trajectory results in the induction of vibrations and decreasing of the average velocity of motion.

![Figure 1. Three phases of the tool’s motion (a) and the decrease of the maximum effector’s speed in the case of the dense arrangement of trajectory points.](image)

The problem of the tool vibration during robot-based machining or realization of precise tasks is widely discussed in the available literature. The research covers wide range of topics, from the counteracting vibrations through appropriate control of the drives [6-8], through the impact of vibration on the tool wear [9], to the cause of transmission of vibrations to the object being manipulated [10]. Elvira-Ortiz et al. [11] also note that the vibrations of the manipulator have a significant impact on the positioning accuracy, because of the distorted readings of the sensors, due to contamination by the noise. It should be noted that the oldest publications on the subject of impact of the manipulator’s vibrations on aspects related to its kinematics and dynamics were published over 30
years ago. Today, due to the increasing requirements for accuracy and speed during realization of tasks with the use of industrial robots, these issues are still topical in the recent years and are the subjects of many publications.

3. The setup of the experiment
The experiment has been carried out on the Fanuc ARC Mate 100iB robot (figure 2). The measurement of vibration has been performed using the XSENS wireless sensor. The sensor was mounted on the third arm of the manipulator, which is directly connected to the last, revolving axis and the tool. The wireless method of data transmission is very reliable, because every data sample has a timestamp and the connection uses synchronous mode. Moreover, the lack of the cable eliminates its influence on the measurements results (both electrical noise and mechanical disturbances). The mass of the sensor (with battery) is negligibly small in comparison to the mass of robot’s manipulator.

![Figure 2. The subject of the experiment: Fanuc ARCMate robot.](image)

Because the sensor consists of several components that can collect the information about its orientation, acceleration and even magnetic field, in the experiment only the accelerometers were used. At this phase of research, the values of the acceleration were not as important as the changes of values in different stages of the experiment. Such approach, in the future may allow comparing the different robots acting in the same condition, without regarding their technical details.

The experiment has been performed in the following manner:

- For the purposes of this test, a 600 mm rectilinear section of the trajectory has been selected,
- In each stage of the experiment, the section of trajectory has been defined by different number of equally distributed points,
- The robot’s arm must achieve each of trajectory points exactly,
- During the realization of the program, the values of the acceleration of the third arm of manipulator have been collected as well as the time of program processing has been measured.
The measurements were performed with the limited accuracy. The acceleration was measured with the 120 samples per second sample rate, while the time of program processing was measured manually from the start of program to the end of last move. According to the Nyquist-Shannon theorem, the effective reconstruction of signal is guaranteed to the ca. 60 Hz bandlimit. It is enough for doing preliminary conclusion, as it was initially assumed. All the tests were performed using point-to-point method of realization of the path, with maximum speed of motion set to 2000 millimeters per second.

4. The results of the tests

The tests results are summarized in the form of tables and graphs.

4.1. Measurement of the program realization time

The results are shown in table 1.

| Run number | Number of points | Time [s] | Theoretical time of single step [s] | Average velocity [mm/s] |
|------------|------------------|----------|-------------------------------------|------------------------|
| 1          | 3                | 1.7      | 0.56                                | 352.9                  |
| 2          | 6                | 2.6      | 0.43                                | 230.77                 |
| 3          | 12               | 4        | 0.33                                | 150                    |
| 4          | 24               | 8        | 0.33                                | 75                     |
| 5          | 60               | 18       | 0.3                                 | 33.33                  |
| 6          | 120              | 34       | 0.283                               | 17.65                  |
| 7          | 600              | 80       | 0.13                                | 7.5                    |

4.2. Measurement of the acceleration

The results of the acceleration measurements are shown in figures 3-7.

Figure 3. The acceleration of the effector: 600 mm long trajectory, 120 points.
**Figure 4.** The acceleration of the effector: 600 mm long trajectory, 60 points.

**Figure 5.** The acceleration of the effector: 600 mm long trajectory, 24 points.
Figure 6. The acceleration of the effector: 600 mm long trajectory, 6 points.

Figure 7. The acceleration of the effector: 600 mm long trajectory, 3 points.

All of the figures present the full measurement scope, but the time scale may differ, because the data collection has been started before the start of the robot’s program. The meaningless parts of the graph were trimmed, but each plot starts with the impulse that is the result of moving the manipulator’s arm to the “zero” point (start of the trajectory). This is because in the real situation, the
robot does the same: the tool is moved from any position in workspace to the starting point of a trajectory and then the process starts. Reaching of the “zero” point is then connected with the vibration of the tool.

5. Discussion

The test have been carried out in order to answer the question how the distribution and the number of points, that determine the robot’s path, affects the vibrations and speed of effector. All of the measurements were done without the load of kinematic chain. The sensor was mounted on the third arm, which is directly connected to the wrist.

![Figure 8. The dependence of velocity on the number of trajectory points.](image_url)

The figure 8 presents the dependence of the effector speed on the number of trajectory points. It can be seen that the speed significantly decreases as the number of trajectory points increases. The greatest drop in speed is observed in the range of up to 100 points, what in the case of a 600 mm long section of trajectory means that the consecutive points are placed every 6 mm. On the other hand, it means that the value of velocity, written in the program code, will be ineffective in relation to the path, which consists of large number of points.

![Figure 9. The modulated signal of acceleration.](image_url)
Referring to the problem of vibrations, the biggest values of acceleration were observed during the processing the trajectory with the smallest number of points – what is convergent with the intuitive approach. The problem of finding the proper number of points (and simultaneously the distance between them) becomes harder if we take into consideration the graphs that illustrate the level of acceleration during the realization of path with dense distribution of points (figure 3-5). It could be seen, that the recorded signal is modulated – there are also other frequencies that are meaningful during processing the program and have significant influence on the effector vibrations (figure 9).
Without additional research, it is difficult to conclusively state the cause of their origination, but probably they may originate from the vibration of other links of the kinematics chain of the manipulator or from the drives.

6. Conclusions
The vibrations of the robot’s tool and their influence on the accuracy are the viable subjects of research. This paper includes in this trend, focusing on the processing of the off-line generated trajectories and the influence of the distribution of points along the path on the effector’s stability of motion. The preliminary findings points out that the question of the path optimization is more complex problem – it depends not only on particular robot (brand, type), but also on the working conditions in which the robot processes the program: in the described case, more investigation is needed to explain the problem of the modulating frequencies during processing the path with dense distribution of points. The measurements should be performed on all of the manipulator’s arms with the use of sensors of higher class. Further work will also continue the searching for the optimal distribution of points along the path for the Fanuc ARCMate robot taking into account the stability of the tool’s motion (velocity vs. vibrations).

7. References
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