Abstract—One of the most important problems to solve in the robots Kinematics and Dynamics is analyze of the joint’s angular and linear accelerations. Because the movements of the robot’s bodies going in the 3D space, the mathematical algorithm must be written in the complex matrix form. The paper show how some cases of the trapezoidal relatives’ velocities characteristics in a joints determine the variation of the acceleration’s vectors in the 3D space. The maximal values of these variations of the angular and linear accelerations influence the variation of the moments and forces. The analyze was made by using the Neutrosophic theory and virtual LabVIEW instrumentation. In a literature are described some methods of the assisted analyze of the acceleration without show the used mathematical model, without one critical analyze of the cases that must be avoid and finally without some conclusions for the researchers. The paper shown all LabVIEW virtual instruments (VI) used for this assisted research. By solving the assisted research of the acceleration will be open the way to the assisted research of the robots’ dynamic behavior, to choose the optimal constructive and functional parameters (dimensions of the bodies, simultaneously, successive or complex configurations of the movements in the robot’s joints, optimal values of the constant relative joint’s velocities, etc.) of the robots to obtain the minimum variation of the forces and moments. The method that was shown in the paper solves one small part of the complex problems of the robot’s kinematics and dynamics.

Index Terms—Assisted research, Joint’s accelerations, Neutrosophic theory, Virtual instrumentation, Multi-objectives optimization.

I. INTRODUCTION

The assisted analyze of accelerations in Robotics is one of the most important problem to be solved that will be assured one good choose of the robots parameters with the final goal—find the optimal dynamic behavior of the robot joints movements. Without the assisted research with the LabVIEW software will be not possible to study the kinematic and dynamic behavior. In [1] Ran Zhao show one synthesis about the trajectory generation for manipulators and cooperation robots. This subject have been discussed in numerous other books and papers, among can find [Brady 2], [Khalil 3] and [Biagiotti 4]. Kroger, in his book [Kroger 5], gives a detailed review on on-line and off-line trajectory generation and propose to reach a goal defined by constraints (position, velocity, acceleration, jerk,…) while respecting bounds \( (V_{\text{max}}, A_{\text{max}}, J_{\text{max}}, D_{\text{max}}) \) where: \( V_{\text{max}} \) is the maximum velocity, \( A_{\text{max}} \) is the maximum acceleration, \( J_{\text{max}} \) is the maximum jerk, \( D_{\text{max}} \) is the maximum first derivative of jerk. The first reason is that the trajectory can be adapted in order to improve the path accuracy. [Dahl 6] proposed to use one-dimensional parameterized acceleration profiles along the path in joint space instead of adapted splines. [Cao 7, Cao 8] used cubic splines to generate smooth paths in joint space with time-optimal trajectories. In this work, a cost function was used to define an optimization problem considering the execution time and the smoothness. [Constantinescu 9] suggested a further improvement of the approach of [Shiller 10] by leading to a limitation of the jerk in joint space, considering the limitation of the derivative of actuator force/torques. [MacFarlane 11] presented a jerk-bounded, near time-optimal, one-dimensional trajectory planner that uses quartic splines, which are computed online. Owen published a work on online trajectory planning [Owen 12]. Here, an off-line planned trajectory was adapted online to maintain the desired path. The work of Kim in [Kim 13] took robot’s dynamics into account. The other one is the robotic system must react to unforeseen events based on the sensor singles when the robot works in an unknown and dynamic environment. [Castain 14] proposed a transition window technique to perform transitions between two different path segments. [Liu 15] presented a one-dimensional method that computes linear acceleration progressions online by parameterizing the classic seven-segment acceleration profile. [Ahn 16] used sixth-order polynomials to represent trajectories, which is named Arbitrary States POLynomial-like Trajectory (ASPT). In [Chwa 17], Chwa presented an advanced visual servo control system using an online trajectory planner considering the system dynamics of a two-link planar robot. An algorithm proposed in [Haschke 18] is able to generate jerk-limited trajectories from arbitrary state with zero velocity. Broquere proposed in [Broquere 19] an online trajectory planner for an arbitrary numbers of independent DOFs. The Motion Conditions (MC) in Cartesian and Joints equations are shown in (1):

\[
\begin{align*}
V_{\text{max}} & \leq V_{\text{max}} \\
A_{\text{max}} & \leq A_{\text{max}} \leq V_{\text{max}} \\
J_{\text{max}} & \leq J_{\text{max}} \leq A_{\text{max}} \\
D_{\text{max}} & \leq D_{\text{max}} \leq J_{\text{max}}
\end{align*}
\]

TABLE I: THE ROBOT MOVEMENTS LIMITS IN JERK, ACCELERATION AND VELOCITIES [1]

| Jerk | Acceleration | Velocity |
|------|--------------|----------|
| 5\(\times\)A_{\text{max}} \text{ rad/s}^3 | 2.5\(\times\)V_{\text{max}} \text{ rad/s}^2 | V_{\text{max}} \text{ rad/s} |
where: \( X(t), V(t), A(t) \) are the position, velocity and acceleration that describe the Cartesian MC, \( Q(t), \dot{Q}(t), \ddot{Q}(t) \) are the relatives position, velocity and acceleration that describe the Joints MC.

**II. MODELING SIMULATION OF THE ROBOT’S JOINTS ACCELERATIONS**

For the assisted research of accelerations were needed firstly create the mathematical 6x6 matrix model, secondly construct some LabVIEW instruments that content this mathematical model, thirdly run these virtual instrumentations to obtain the accelerations characteristics versus time in some different cases of the robot’s movements and with different body’s length and finally analyze and chose the optimal values of the constructive and functional robot’s parameters. Some of the proper results were obtained in the papers [20]-[25].

**A. Mathematical 6x6 Matrix Model for Robot Joint’s Accelerations**

The dual matrix form of the accelerations equations assure the easily way for the assisted research of the kinematics and dynamics behaviour of robots. The matrix form of the dual absolute vector equations for accelerations are:

\[
\begin{pmatrix}
(e_{i,0}^l) \\
(a_{i,0}^l)
\end{pmatrix} = \begin{bmatrix}
T_{i-1}^l \\
S_{i-1}^l
\end{bmatrix} \begin{pmatrix}
(e_{i-1,0}^l) \\
(a_{i-1,0}^l)
\end{pmatrix} + (S''(i))
\]

\[S''(i) = \begin{pmatrix}
\epsilon_{i-1,0}^l + \omega_{i-1,0}^l \omega_{i-1,0}^l \\
\alpha_{i-1,0}^l + \omega_{i-1,0}^l \gamma_{i-1,0}^l + 2 \omega_{i-1,0}^l \nu_{i-1,0}^l
\end{pmatrix}
\]

\[
\begin{pmatrix}
(e_{i,0}^0) \\
a_{i,0}^0
\end{pmatrix} = \begin{bmatrix}
[D_i^0] & [0] \\
[0] & [D_i^l]
\end{bmatrix} \begin{pmatrix}
(e_{i,0}^l) \\
(a_{i,0}^l)
\end{pmatrix}
\]

where: \( \begin{pmatrix}
(e_{i,0}^l) \\
(a_{i,0}^l)
\end{pmatrix} \) is the dual matrix vector of the absolute acceleration of the \( i \) joint versus the \( i \) Cartesian system; \( \begin{pmatrix}
(e_{i,0}^0) \\
a_{i,0}^0
\end{pmatrix} \) - the dual matrix vector of the absolute acceleration of the \( i \) joint versus the base Cartesian system; \( \begin{pmatrix}
(e_{i-1,0}^l) \\
(a_{i-1,0}^l)
\end{pmatrix} \) - the dual matrix vector of the absolute acceleration of the \( i-1 \) joint versus the \( i-1 \) Cartesian system; \( \begin{bmatrix}
T_{i-1}^l
\end{bmatrix} \) - the quadratic 6x6 transfer matrix from the \( i-1 \) to \( i \) system; \( (S''(i)) \) - the dual matrix vector of the relative joint’s acceleration between \( i \) and \( i-1 \) joints versus \( i \) Cartesian system; \( (\omega_{i-1,0}^l) \) - antisimetrical absolute vector of the angular velocity of the \( i-1 \) joint versus \( i \) Cartesian system; \( (\alpha_{i-1,0}^l) \) - velocity angular

Fig. 1. Position, velocity, acceleration and jerk profile of unsynchronized 2D via-points motion [1].

Fig. 2. The didactical arm type robot used in the assisted research.
relative column matrix vector between \( i \) and \( i-1 \) joints; 
\[
\begin{pmatrix} a_{i,i-1} \\ \vdots \\ a_{1,0} \end{pmatrix}
\] – linear relative acceleration column matrix form between \( i \) and \( i-1 \) joints versus \( i \) Cartesian system; 
\[
(\omega_{i-1,0})^T \begin{pmatrix} r_{i,i-1} \end{pmatrix}
\] - column matrix centrifuge relative acceleration between \( i \) and \( i-1 \) joints versus \( i \) Cartesian system; 
\[
2(\omega_{i-1,0}) (v_{i,i-1}) - \text{column matrix form of the Coriolis relative acceleration between } i \text{ and } i-1 \text{ joints versus } i \text{ Cartesian system;}
\]
\[
(r_{0i}) \text{ is the column matrix vector for absolute position } i \text{ joint versus the zero point; } (r_{0i-1}) - \text{column matrix vector for absolute position } i-1 \text{ joint; } \[D^0_{i-1}] - \text{quadratic matrix for transfer vector from } i-1 \text{ to base system; } i \text{ - the current robot’s joint and have the 1-5 values.}
\]

Relation (2) is the 6x6 matrix equation of the dual matrix vector of the absolute accelerations by recursive calculus. Relation (3) describe the dual matrix vector of the relative acceleration using the transfer 6x6 matrix (5) between the Cartesian systems. With relation (4) will be possible to redefine all dual accelerations vectors vs. the robot’s base.

\[ Fig. 3. \text{ The front panel of the LabVIEW program.} \]

B. Description of the used LabVIEW Programs

The mathematical matrix model used in the assisted analyze of the robots joints accelerations was transposed in some virtual LabView instruments shown in Figs.3-6.

The front panel of the base program, Fig.3, and the icon, Fig.6, contents the part for the input data for each robot’s module and the results of simulation, the linear and angular acceleration characteristics and also the angular variation of the linear and angular acceleration in the 3D space, Fig. 4.

\[ Fig. 4. \text{ Front panel of the LabVIEW VI with some results after numerical simulation.} \]

The base program, Fig. 5, contents some sub VI-s that could be used in many other LabVIEW programs. The base program used the sub VI-s for the following actions: to determine all dual absolute vector velocity, the sub VI-s to generate the translation matrices between all Cartesian systems, the sub VI-s to generate all relative dual vectors of acceleration and the sub VI-s to generate the trapezoidal characteristics of each joints movements.

\[ Fig. 5. \text{ Part of the block schema of the LabVIEW program.} \]

\[ Fig. 6. \text{ Icon of the LabVIEW VI-s to determine the transfer matrices between the Cartesian robot’s joints.} \]

C. The Results of the Assisted Research

The theoretical assisted research with the proper LabView VI-s to determine the joint’s acceleration was done by using different velocities characteristics like: with simultaneously movements of all joints, with successive movements or simultaneously and successive after the acceleration time, or combine two movements to be simultaneously and other successive. All these results are shown in the Tables II and III. In the simulation activities, to be obtained good results, we used the trapezoidal characteristics of relative joint’s velocities in some different cases: simultaneously, successive, some successive and some simultaneously after acceleration time, some successive and some simultaneously after the constant velocity period, successive after the deceleration time, simultaneously with the same or different velocities values and also simulation with different measure of each robot’s body.

In all studied cases were shown the maximal variation of the linear and angular velocities, the space angle between the
base robot Cartesian system and the angular and linear acceleration of the end-effector. All these could influence the dynamic behavior of the robot in different types of applications. The maximum variation of the angular or linear acceleration, the increasing of the frequencies variation, influence the force and moment in the joints and determine the same variation of the dynamic behavior.

III. NEUTROSOPHIC THEORY APPLIED IN MULTI OBJECTIVES OPTIMIZATION OF THE ROBOT’S JOINTS ACCELERATIONS

The steps to optimize some of the functional parameters of the robot must be the followings: - chose the objective and if the action will be with only one objective function (f) or with multi objective function (mof); - define these objective functions; - define all constraints for the constructive and functional parameters imposed by the robot’s design of the structure and by physical application; - construct one complex algorithm in a iterative manner and apply them together with Neutrosophic theory because in other case the results must be null; - adjust the algorithm before will be touched the convergence process and will be obtained the results of the multi objective functions and apply the pounders and calculate the current pounders; - determine the values of the variables of the parameter of the (mof).

A. Generality of Optimization of the Acceleration’s Variation

The optimization of the acceleration contents the following steps:
1) We defined the mof vs. the following parameters, where p is the case study: from the relative velocity characteristics: t - time to origin; t - time delay between the joint’s movements; q - relative constant velocity in each joint; from the robot: - length L, of each robot’s body.

\[mof(t_i, t_d; q_i, L_i) \equiv \left\{ \begin{array}{l}
(p \text{ of min range } A_x) \cap \\
(p \text{ of min range } A_y) \cap \\
(p \text{ of min range } A_z) \cap \\
(p \text{ of min range } \epsilon_x) \cap \\
(p \text{ of min range } \epsilon_y) \cap \\
(p \text{ of min range } \epsilon_z) \cap \\
(p \text{ of min range } \epsilon_{angle}) \cap \\
(p \text{ of min range } v_{x,y,z})
\end{array} \right\}
\]

(6)

Define the constraints

\[A_{x \text{ min}} \leq A_x \leq A_{x \text{ max}}
\]
\[A_{y \text{ min}} \leq A_y \leq A_{y \text{ max}}
\]
\[A_{z \text{ min}} \leq A_z \leq A_{z \text{ max}}
\]
\[\epsilon_{x \text{ min}} \leq \epsilon_x \leq \epsilon_{x \text{ max}}
\]
\[\epsilon_{y \text{ min}} \leq \epsilon_y \leq \epsilon_{y \text{ max}}
\]
\[\epsilon_{z \text{ min}} \leq \epsilon_z \leq \epsilon_{z \text{ max}}
\]
\[\dot{q}_{\text{min x,y,z}} \leq \dot{q}_{x,y,z} \leq \dot{q}_{\text{max x,y,z}}
\]
\[\dot{q}_{\text{min x,y,z}} \leq \dot{q}_{x,y,z} \leq \dot{q}_{\text{max x,y,z}}
\]
\[\text{angle}_{\text{min}} \leq \angle A \leq \text{angle}_{\text{max}}
\]
\[\text{angle}_{\text{min}} \leq \angle A \leq \text{angle}_{\text{max}}
\]

(7)

2) Define the algorithm to obtain the best solution of the robot’s joints movements (mof):
3) Impose one time to origin t and time delay between each of joints, t and calculate all internal coordinates of each joints q(t), q(t), q(t);
4) Determine all relative velocity characteristics q(t), q(t), q(t);
5) Determine the characteristics of all absolute angular and linear accelerations:

\[f_1 = \text{acc}_x[q(t_i, t_d); \dot{q}_x(t_i, t_d), \ddot{q}_x(t_i, t_d)]
\]
\[f_2 = \text{acc}_y[q(t_i, t_d); \dot{q}_y(t_i, t_d), \ddot{q}_y(t_i, t_d)]
\]
\[f_3 = \text{acc}_z[q(t_i, t_d); \dot{q}_z(t_i, t_d), \ddot{q}_z(t_i, t_d)]
\]
\[f_4 = \arctan\left(\frac{\text{acc}_x}{\text{acc}_y}\right)\]
\[f_5 = \text{eps}_x[q(t_i, t_d); \dot{q}_x(t_i, t_d), \ddot{q}_x(t_i, t_d)]
\]
\[f_6 = \text{eps}_y[q(t_i, t_d); \dot{q}_y(t_i, t_d), \ddot{q}_y(t_i, t_d)]
\]
\[f_7 = \text{eps}_z[q(t_i, t_d); \dot{q}_z(t_i, t_d), \ddot{q}_z(t_i, t_d)]
\]
\[f_8 = \arctan\left(\frac{\text{eps}_x}{\text{eps}_y}\right)
\]

6) Determine the range of angular and linear accelerations:
\[R_{\text{acc x}}, R_{\text{acc y}}, R_{\text{acc z}}, R_{\text{acc angle}}, R_{\text{eps x}}, R_{\text{eps y}}, R_{\text{eps z}}, R_{\text{eps angle}}
\]
7) Determine the times t and t what will be obtained the minimum of each range;
8) Apply the (mof), or partial of complex function and determine the optimal values of the analyzed parameters t, t, t, q' .

B. Case Study of the Robot Arm Type

The analyse will be done after study of the synthetic report presented in the Tables II and III.

TABLE II: THE SYNTHETIC REPORT OF THE STUDIED CASES: 3D VARIATION OF THE EPS, ACC, ANGLE EPS, ANGLE ACC

| Case study | Eps. space variation | Acc. space variation | Eps. angle space variation | Acc. angle space variation |
|-----------|----------------------|----------------------|---------------------------|---------------------------|
| 0-0-0-0   | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |
| 0-2-4-6   | ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |
| 0-3-3-0   | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 3-0-0-3   | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) | ![Image](image16.png) |
| 3-3-0-0   | ![Image](image17.png) | ![Image](image18.png) | ![Image](image19.png) | ![Image](image20.png) |
To be analysed and to be compared between them, the synthetic results could be put in the form of the Table IV.
The values of the Table V will be calculate using the values from the Table IV with the maximal ranges of angular and linear acceleration is minimum. All others will be calculate by compare them with the minimal value and the maximum value of the ponder equal with 100. Consider that, all analyzed parameters are the same importance in a dynamic behavior of the robot and for that all parameters will have the same maximal ponderers $p=100$. The best solution that obtained after applied the mof was the case when the movements were simultaneously (0-0-0) and the lengths of the bodies were are different 100, 200, 300, 400, 100 (in inch) and the relative velocity is the same 200grd/s (bold case -the Table V).

| Case     | Eps. in the space | Acc. in the space | Eps. in the space | Acc. in the space | Eps. in the space | Acc. in the space | Eps. in the space | Acc. in the space | Results     |
|----------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|-------------|
| p        | 100              | 100              | 100              | 100              | 100              | 100              | 100              | 100              | 100         |
| 0-0-0     | 50               | 100              | 100              | 48               | 1,8              | 51,42            | 32               | 59,25            | 32          | 574,48      |
| 0-2-4-6   | 100              | 100              | 95,23            | 97,14            | 63,63            | 100              | 100              | 100              | 29,25        | 799,27      |
| 0-4-5-3   | 50               | 25               | 100              | 94,64            | 63,63            | 103               | 58,25            | 33,23            | 66,66       | 73,33        | 621,56      |
| 0-3-5-0   | 50               | 50               | 100              | 48               | 1,8              | 51,42            | 50               | 33,33            | 92,45        | 71,31        | 525,76      |
| 0-0-3-3   | 50               | 66,66            | 94,44            | 64               | 47,33            | 50               | 33,33            | 80               | 100          | 598,19      |
| 0-0-3-3   | 50               | 33,33            | 100              | 60               | 6                | 100              | 80               | 100              | 800          | 629,33      |
| 0-0-3-3   | 50               | 66,66            | 94,44            | 65,75            | 25,7              | 50               | 52,63            | 100              | 51,33        | 586,21      |
| 0-0-0-0  | 50               | 66,66            | 94,44            | 65,75            | 3                | 52,94            | 51,01            | 94,11            | 53,33        | 567,68      |
| 0-0-4-0  | 50               | 61,53            | 100              | 65,53            | 3,51              | 51,42            | 100              | 100              | 101,91       | 662,46      |
| 0-0-0-0  | 50               | 33               | 53,33            | 97,14            | 40               | 25,7              | 50               | 88,88            | 94,21        | 100          | 582,14      |
| 0-0-0-0  | 33               | 88,88            | 97,14            | 40               | 1,8               | 48,64            | 50               | 64               | 51,61        | 580,09      |
| 0-0-0-0  | 50               | 100              | 97,14            | 40               | 1,8               | 51,42            | 50               | 69,56            | 52,63        | 545,56      |

IV. CONCLUSION

The assisted research, proposed by this paper, with original contribution in modelling by 6x6 matrix form, and in the simulation with proper virtual LabVIEW instrument for the assisted research of the open way to the optimal assisted research in the future of the Kinematics and Dynamics for the different type of robots and for different robot’s applications in singular, multi robot application, or in the cooperation manner of the action. The analyse of the acceleration is one of the most important problem that must be solved in the robot’s kinematics. Positions, velocities, accelerations and jerks are the most important components in the dynamic behaviour equations and by known these will be possible to optimal choose the kinematic robot’s parameters to obtain finally the goals in robotics: the reduction of the space errors of the end-effector. The presented matrix equations to determine the linear and angular accelerations, the used mathematical algorithm, the virtual LabView instrumentation are generally and they could be applying in many other robotic applications.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

AO conducted the research and all mathematical model, algorithm and wrote the paper; SO analyzed the data and the English grammar; NM assured the experimental stand; NS work in the research of actual stage. All authors had approved the final version.

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Adrian Olaru graduated from 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 teaches the following courses: industrial robots Dynamics behavior, LabVIEW application in modeling and simulation of the dynamic behavior of robots and Personal and social robots. He is a doctor from 1989. In the last ten years he have 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 behavior of the forging manipulator orientation modulus; computer aided research over dynamic behavior of the charging manipulators tipping modulus; computer aided research over dynamic behavior 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 magnetorheological dampers; assisted research of the intelligent dampers; assisted research of the neural networks; optimizing of the robots dynamic behavior by using the Fourier proper analyzer; optimizing the dynamic compliance and global transmissibility by using the assisted research and proper LabVIEW instrumentation; optimize the dynamic behavior and the space trajectory by using the proper neural network.

Serban Olaru graduated from 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 RomSYS private 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 modeling with LabVIEW instrumentation.

Niculai Mihai graduated from the University Politehnica of Bucharest, Faculty of Machines and Manufacturing Systems, Romania. From 2006 he become Ph.D.Eng. in the field of robotics. Now, he is the manager of the private company in mechatronics systems, Technoaccord, Quebec, Canada.

Natalia Smidova graduated from Faculty of Mathematics and Physics, Charles University in Prague in 2005. He works at Department of Physics, Faculty of Electrical Engineering and Informatics, Technical University of Kosice. He oriented on investigation of material properties by spectroscopic (nuclear magnetic resonance (NMR) and Raman) methods. She is interested in polymers and polymer nanocomposites made from renewable resources.