AUTOMATED RESEARCH OF TRAJECTORY PROBLEMS IN INDUSTRIAL ROBOTICS BY THE CRITERION OF POWER CONSUMPTION

Valerii KYRYLOVYCH[*], Petro MELNYCHUK[*], Lubomir DIMITROV[**], Roman MORGUNOV[*], Aleksandr PIDTYCHENKO[***]

[*] Zhytomyr State Technological University, Ukraine

[**] Technical University of Sofia, Bulgaria

Abstract. The modeling of the movements of industrial robots' grippers between two random points of its (industrial robots) working area with generation of appropriate trajectories is presented. The values of power consumption for each trajectory are determined. Examples of trajectories based on the criterion of minimum power consumption for each generated trajectories are presented. For modeling was used developed by authors special program.

Keywords: industrial robot, trajectory, modeling, power, automation

1. Introduction

According to the International Federation of Robotics (IFR) the number of industrial robots (IR) installations in the manufacturing sector is growing rapidly every year [1], which certainly points to the need and expediency of carrying out research related to the effective use of IR. Reducing the cost of robotic manufacturing processes has always been and remains one of the major problems which need to be solved when designing and synthesis of robotic mechanical assembly technology (RMAT).

One of the key components of automated synthesis (AS) RMAT is solving the trajectory of tasks, including trajectories planning in IR's working area by relevant criteria, such as trajectory's working time, IR's power consumption, accuracy of gripper's (Gr) pole movement etc.

For today the problem of determining such a change of generalized coordinates (GC) of IR's links, which ensures minimum power consumption when GrIRR moves between somehow defined or specified anchor points of the trajectory is still unresolved.

The purpose of work is to highlight and illustrate the capabilities of developed program for trajectories generation that are processed with the possible values of optimizational parameters of their implementation, such as performance and energy efficiency.

2. Brief description of the developed program

In Zhytomyr State Technological University (ZSTU) in close cooperation with the Technical University of Sofia (TUS) was developed the program for researching the trajectory's movement tasks of Gr and IR's links by performance criterion (in the future - cyclic performance) and energy-saving criteria - minimum power consumption. The last criterion is technical and can be defined by its (power) cash equivalent, taking into account the cost of 1 kW of power for industry.

The program was written in the programming language "Delphi" and requires the use such OS: Windows XP/Windows Vista/Windows 7/Windows 8.

The features of developed program are:

– the build of 3D models of flexible manufacturing cell's (FMC) structural elements, with using, for example, IR's mathematical models of manipulation system (MS) and Gr [2, 3], which are based on the mathematical theory of quaternions;

– the build of Gr's pole's initial trajectory moving;

– manual and / or automated changing of the activated GC for the analyzed conditions: the sequence of working, and the performance, which automatically leads to the generation of new trajectories moving of Gr and links of IR's MS;

– manual and / or automatic setting of GC's work by changing the beginning and finishing of each GC and their arbitrary set;

– the building of graphing of linear velocity and acceleration, angular velocity and acceleration, MS's links torques by recursive Newton-Euler method [4], the power consumption of each activated MS's link and their total value, with taking into account the most performance work for each GC by preset or minimum possible time.

Methodical basis for solving most of mentioned problems are the methods for solving direct and inverse problems of kinematics and dynamics.

Debugging of developed program's functionality was performed using the program RoboAnalyzer [5].

3. Summary of research

Let need to generate a move of Gr between randomly selected points T1 and T2 in IR's working area and analyze possible trajectories, calculate the value of the power consumption N (in [W]) with their relative deviations (in [%]) for the trajectory with minimum power value, duration of generated working trajectories τ_{T1-T2} (in [s]) and their relative deviations on the lowest value of τ_{T1-T2}.

The input data chosen for research are following:

1. Formalized descriptions of FMC's structural elements:

– IR mod. KUKA KR-30-3 [6], kinematic structure of which is shown in Figure 1:

KUKA KR-30-3 = {P:0,0,0; O:1,0,0,0; L1:(D:0,1,0; S:350; GP:[cr:0,0,0,300,350;]); L2:(D:0,1,0; S:150; Qmin:0.001,0,1,0; Qmax:0.001,0,-1,0; GP:[cr:0,0,0, 300,150;]); L3:(D:1,1,0; S:450; GP:[tz:220,220, -100,200,400,600,500,300,0,0.924, 0,0,0.383;]); L4:(D:-1,1,0; S:850; Qmin:0.924,0,0,0.383; Qmax:0.462,0,0,-0.887; GP:[cr:0,0,0,150,300,0.707, 0.707,0,0; pd:0,0,200,850,250,200;]); L5:(D:-1,0,0; S:145; Qmin:0.500,0,0,0.866; Qmax:0.191,0,0, -0.982; GP:[cr:0,0,0,150,300,0.707,0.707,0,0; pd: -50,-150,0,400,500,200;]); L6:(D:1,0,0; S:350; GP:[cr:0,0,0,100,350;]); L7:(D:0,1,0; S:465; Qmin:0.001,0,1,0; Qmax:0.001,0,-1,0; GP:[cr:0,0,0, 100,150; pd:0,150,0,200,100,100; pd:0,310,-60,200, 100,30; pd:0,310,60,200,100,30;]); L8:(D:0,1,0; S:170; Qmin:0.508,0,0,0.862; Qmax:0.508,0,0, -0.862; GP:[cr:0,0,0,50,170;]); L9:(D:0,1,0; S:10; Qmin:0.001,0,1,0; Qmax:0.001,0,-1,0; GP:[cr:0,0,0, 40,10;]); }.

Passport maximum speed of working GC in joints J1..J6, ie relevant MS' links (listed in parentheses) [6]:

J1 (l_1-l_0) 140 °/s (2.44 rad/s);
J2 (l_3-l_2) 126 °/s (2.20 rad/s);
J3 (l_4-l_3) 140 °/s (2.44 rad/s);
J4 (l_5-l_4) 260 °/s (4.54 rad/s);
J5 (l_7-l_6) 245 °/s (4.28 rad/s);
J6 (l_8-l_7) 322 °/s (5.62 rad/s).

– Gr mod. Schunk LGR 32 [7]:

Schunk LGR 32 = {CFP[(0, 0, 0)(0.707106781, 0,0,0.707106781)]C{pd[(130.5, 60, 37)(0, 0, 0)]} V{lim[(0, 119, 24, 0)(0, 119, 24, 0)(1, 0, 0, 0)(0.71, 0, 0, 0.71)]pd[(30, 12.5, 16)(-15, 0, 0)]pd[(30, 12.5, 16)(15, 0, 0)]pd[(58, 14, 16)(20, 12.5, 0)]pd[(40, 12.5, 16)(42.5, 0, 0)(0.9848,0,0,0.1736)]pd[(40, 12.5, 16)(76, 13.2, 0)(-0.9848,0,0,0.1736)]pd[(6, 11.5, 16) (110, -0.5, 0)]}V{lim[(0, 119, -24, 0)(0, 119, -24, 0)(1, 0, 0, 0)(0.71, 0, 0, -0.71)]pd[(30, 12.5, 16)(-15, 0, 0)]pd[(30, 12.5, 16)(15, 0, 0)]pd[(58, 14, 16)(20, -12.5, 0)]pd[(40, 12.5, 16)(42.5, 0, 0)(-0.9848,0,0, 0.1736)]pd[(40, 12.5, 16)(76, -13.2, 0)(0.9848,0,0, 0.1736)]pd[(6, 11.5, 16)(110, 0.5, 0)]}}.

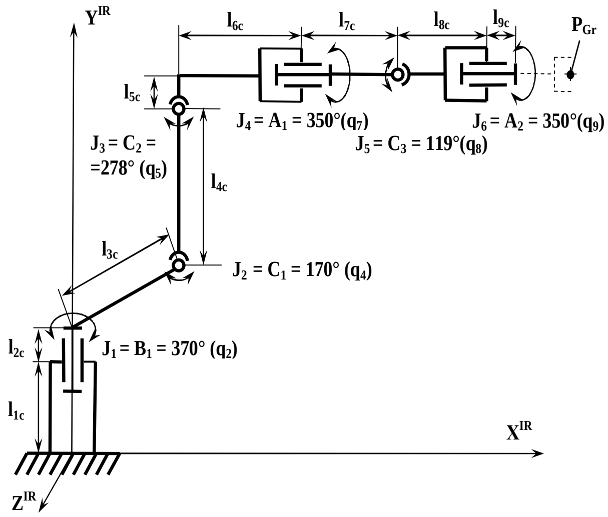


Figure 1. Kinematic structure of MS if IR mod. KUKA KR-30-3

2. Coordinates, in mm, of randomly selected position points T1 and T2 are following:

T1: X = 2234.8; Y = 1012.9; Z = 0;
T2: X = 996.1; Y = 1327.8; Z = 1110.1.

3. The maximum duration of working between selected points T1 and T2 [τ_{T1-T2}] = 2 seconds (special case, see option 10 in Table 2).

4. Amount of:

active links of IR's MS n = 6 [3];
activated links n = 6;
total links n_l = 9;
trajectory's generated intermediate points used in modeling, 1000.

5. For analyzed points T1 and T2 the initial and final values of GC, and also the values of their changes |Δq| in the notation of Figure 1 are listed in Table 1.

Table 1. Initial (q_{T1}) and final (q_{T2}) values of GC, in [°]

	q_2	q_4	q_5	q_7	q_8	q_9
q_{T1}	223.1	51.0	216.8	208.6	159.4	320.1
q_{T2}	180.0	102.0	172.3	180.0	118.9	180.0
|Δq|	43.1	51.0	44.5	28.6	40.5	140.1

The research which has been held with randomly selected conditions are following:

▶ two options of change of direction of GC of IR's MS: from the first link of IR's MS (base) to Gr (final link of IR's MS) and reverse direction – from the Gr to the base link of IR's MS (see options 1-7, 9 in Table 2). For each option of change of direction GC of IR's MS were selected the next working durations of GC:

- smallest duration of movements caused by the maximum allowable speed for GC by passport data of IR's MS [6];
- the duration of all links of MS for 1 second;
- the reducing of duration of GC working was calculated by the expression:

$$\tau_{q_{l_i}} = \tau_{T1-T2} + \frac{n_l - i_l}{n_l} \cdot \tau_{T1-T2}, \quad (1)$$

where $\tau_{q_{l_i}}$ – duration of working relevant GC by l_i link; τ_{T1-T2} – the movement time of Gr's pole P_{Gr} from T1 to T2; n_l – total amount of links of IR's MS; i_l – sequence number of link of IR's MS;

- the increasing of duration of GC working was calculated by the expression:

$$\tau_{q_{l_i}} = \tau_{T1-T2} + \frac{i_l}{n_l} \cdot \tau_{T1-T2}; \quad (2)$$

- ▶ simultaneous working start of GC with the largest permissible rate of change GC;
- ▶ simultaneous working completion of GC with the largest permissible rate of change GC;
- ▶ simultaneous start and completion at the same time working of GC for 2 seconds;
- ▶ the search of GC sequence work for IR'S MS with with positional CNC and with minimal power consumption.

For each option of research (see Table 2) by computer modeling the calculation of IR's MS's powers caused by Gr's pole P_{Gr} moves from T1 to T2 by generated trajectories was carried out. Generated trajectories were built by displacement of the duration of each GC in a given time interval [0, 2] seconds, with time step $\Delta\tau = 0.1$ second. For IR's MS with positional CNC necessary observe the strict sequence of GC so for this case the exhaustive search of sequences of activated GC was implemented, the number of analyzed options equal n = 6! = 720.

Obtained results of power values for each option of research are ranked in increasing order from lowest to highest and presented in Table 2, where:

option 1 – reducing the duration of GC's working from the first link (rack) of IR's MS to Gr;
option 2 – reducing the duration of GC's working from Gr to the first link of IR's MS;
option 3 – duration of activated GC's working for one second from Gr to the first link of IR's MS;
option 4 – duration of activated GC's working for one second from the first link of IR's MS to Gr;
option 5 – increasing the duration of GC's working from the first link of IR's MS to Gr;
option 6 – increasing the duration of GC's working from Gr to the first link of IR's MS;
option 7 – GC's working from the first link of IR's MS to Gr with the highest allowable speed;
option 8 – simultaneous start and completion at the same time of GS's working;
option 9 – GC's working from Gr to the first link of IR's MS with the highest allowable speed;
option 10 – GC's working with the highest allowable speed for MS with positional control system;
option 11 – simultaneous completion of GC's working with the largest allowable speed;
option 12 – simultaneous start of GC's working with the largest allowable speed.

4. Conclusions

As shown by modeling results for listed cases (see Table 2) between randomly selected anchor points T1, T2 within the IR's working area the new trajectories which are processed with corresponding power consumption are generated.

The trajectory with minimum power consumption for each of the generated trajectories is determined. Duration of Gr's movement for given anchor points considering maximum working speed of activated GC is calculated. For example, the minimum energy-intensive trajectory was received in option 1 in Table 2 (N = 2009.42 W), and the most energy-intensive trajectory corresponds to option 12 in Table 2 (N = 4553.89 W) that 2.27 fold exceeds the power of option 1.

However the option 12 is characterized by the highest speed (τ_{T1-T2} = 0.9 seconds), and the longest by time trajectory (option 10) is worked for 3.9 seconds, that is 3.33 fold slower than working the trajectory of options 12 and 11. This enables to choose the trajectory by the criterion of speed and the criterion of power.

Particular importance is developed for research of IR with positional CNC. In this case by the method of exhaustive search for the conditions of the research the minimal power consumption and the duration of the trajectory (see option 10, Table 2) are defined. Obviously, in this case it is possible to generate trajectories between randomly selected points when $n \neq 6$.

For IR with contour CNC there are obvious opportunity to choose for different modeling conditions the trajectory with the lowest power consumption (see option 1, Table 2) or the trajectory with the highest speed (see option 11 and 12, Table 2).

Table 2. The results of research

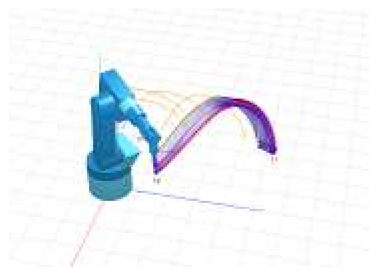
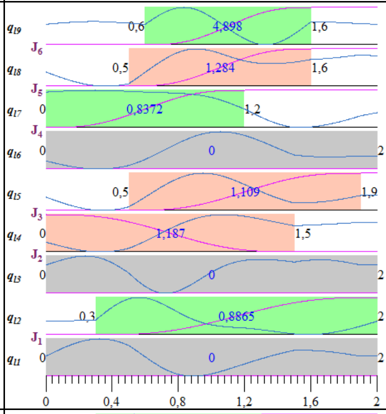
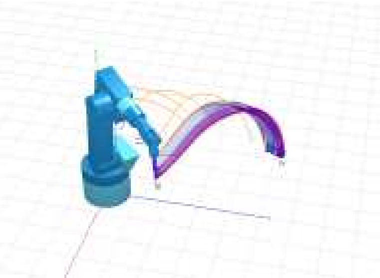
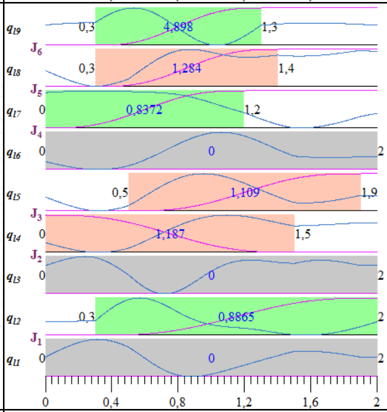
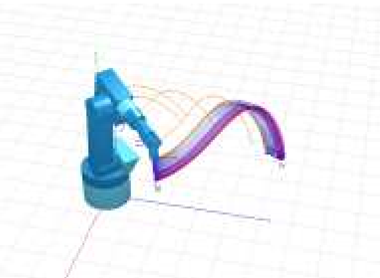
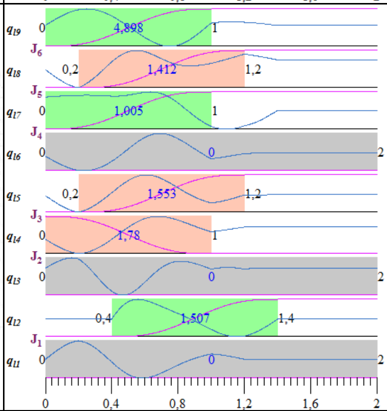
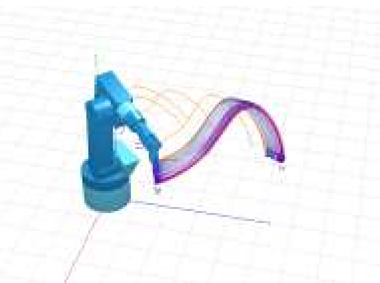
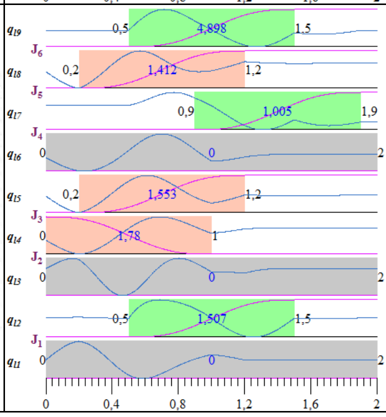
№ crt.	IR's trajectory	Duration of activated GC's motion	N [W]	ΔN [%]	$\tau_{T1\text{-}T2}$ [s]	$\Delta\tau_{T1\text{-}T2}$ [%]
1			2009.42	0	2	122.22
2			2022.49	0.65	2	122.22
3			2054.70	2.25	1.4	55.55
4			2088.07	3.91	1.9	111.11

Table 2. Continuation

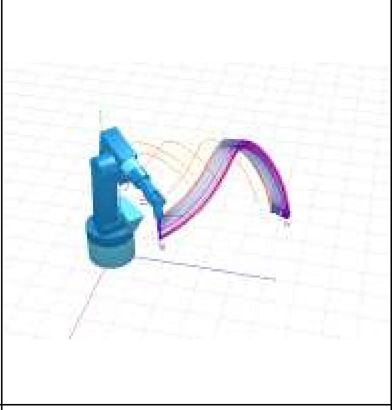
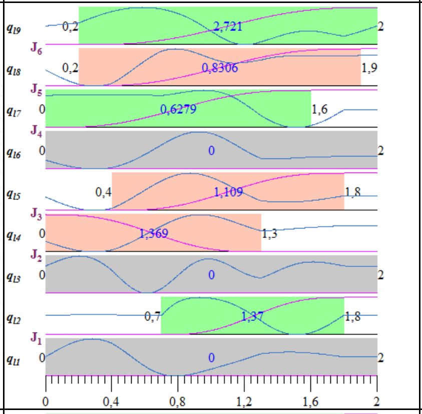
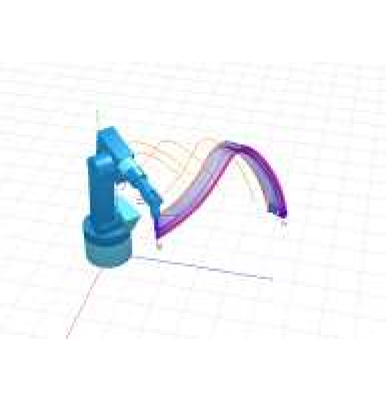
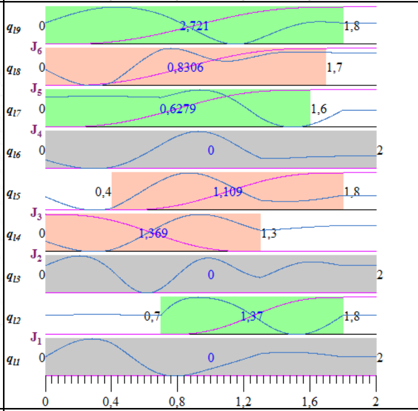
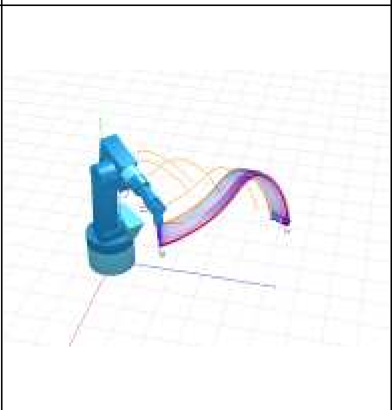
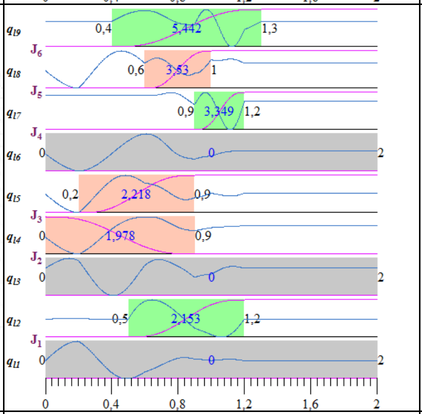
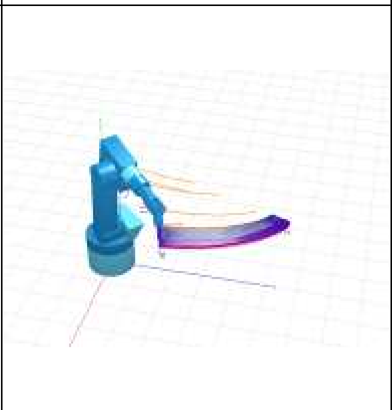
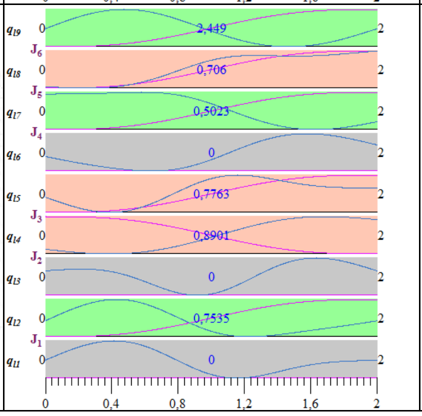
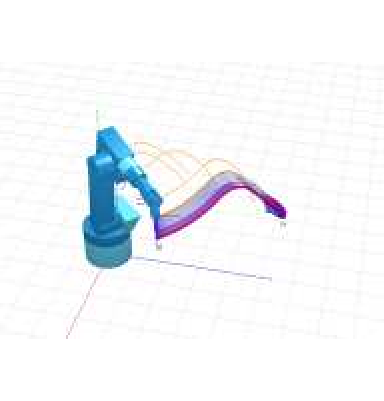
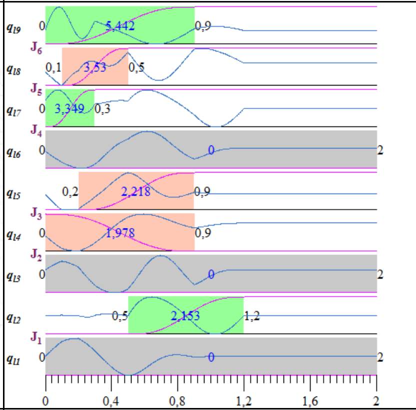
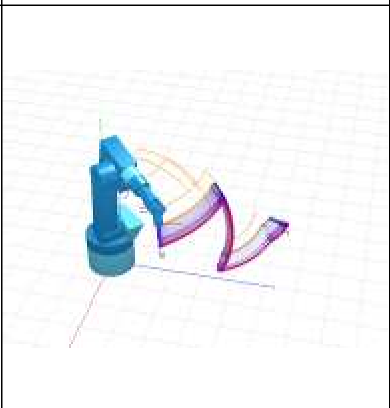
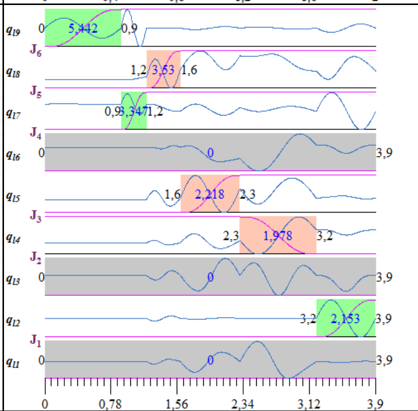
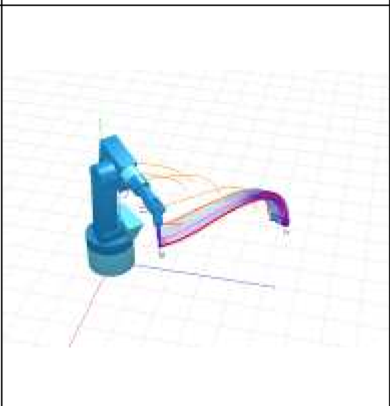
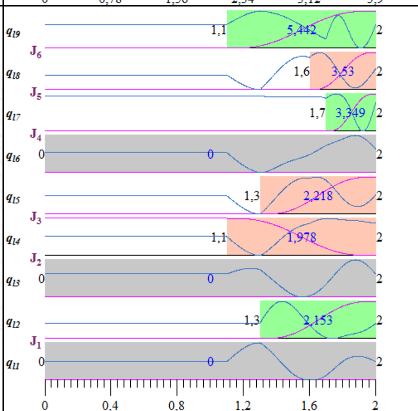
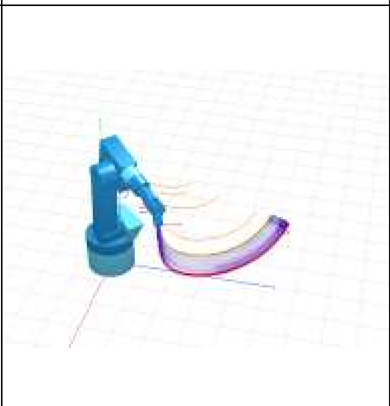
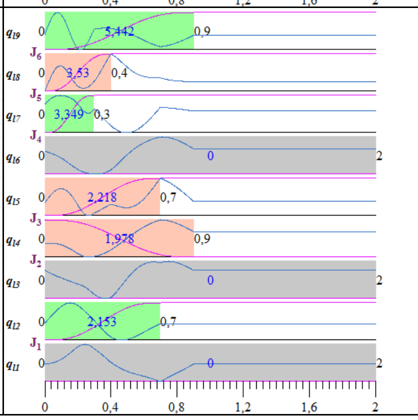
№ crt.	IR's trajectory	Duration of activated GC's motion	N [W]	ΔN [%]	τ_{T1-T2} [s]	$\Delta\tau_{T1-T2}$ [%]
5			2113.47	5.17	2	122.22
6			2118.89	5.44	1.8	100.00
7			2329.78	15.94	1.3	44.44
8			2394.92	19.18	2	122.22

Table 2. Continuation

№ crt.	IR's trajectory	Duration of activated GC's motion	N [W]	ΔN [%]	τ_{T1-T2} [s]	$\Delta\tau_{T1-T2}$ [%]
9			2406.65	19.76	1.2	33.33
10			2879.17	43.28	3.9	333.33
11			3120.12	55.27	0.9	0
12			4553.89	126.62	0.9	0

Moreover, among the fastest trajectories advisable to choose one that processed with the minimum power. For example when $\tau_{T1\text{-}T2}$ = 0.9 s for options 11 and 12 in Table 2 it is advisable to choose the trajectory option 11 which has a lower power consumption N = 3120.12 W than trajectory in option 12 where N = 4553.89 W.

5. Directions for future research

1. Automatically checking for each of the generated trajectories for the possibility of conflicts of 1st and 2nd kind [8] of trajectory space.

2. Conducting similar researches of the objects of manipulations (OM) with different location of the center of OM's mass (G_{OM}) relative to P_{Gr}.

3. Integration of the parts of trajectories into cyclic trajectory.

4. The integration of this program to generalized systems of RMAT, developed in ZSTU and TUS.

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