Software Platform for the Assisted Research of the Kinematics and Dynamics of Industrial Robots

Olaru A., Dobrescu T., Olaru S., and Mihai I.

***Abstract*—The paper presents a software platform made with LabVIEW™ for the assisted research of the kinematic and dynamic behavior of industrial robots. The platform comprises a series of virtual instrumentation LabVIEW™ programs (sub*VI*-s) with: the input data modules in the form of several clusters with the parameters of the trapezoidal velocity characteristics of each joint, the axes of movement and the type of each joints, the dimensions of each body, the graph associated to the robot's structure, the incidence matrices bodies - joints and joints- bodies, as well as the control buttons for movement up or down with or without object in the end- effecter, some modules with 2D characteristics of positions, velocities, accelerations, forces and moments in each joints and also the 3D characteristics of them. The research of the current stage shows that such a complex platform like this was not realized, the current research being limited to the animation of motion trajectories, determining the characteristics of positions, velocities, accelerations, forces and moments without the possibility of changing all motion parameters and robot's dimensions and without show how these parameters change the behavior. The paper studies the case of an articulated arm type robot, but the platform can be used for any type of robot with four degrees of freedom (DOF).**

***Index Terms*—Assisted research, dynamics behavior, kinematics behavior, industrial robots, software platform.**

I. Introduction

Analyze of the kinematic and dynamic behavior is the more important problem to be optimized in the research of the industrial robots. For that many researchers in the world studied this field with some proper software to obtain more and important results to assure the better movement in the space of the robot's end-effecter without vibration, with better precision, without big variation of the forces and moments.In the papers [1]-[3] the authors analyses the kinematics of a special 6-DOF parallel micro-manipulator with offset RR-joint configuration. Inverse Kinematics (IK) and Forward Kinematics (FK) of the studied case are modelled and was verified the accuracy of the proposed methodologies. In the [4] author uses the idea of "direct sensor-to-microcontroller" technique. Analog sensors are interfaced directly to a typical microcontroller PIC18. The accuracy depends mainly on the output impedance of the system's I/O ports and the precision depends on the level noise.

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A. Olaru and T. Dobrescu are with University Politehnica of Bucharezst, Romania, Romania (e-mail: aolaru_51@ymail.com, tibidobrescu@yahoo.com).

S. Olaru was with METRA Company, Bucharest, Romania (e-mail: serban1978@yahoo.com).

I. Mihai was with the Iumirobo Company, Leuval, Quebec, Canada (e-mail: mniculae@yahoo.com).

To achieve a high degree of performance [5], various parameters and characteristics of robots should be known. Some software are used for simulation, modeling, and analysis of a robot to improve the robotic operations. The objectives of this article is to derive FK, IK and dynamic model of a 6DOF robot through both analytical and software numeric approaches and study the results. The analyze using 3D CAD Modelling, Robotic Toolbox in MATLAB and RoboAnalyzer was done. The article [6] does study only FK and IK of a KUKA KR6 robot, not the dynamic behavior. Another article [7], [8] follows the method to import CAD Models which are not preinstalled in RoboAnalyzer. But this article covers only the Kinematic analysis. In the paper [9], was developed a model for two cooperating flexible manipulators handling a rigid and analyzed with MATLAB. To validate the model, was developed one program using ADAMSTM (Automatic Dynamic Analysis of Mechanical System).

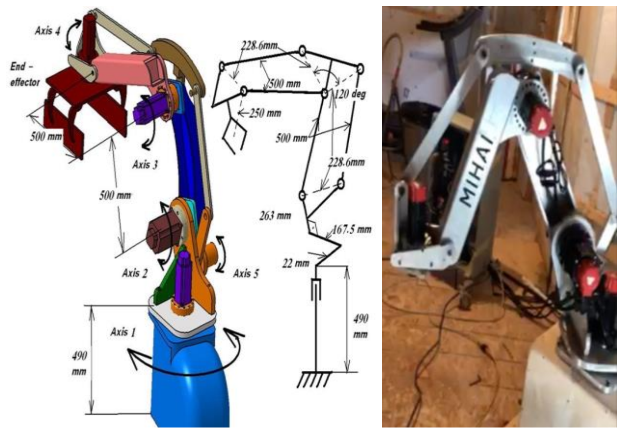

Fig. 1. The arm type robot from IUMIROBO company, Quebec, Canada.

After was analyzed the state of art in this field we can do the followings remarks: many of them used some known software for solving the FK and IK but incomplete study of the dynamic behavior; the parameters that were analyzed like the more important parameters in the dynamic behavior, not included the different origin of movement time for each joints; many of them don't have the possibility to change on-line the dimensions of the robot's bodies, the movements in the space, the home positions and to see how these parameters influence the dynamic behavior; the actual research didn't study the variation of all module's vectors of velocities, accelerations and space angle of them and didn't study separately the variation of the linear and angular velocities and acceleration to see the maximal variation of them, to better control the Coriolis and Centrifugal/ Centripetal forces and also the influence of them to the moments in each robot's joints; the actual stage of the research does not take into account the graph associated with the structure in order to generate the incidence matrices bodies- joints and joints- bodies to

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highlight the principle of action and reaction of forces in the joints; all research does not take into account, in the dynamic behavior, the movement of the arm in up or down direction and also the presence of the object in the end-effecter and how these influence the dynamic behavior; any actual research doesn't study the influence of the variation angle in the space of all vectors of linear and angular velocities, linear and angular accelerations, of inertial moments to the dynamic behavior. Some constructive- functional parameters were established using this platform for one didactical arm type robot and was designed and constructed in the IUMIROBO private company from Canada.

II. Description of the Software Platform

The project was designed in LabVIEW software 14.0 version and contents some sub*VI*-s for each component of the used mathematical matrix model, Fig. 2.

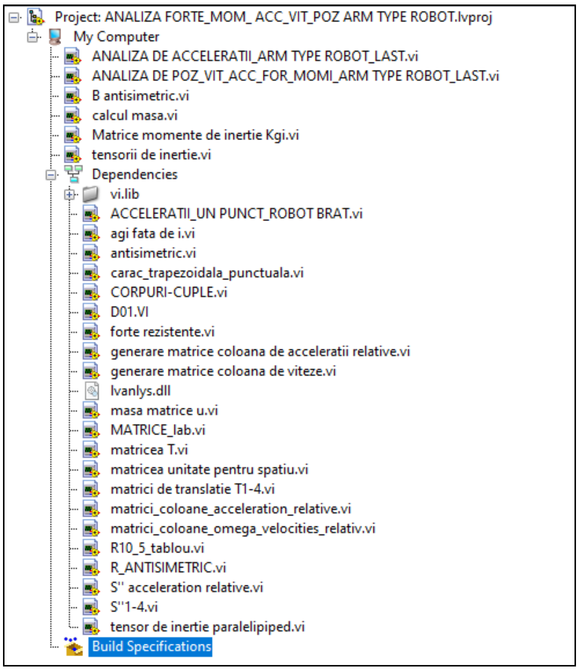


Fig. 2. Sub*VI*-s of the project Platform LabVIEW.

The front panel of the platform is shown in the Fig. 3 and contents the following components: one table with the relative position vectors in each column (the component are only in oz because the scheme associated with the robot contains the oz axis only along of each robot's body), table with the values of the vectors of the centers of gravity, the clusters for trapezoidal characteristics parameters, type of each joints, home positions for each robot's body, cluster with the parallelepiped dimensions of each body, buttons for choose the up/down direction of movement and with/without object in the end-effecter. Front panel contents also the column matrix for incidence matrices bodies- joints and joints- bodies, the graph associated to the structure in order to generate the principle of action and reaction of forces in the joints. For the results, the project contents: the 3D graphs for positions, linear and angular velocities, linear and angular accelerations, forces, moments, variation of inertial moments; the 2D graphs for the positions, velocities, accelerations, forces and moments in each joints, Fig. 3.

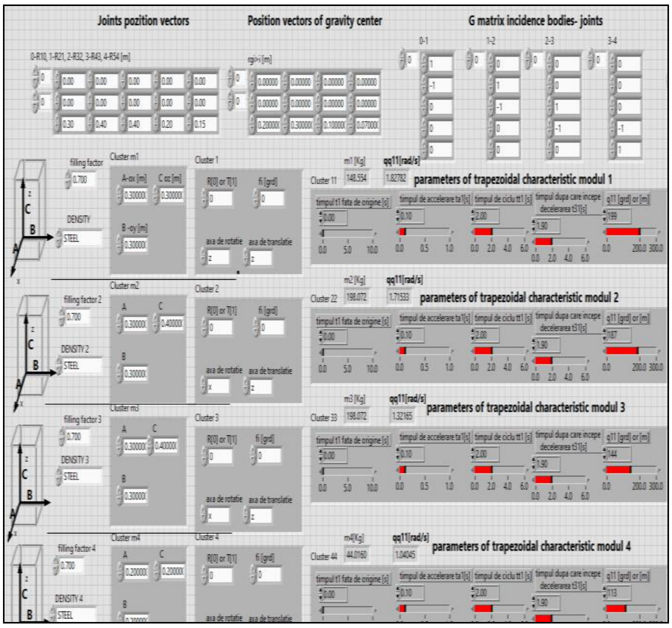


Fig. 3. Part of front panel of the platform for the assisted analyse of the pozitions, velocities, accelerations, forces and moments in all joints.

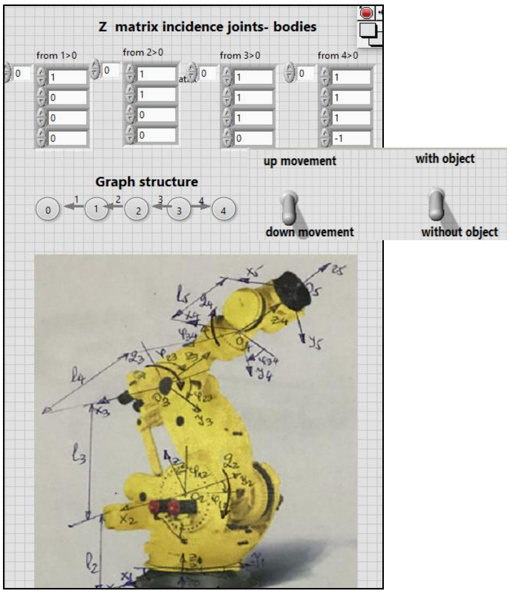


Fig. 4. Part of front panel with the robot's structure with each Cartesian systems in all robot's joints, the graph associated, the buttons for the up/down movement command and with/without object in end-effecter, and the incidence matrix joints- bodies.

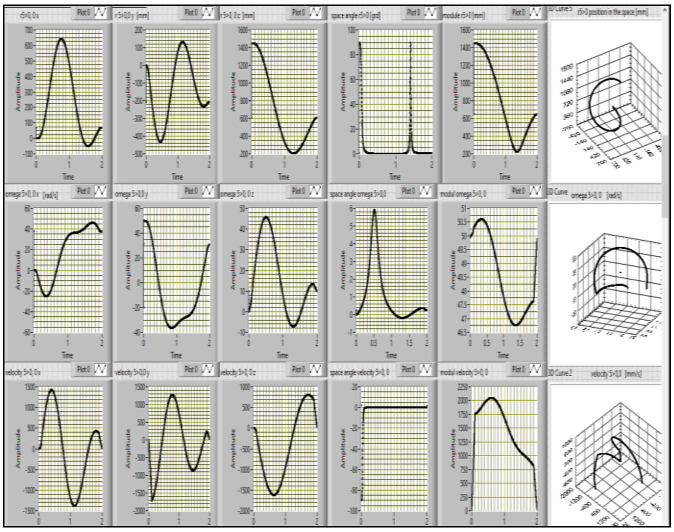


Fig. 5. 2D and 3D characteristics for pozitions and velocities.

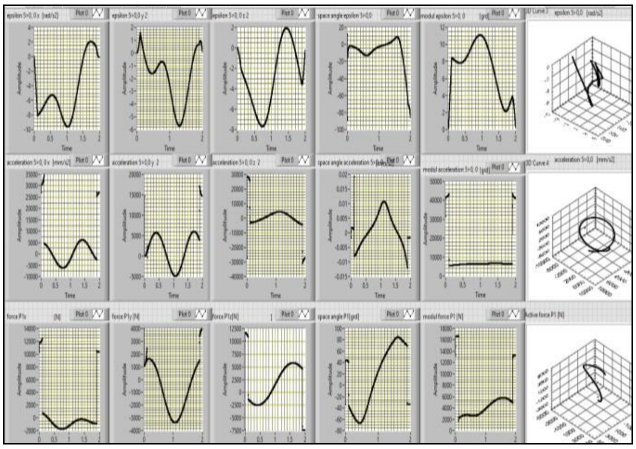


Fig. 6. 2D and 3D characteristics for accelerations

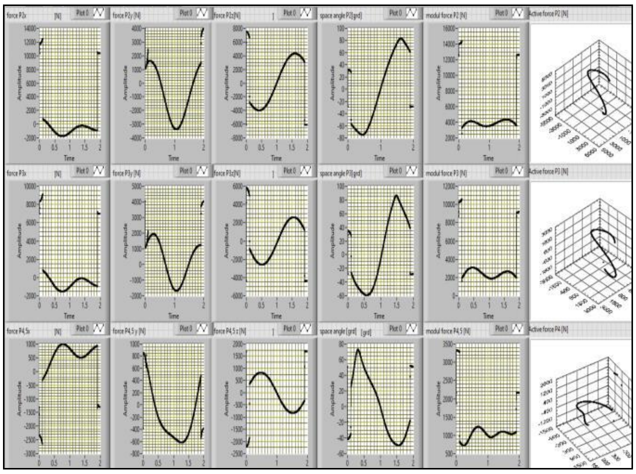


Fig. 7. 2D and 3D characteristics for active forces in joints

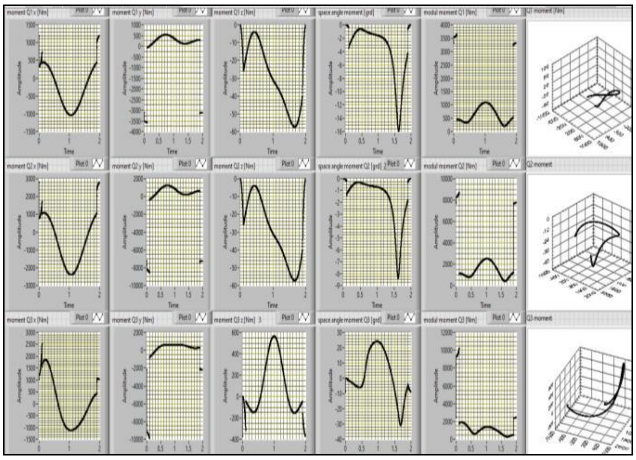


Fig. 8. 2D and 3D characteristics for active moments in all joints

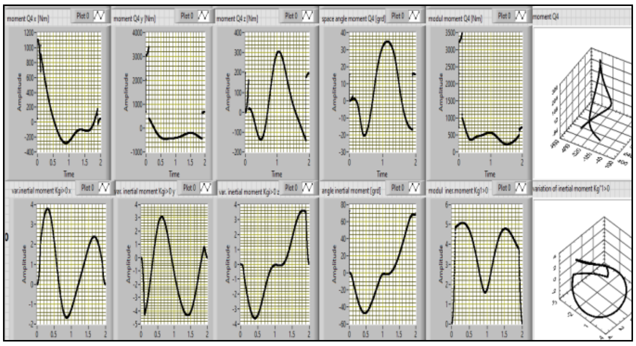


Fig. 9. 2D and 3D characteristics for active moments and variation of the kinetic moments with button to select the joint

The icons of the *sub*VI-s that is used in the LabVIEW project are shown in fig.10.

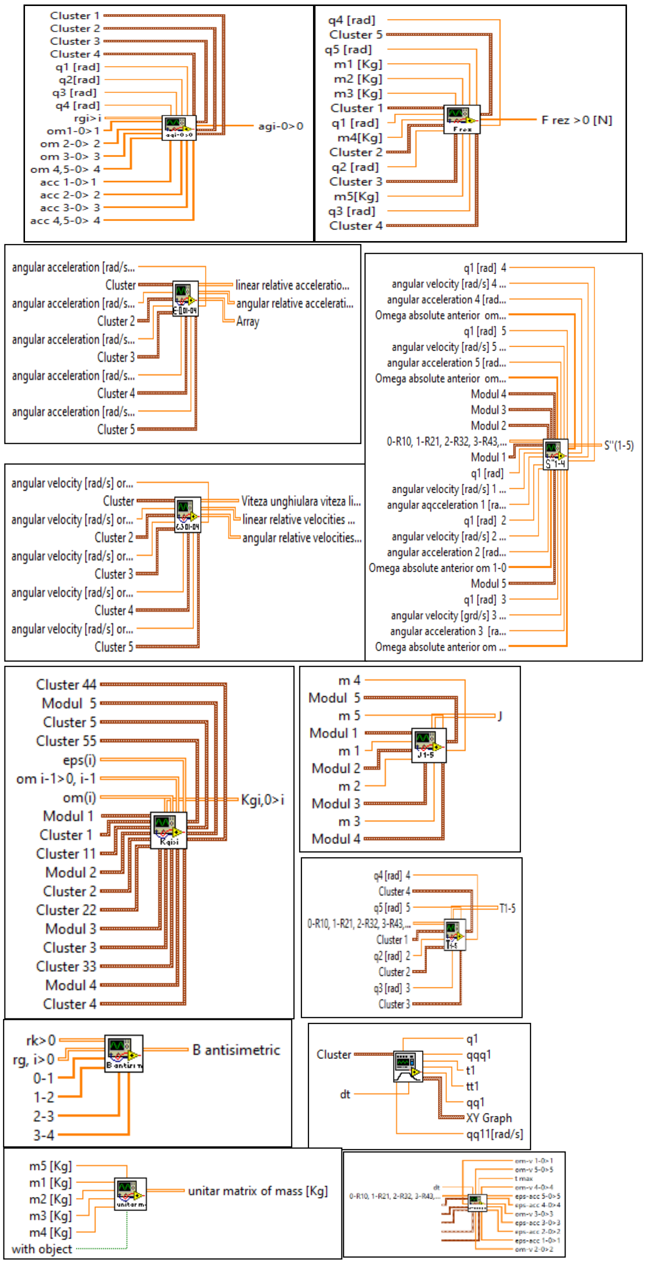


Fig. 10. Icons of the sub*VI*-s for calculus of mass, resistive forces, accelerations, the anti-symmetrical matrix of the arms of the active forces, matrix of variation of kinetic moments, matrix of inertial tensors, transfer matrices T1-4, trapezoidal velocity, matrices of velocities and accelerations

III. Mathematical Model of the Arm Type Robot

The mathematical model of the FK and dynamics analyze contents the matrix form in analyze of joints positions, linear and angular velocities, linear and angular accelerations, forces, moments and variation of kinetic moments [10].

The analyzed case was the arm type robot with 4 DOF (only roll for the last module).

(i) Matrix 3x3 equation for the positions analyze for the arm type robot is:

$$\left(r_5^0\right)=\left(r_1^0\right)+\left[D_1^0\right]\left(r_2^1\right)+\left[D_2^0\right]\left(r_3^2\right)+\left[D_3^0\right]\left(r_4^3\right)+\left[D_4^0\right]\left(r_5^4\right) \qquad (1)$$

$$D_4^0=D_1^0 D_2^1 D_3^2 D_4^3$$

$$D_1^0 = \begin{bmatrix} c1 & -s1 & 0 \\ s1 & c1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, c1 = \cos(\varphi_{01} + \rho_1) \quad (2)$$

where: r_i^0 is the absolute position vector of the i joints to the robot's base Cartesian system; r_i^{i-1}- relative position vector; D_i^0- transfer matrix 3x3 from i Cartesian system to the base; c_i- cosine of the rotation module i; φ_{ij}- rotation axe between i and j Cartesian systems for the anterior movement; ρ_i-variable internal coordinate of the i joint.

(ii) Matrix 6x6 equation for the velocities analyze of the arm type robot is:

$$\begin{pmatrix} \omega_{5,0}^5 \\ v_{5,0}^5 \end{pmatrix} = T_4^5 \left[T_3^4 \left[T_2^3 \left[T_1^2 \begin{pmatrix} \omega_{1,0}^1 \\ v_{1,0}^1 \end{pmatrix} + \begin{pmatrix} \omega_{2,1}^2 \\ v_{2,1}^2 \end{pmatrix} \right]_1 + \begin{pmatrix} \omega_{3,2}^3 \\ v_{3,2}^3 \end{pmatrix} \right]_2 + \begin{pmatrix} \omega_{4,3}^4 \\ v_{4,3}^4 \end{pmatrix} \right]_3 + \begin{pmatrix} \omega_{5,4}^5 \\ v_{5,4}^5 \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} \omega_{5,0}^0 \\ v_{5,0}^0 \end{pmatrix} = \begin{bmatrix} D_5^0 & 0 \\ 0 & D_5^0 \end{bmatrix} \begin{pmatrix} \omega_{5,0}^5 \\ v_{5,0}^5 \end{pmatrix}$$

$$D_5^0 = D_1^0 D_2^1 D_3^2 D_4^3 D_5^4$$

$$T_i^j = \begin{bmatrix} D_i^j & 0 \\ -D_i^j \hat{r}_j^i & D_i^j \end{bmatrix}$$

where: $\begin{pmatrix} \omega_{5,0}^5 \\ v_{5,0}^5 \end{pmatrix}$ – dual absolute angular and linear velocity vector of the 5 joint versus the 5 Cartesian system; $\begin{pmatrix} \omega_{5,0}^0 \\ v_{5,0}^0 \end{pmatrix}$- dual absolute velocity angular and linear vector of the 5 joint versus the Cartesian base system; T_i^j- matrix transfer 6x6 from i to j Cartesian system; $\begin{pmatrix} \omega_{i,j}^i \\ v_{i,j}^i \end{pmatrix}$- dual relative angular and linear velocity vector of the i joint versus the j Cartesian system.

(iii) Matrix 6x6 equation for the accelerations of the arm type robot is:

$$\begin{pmatrix} \varepsilon_{5,0}^5 \\ a_{5,0}^5 \end{pmatrix} = T_4^5 \left[T_3^4 \left[T_2^3 \left[T_1^2 \begin{pmatrix} \varepsilon_{1,0}^1 \\ a_{1,0}^1 \end{pmatrix} + S''(2) \right]_1 + S''(3) \right]_2 + S''(4) \right]_3 + S''(5)$$

$$\begin{pmatrix} \varepsilon_{5,0}^0 \\ a_{5,0}^0 \end{pmatrix} = \begin{bmatrix} D_5^0 & 0 \\ 0 & D_5^0 \end{bmatrix} \begin{pmatrix} \varepsilon_{5,0}^5 \\ a_{5,0}^5 \end{pmatrix} \quad (4)$$

$$S''(i) = \begin{pmatrix} \varepsilon_{i,i-1}^i + \hat{\omega}_{i-1,0}^i \omega_{i,i-1}^i \\ a_{i,i-1}^i + \hat{\omega}^{2\,i}_{i-1,0} r_{i,i-1}^i + 2\hat{\omega}_{i-1,0}^i v_{i,i-1}^i \end{pmatrix}$$

where: $\begin{pmatrix} \varepsilon_{5,0}^5 \\ a_{5,0}^5 \end{pmatrix}$- dual absolute angular and linear acceleration vector of the 5 joint versus the 5 Cartesian system; $\begin{pmatrix} \varepsilon_{5,0}^0 \\ a_{5,0}^0 \end{pmatrix}$- dual absolute angular and linear acceleration vector of the 5 joint versus the base Cartesian system; $S''(i)$- dual relative angular and linear acceleration vector of the i joint versus i Cartesian system; $\varepsilon^i_{i,i-1}$- relative angular acceleration vector between i and i-1 joints versus i Cartesian system; $(\hat{\omega}_{i-1,0}^i)$ - anti-symmetrical absolute vector of the angular velocity versus i Cartesian system; $(\omega_{i,i-1}^i)$- relative angular velocity versus i Cartesian system; $(a_{i,i-1}^i)$-relative linear acceleration; $(\hat{\omega}^{2\,i}_{i-1,0} r_{i,i-1}^i)$ - relative centrifuge acceleration; - $(2\hat{\omega}_{i-1,0}^i v_{i,i-1}^i)$ relative Coriolis acceleration.

(iv) Matrix equation for the joint's forces analyze for the arm type robot is:

$$(P^0) = [z_u]\left[(F^0) \mp [m_u](a_{gi,0}^0)\right]$$

$$(F^0) = \begin{pmatrix} \overline{D_1^0 F_1^1} \\ \overline{D_2^0 F_2^2} \\ \overline{D_3^0 F_3^3} \\ \overline{D_4^0 F_4^4} \end{pmatrix}, [m_u] = \begin{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}[m_1] & 0 & 0 \\ & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}[m_2] & \\ & & 0 \quad [m_{4,5}] \end{bmatrix} \quad (5)$$

$$(a_{gi,0}^0) = \begin{pmatrix} \overline{D_1^0 a_{g1,0}^1} \\ \overline{D_2^0 a_{g2,0}^2} \\ \overline{D_3^0 a_{g3,0}^3} \\ \overline{D_4^0 a_{g4,0}^4} \end{pmatrix}, [z_u] = \begin{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\cdot(1) & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\cdot(-1) \end{bmatrix}$$

where: (P^0)- is the active force matrix reduced to the base; $[z_u]$- unitary joints-bodies matrix; (F^0)- resistive force matrix reduced to the base; (F_i^i)- resistive force matrix reduced to the proper Cartesian system; $[m_u]$- mass matrix where m_i was multiply by unitary matrix for the space; $(a^i_{gi,0})$- absolute linear acceleration matrix for the centre of gravity g_i reduced to the i Cartesian system.

(v) Matrix equation for the active moments in arm type robot's joints is:

$$(M^0) = [z_u]\left[(M_R^0) + (K_{gi}'^0) + [\hat{B}^0](P^0)\right]$$

$$(M_R^0) = \begin{pmatrix} \overline{D_1^0 M_1^1} \\ \overline{D_2^0 M_2^2} \\ \overline{D_3^0 M_3^3} \\ \overline{D_4^0 M_4^4} \end{pmatrix}, \left[\hat{B}^0\right] = \begin{bmatrix} [\hat{b}_{11}^0] & [\hat{b}_{12}^0] & [\hat{b}_{13}^0] & [\hat{b}_{14}^0] \\ [\hat{b}_{21}] & \begin{bmatrix} 0 & -b_{22z} & b_{22y} \\ b_{22z} & 0 & -b_{22x} \\ -b_{22y} & b_{22x} & 0 \end{bmatrix} & [\hat{b}_{23}^0] & [\hat{b}_{24}^0] \\ [\hat{b}_{31}^0] & [\hat{b}_{32}^0] & [\hat{b}_{33}^0] & [\hat{b}_{34}^0] \\ [\hat{b}_{41}^0] & [\hat{b}_{42}^0] & [\hat{b}_{43}^0] & [\hat{b}_{44}^0] \end{bmatrix} \quad (6)$$

$$(b_{12}^0) = (r_2^0) - (r_{g1}^0)$$

$$(K_{gi}'^0) = \begin{pmatrix} \overline{D_1^0 K_{g1}'^1} \\ \overline{D_2^0 K_{g2}'^2} \\ \overline{D_3^0 K_{g3}'^3} \\ \overline{D_4^0 K_{g4}'^4} \end{pmatrix}, (K_{g2}'^2) = [J_{g2}^2](\varepsilon_{2,1}^2) + [\hat{\omega}_{1,0}^2][J_{g2}^2](\omega_{2,1}^2)$$

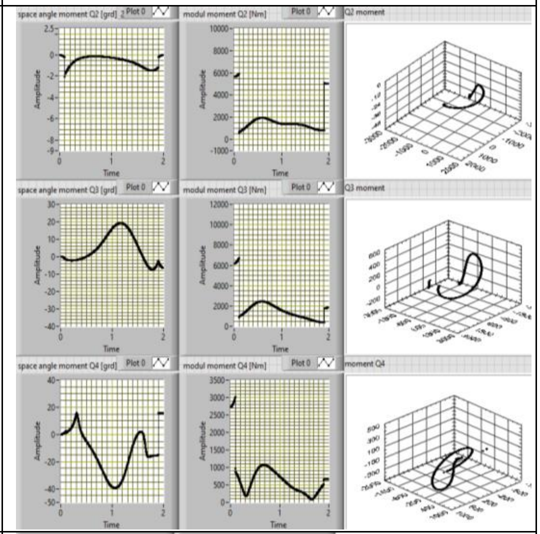
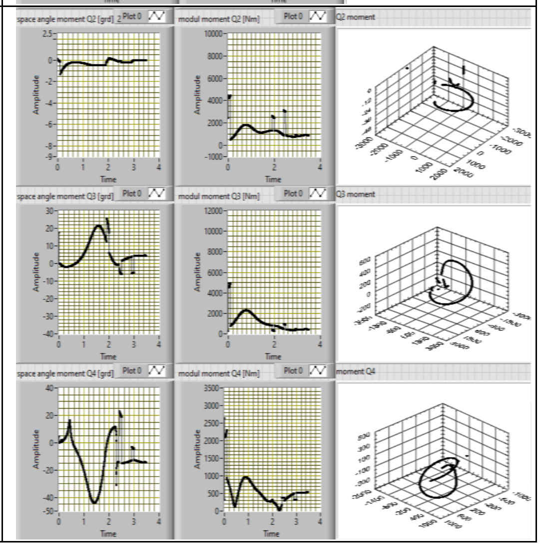
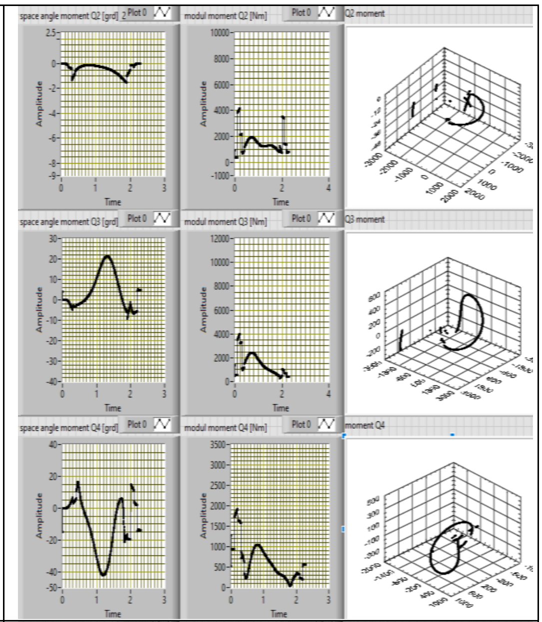
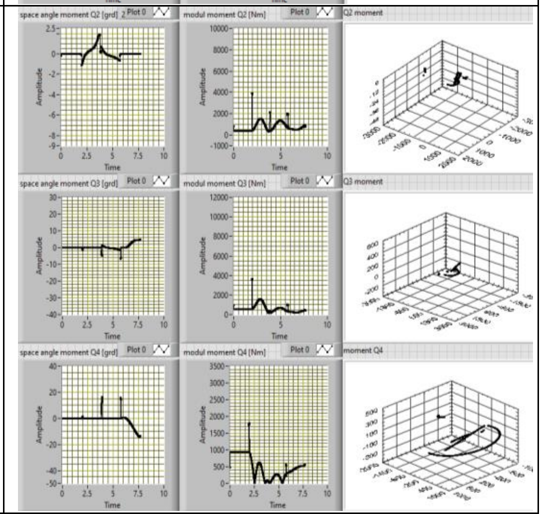
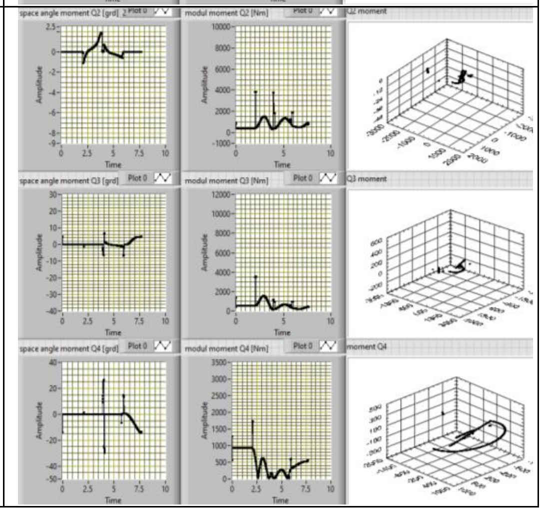
where: (Q)- column matrix of the active moments in a joints; (M_R^0)- column matrix of the resistant moments in a joints; $\left[\hat{B}^0\right]$- anti-symmetric force's arm matrix; (P^0)- column matrix for active forces; $(K_{gi}'^0)$ - column matrix of the variation of the kinetic moment reduced to the base Cartesian system; $(K_{g2}'^2)$- column matrix of the variation of the kinetic moment of the second centre of gravity reduced to the second Cartesian system.

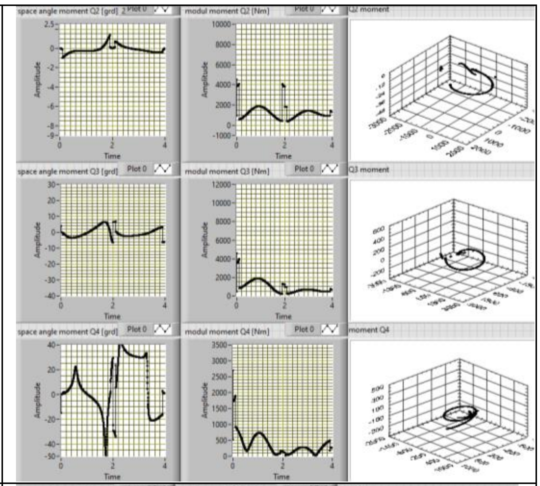
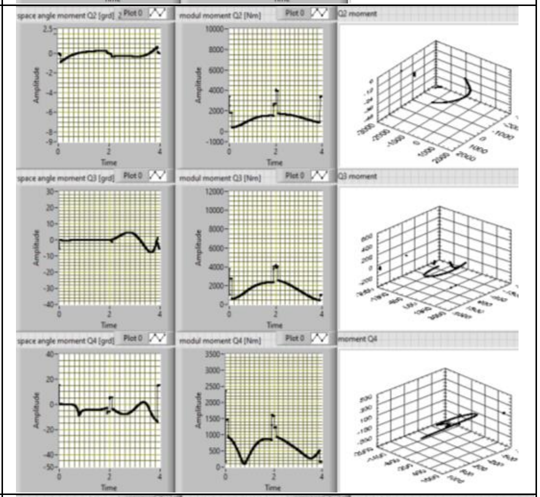
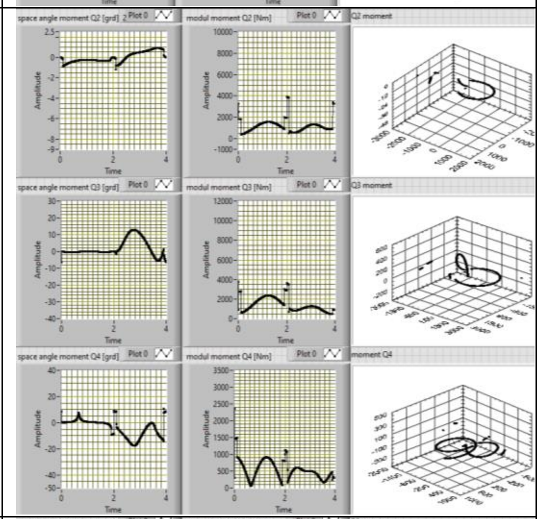
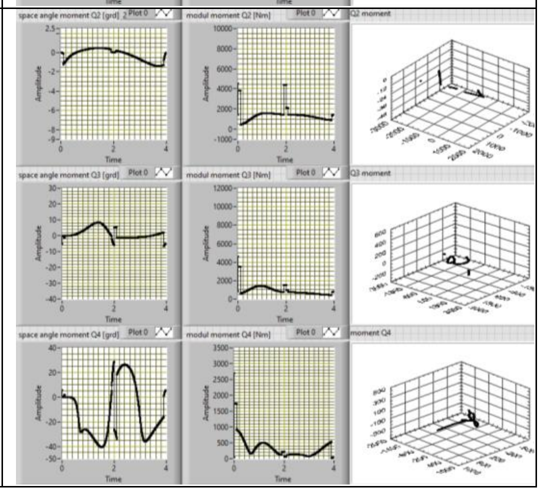
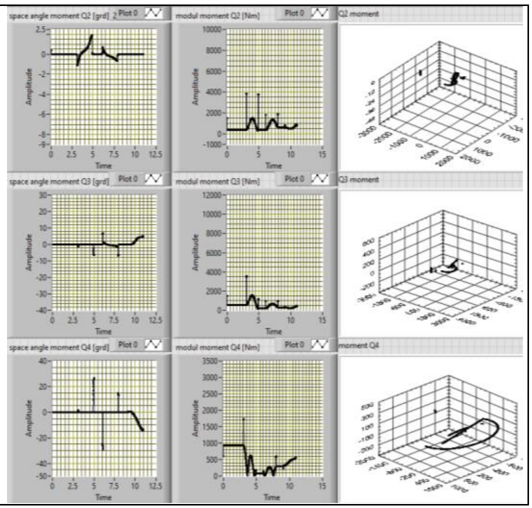
III. Analyze of the Results

In assisted analyze with this platform were shown some

2D and 3D characteristics vs. time of forces, moments, velocities accelerations, in each axes, the module variation and the space variation angle of all these vectors, by changing some parameters from trapezoidal characteristics in each movement joints: time before origin for each joint's movements; different times of each movement cycle; the movement in up or down direction with or without the object in the end-effecter of the robot's arm. Some of the results we can see on the Table I.

TABLE I: THE CHARACTERISTICS OF SPACE ANGLE AND MODULE OF VECTORS OF MOMENTS

Studied case	Characteristics
0-0-0-0 tt-ct	
0-0-0-0 tt=dif. +0.5s in each joints	
0-0.1-0.2-0.3	
0-1.9-3.9 5.9	
0-2-4-6	

0-0-2-2	
2-2-0-0	
0-2-0-2	
2-0-2-0	
0-3-6-9 Successive with 1s pause	

After were analyzed the results we can do the followings remarks: (i) simultaneous movement determines the largest variation of the angle of the moment vector in the joint four, which causes forced vibrations at the end-effector; (ii) the simultaneous-successive motion 2-2-0-0 determines a small variation of the angle of the moment vector compared to the motion 0-0-2-2; (iii) the successive movement after the period of uniform movement 0-1.9-3.9-5.9 determines a much reduced variation of the spatial angle from 60 to 35 [degrees] compared to the completely successive movement 0-2-4-6; (iv) the simultaneous-successive movement 0-2-0-2 (30 [degrees] and 3 jumps) determines a reduced variation of the spatial angle compared to the case of 2-0-2-0 (60 [degrees] and 2 jumps); (v)the successive movement 0-3-6-9 (1s pause between the movements of the joints) determines a reduced variation compared to the case of the successive movement 0-2-4-6; (vi) among the studied cases, the movement 2-0-2-0 and 0-3-6-9 determines the smallest variation of the moment vector module in the joint 4, 0-500 [Nm] other cases have the variation between 0-2000 [Nm] with ultimately leads to poor vibratory behavior. Compared to those mentioned, it results that from the point of view of the optimal motion with the smallest variation of both the spatial angle and the module of the moment vector Q4, the best solution is the movement simultaneously- successive 2-0-2-0.

IV. Conclusions

The LabVIEW project was designed by using the proper complex mathematical matrix model. The project contents many sub*VI*-s to cover all aspects in the dynamic behavior of robots. The assisted platform open the way to the multi-objective optimization of the dynamic behavior of robots by using the moving algorithm in all robot's joints. This platform could be applied in all other types of industrial robots with 4 DOF.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The contribution of each author are: Olaru Adrian design the LabVIEW project, the sub*VI*-s and written some part of the paper; Dobrescu Tiberiu contributed at the mathematical model of the kinematics modelling, check the English grammar of the content and written some part of the paper; Olaru Serban contributed at some sub*VI*-s design, check the English language of the paper and written some part of the paper; Mihai Iulia contributed with some experimental research on the proper arm type robot from his private company, Canada. All authors had approved the final version.

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Adrian Olaru finishes the University Politehnica of Bucharest, the Faculty of Machine-Tools, Machine and Manufacturing Systems Department. Now, from 1998, he is a university full professor, and he teach the following courses: industrial robots dynamics behaviour, labview application in modelling and simulation of the dynamic behaviour of robots and Personal and social robots. He is a doctor from 1989. In the last ten years he has been leading the following research projects: computer aided research and design for the hydraulic amplifiers of pneumatic and hydraulic screwdrivers; computer aided research over the dynamic behaviour of the forging manipulator orientation modulus; computer aided research over dynamic behaviour of the charging manipulators tipping modulus; computer aided research over dynamic behaviour of the charging manipulators translation modulus; experimental validation for mathematical models of hydraulic elements and servo system; methodological guide for dimensioning and optimizing electrohydraulic elements; design of the mobile robots; assisted research of the magneto rheological dampers; assisted research of the intelligent dampers; assisted research of the neural networks; optimizing of the robots dynamic behaviour by using the Fourier proper analyser; optimizing the dynamic compliance and global transmissibility by using the assisted research and the proper neural networks.

Tiberiu Dobrescu finish the University Politehnica of Bucharest, the Faculty of Machin and Manufacturing Systems and now it is the head of the Robotics and Production Systems Department from Industrial Engineering and Robotics faculty. He is the doctor from 1995. In the last 10 yers professor published more than 100 research papers in the field of manufacturing systems, robotics, machenical engineering and assisted research.

Serban Olaru finished the University Politehnica of Bucharest, Faculty of Machines and Manufacturing Systems, Romania. From 2008 he become the Ph.D.Eng.in the field of mechatronics. Now, he works in METRA company, from Bucharest, Romania, in the Department of Mechatronics. He write more than 50 research papers in the fields of intelligent damper systems, mechatronic systems, simulation and modelling with LabVIEW instrumentation.

Iulia-Andra Mihai is currently pursuing a bachelor's degree in robotics and mechanical engineering at School Of Higher Technology (Éts), Montreal. In 2018 she obtained a college degree in Industrial Electronics Technology at Cégep Vanier, Montréal. She is currently manager of IUMIROBO Inc. (www.iumirobo.ca) from Quebec, Canada, which works in the field of design and manufacture of robotic production cells, especially in the field of automatic manufacture of PVC windows and metal doors.