New 5-DOF Industrial Robot Structure, Modeled and Optimized by the Finite Element Method

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***Abstract*—This paper presents the cinematic and dynamic performances of a new 5-DOF industrial robot structure that has been conceived, optimized and modeled using the finite element method. Finite element analysis has helped to find optimal solutions for locating kinematic elements, sizing the 5 robot modules accordingly, and improving the kinematic-mechanical behavior of component elements. The material used in the manufacture was T6061 aluminum.**

***Index Terms*—Forward and inverse kinematics, static finite element analysis.**

I. Introduction

The new industrial robot structure with 5 degrees of mobility has emerged from the need to obtain some higher cinematic and dynamic performance than the current level of industrial robots and the desire to minimize their manufacturing costs. The study of existing robots [1], already implemented in production, as well as the need to implement them suspended on the ceiling, led us to the conclusion that they are very heavy. This is due to the fact that the material used to construct the mechanical structure is too heavy, and that the kinematic elements are badly placed, which leads to their oversize, with a final result - an extremely large mass. This leads to extremely great difficulties in their implementation in specific production applications and even greater difficulty in suspending them on the ceiling. The metal structures need to be large enough to support them.

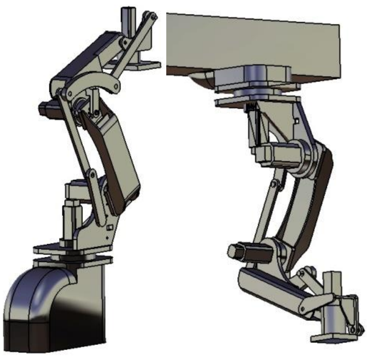

Fig. 1. Two possibilities of using the robot.

Many companies in the manufacturing industry want to implement robots on the ceiling, due to space considerations and easier cleaning of the workspace, especially in the wood industry and wood derivatives, where dust creates work problems.

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This is why we designed and optimized this dual-use structure both for placement in a normal position on the floor and suspended on a metallic structure (Fig. 1). Some technical features of the robot studied: payload 10 kg, total weight 72 Kg, maximum length of the arm 1300 mm, maximum speed 1.5 m / s.

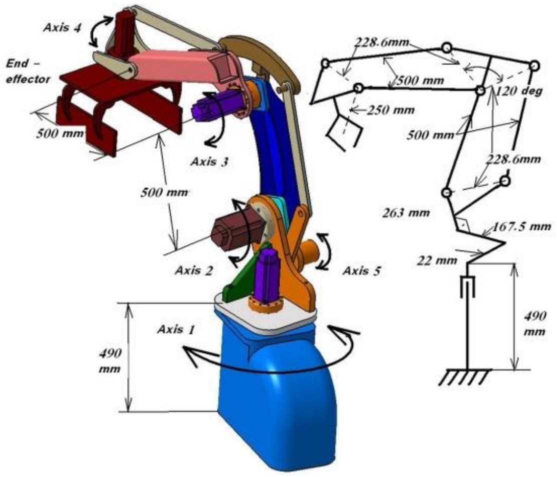

Fig. 2. The kinematic scheme and the main elements.

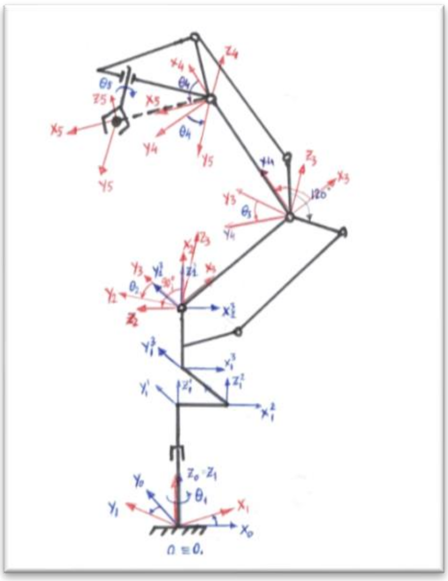

Fig. 3. The kinematic scheme.

II. The Mathematical Model of 5 DOF Robot

The mathematical model is required for real-time control and control of all five AC servomotors, each driven by an axis

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controller. The algorithms used are specific for solving the direct and inverse kinematics problems with the 4x4 transformation matrices using Denavit & Hartemberg parameters [2].

A. Solving the Problem of Direct Kinematics

In order to solve the problem of direct kinematics, we proceeded to the preparation of the kinematic diagram of the robot, presented together with the main elements in Fig. 2 [3].

In this figure are presented the robot modules, the kinematic elements, the joints, the segments dimensions, the axes and the angles of rotation. To obtain homogeneous 4x4 transformation matrices, we created the consecutive coordinate systems shown in Fig. 3. All the joints are rotation [4].

A homogeneous matrix T_0^i that specifies the position and orientation of the local and coordinate system [5], according to the coordinate system of the base, is obtained by making the product of the coordinate transformation matrices A_{j-1}^i (1).

$$T_0^i = \prod_{j=1}^{i} A_{j-1}^i = \begin{bmatrix} x_i & y_i & z_i & p_i \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} R_0^i & p_0^i \\ 0 & 1 \end{bmatrix}; \qquad (1)$$

In the case of our robot i = 5 (i represents the number of degrees of freedom) and then the relation (1) becomes (2).

$$T_0^5 = \prod_{j=1}^{5} A_{j-1}^5 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}; \qquad (2)$$

After all passage matrices have been obtained, according to the coordinate systems shown in Fig. 3, by multiplying them according to relation (2), the values of the final matrix coefficients T are shown in relations (3).

$$n_x = -c_4(s_1s_2c_3 + s_1c_2s_3) + s_4(s_1s_2s_3 - s_1c_2c_3);$$

$$n_y = c_4(c_1s_2c_3 + c_1c_2s_3) + s_4(c_1c_2c_3 - c_1s_2s_3);$$

$$n_z = c_4(s_2s_3 - c_2c_3) + s_4(c_2s_3 + s_2c_3);$$

$$o_x = s_4(s_1s_2c_3 + s_1c_2s_3) + c_4(s_1s_2s_3 - s_1c_2c_3);$$

$$o_y = -s_4(c_1s_2c_3 + c_1c_2s_3) + c_4(c_1c_2c_3 - c_1s_2s_3);$$

$$o_z = s_4(c_2c_3 - s_2s_3) + c_4(c_2s_3 + s_2c_3);$$

$$a_x = c_1; \quad a_y = s_1; \quad a_z = 0; \qquad (3)$$

$$p_x = -a_4c_4(s_1s_2c_3 + s_1c_2s_3) + a_4s_4(s_1s_2s_3 - s_1c_2c_3) +$$

$$+a_1c_1 - a_3s_1s_2c_3 - a_3s_1c_2s_3 - a_2s_1s_2 - bs_1;$$

$$p_y = a_4c_4(c_1s_2c_3 + c_1c_2s_3) + a_4s_4(c_1c_2c_3 - c_1s_2s_3) +$$

$$+a_1s_1 + a_3c_1s_2c_3 + a_3c_1c_2s_3 + a_2c_1s_2 + bc_1;$$

$$p_z = a_4c_4(s_2s_3 - c_2c_3) + a_4s_4(c_2s_3 + s_2c_3) -$$

$$-a_3c_2c_3 + a_3s_2s_3 + a_2c_2 + d;$$

where $s_i = \sin\theta_i$ et $c_i = \cos\theta_i$.

B. Solving the Problem of Inverse Kinematics

The problem of reverse kinematics can be solved by several methods: inverse transformation, dual matrices, dual quaternion, iterative or geometric approaches [6]. In the case of our robot we have implemented a geometric solution given the particularity that the robot arm is equal to the forearm (a2 = a3 = a), but also the fact that the robot has a deformable parallelogram system, which allows the parameter q4 to be preserved at a preset value. This means we have to obtain the values of the inter qi coordinates for each joint (4) [3].

$$q = (q_1, q_2, q_3, q_4, q_5)^T; \qquad (4)$$

Thus, we made the projection of the mechanical structure of the robot in two planes perpendicular to each other [4], [7].

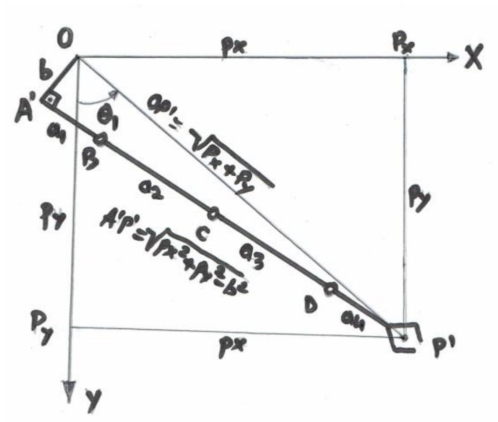

Fig. 4. Horizontal projection of the robot structure.

One is horizontal *xOy* (Fig. 4) and the other is vertical, which passes through the characteristic point and which perpendicularly articulates the parallels 2,3 and 4 (Fig. 5).

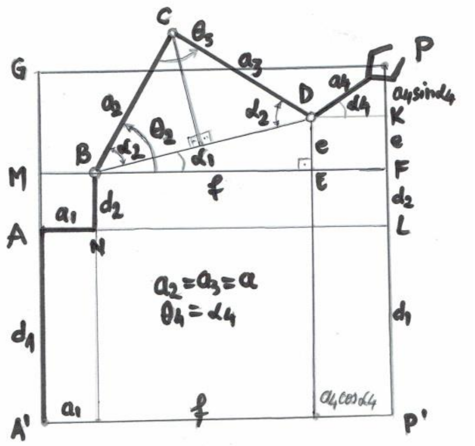

Fig. 5 Vertical projection of the robot structure.

According to Fig. 4, we can easily calculate the pivot angle of the robot with the relationship (5).

$$q_1 = \theta_1 = arctg\,\frac{p_x}{p_y}; \qquad (5)$$

For the calculation of the other internal coordinates, it is necessary to first determine the value of the segments "e" (6) and "f" (7), presented in Fig. 5 as DE and BE segments.

$$e = p_z - a_4 \sin \alpha_4 - d_1 - d_2; \quad (6)$$

$$f = \sqrt{p_x^2 + p_y^2 - b^2} - a_1 - a_4 \cos \alpha_4 ; \quad (7)$$

Once these mathematical relationships are determined, we introduce them into the internal parameter calculation formulas $q2$, $q3$, $q4$ and $q5$ (8).

$$q_2 = \theta_2 = \alpha_1 + \alpha_2 = arctg\, \frac{e}{f} + \, arcos\, \frac{\sqrt{e^2 + f^2}}{2a};$$

$$q_3 = \theta_3 = 180 - 2\, \alpha_2 = 180 - 2\, arcos\, \frac{\sqrt{e^2 + f^2}}{2a};$$

$$q_4 = \theta_4 = \alpha_4; \quad (8)$$

$$q_5 = \theta_5 = \alpha_5;$$

where α_4 represents the angle in the 4th joint, permanently imposed on the mechanical hand, by the deformed parallelogram system attached to the base of the robot, and α_5 represents the angle in the number 5 (roll), and which allows the mechanical hand to rotate independently of the other internal joints.

III. Static Analysis with Finite Elements of the Robot's Mechanical Structure

We have used finite element analysis to optimize the robot's mechanical structure because this method gives us the ability to correct errors in points where applied forces generate stress inappropriate to the mechanical structure. The optimization was carried out in successive stages, modifying the dimensions of the component elements, especially their thickness, as well as how to place the kinematic elements on the structure as well as the fixing methods. For a good finite element analysis we proceeded to design each element of the mechanical structure in 3D, and then we assembled them using the centering arms and the clamping screws. We have fixed the rigid fixing surface as the base of the robot and have chosen the surface that is subjected to evenly distributed forces. Figure 6 shows the mechanical structure rigidly fixed at the base of the robot, to which normal forces are applied on the surface of the mechanical hand, 100 N, oriented in the opposite direction of the axis Oz [8].

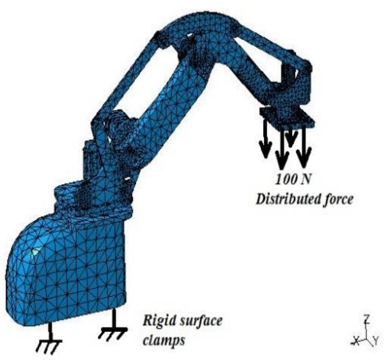

Fig. 6. Distribution of applied forces.

These forces generate tensions in the structure, leading to uneven deformations in the various nodes.

TABLE I: Structure Computation

Number of nodes	8769
Number of elements	29373
Number of DOF	26379
Number of contact relations	112
Number of coefficients	448
Number of kinematic relations	9084

The octree tetrahedron mesh has the element type parabolic shape, with maximum size at 1 inch. The connections between elements are type contact and rigid. The structure computation is presents in Table I.

TABLE II: Torques and Forces Equilibrium

Components	Applied Forces	Reactions	Residual	Relative Magnitude Error
Fx (N)	-4.2201e-010	9.4811e-011	-3.2719e-010	8.4489e-013
Fy (N)	0.0000e+000	4.9865e-010	4.9865e-010	1.2876e-012
Fz (N)	-1.0000e+002	1.0000e+002	1.5248e-009	3.9374e-012
Mx (Nxm)	1.8291e+001	-1.8291e+001	-5.1866e-010	1.4175e-012
My (Nxm)	-6.7947e+001	6.7947e+001	1.9407e-009	5.3040e-012
Mz (Nxm)	-1.1244e-010	-5.3142e-010	-6.4386e-010	1.7597e-012

The Von Mises stress is calculated in all nodes of the network, and the strongest are highlighted in the color code shown in Fig. 7. It is thus observed that the highest value is found on the robot arm near the J2 joint.

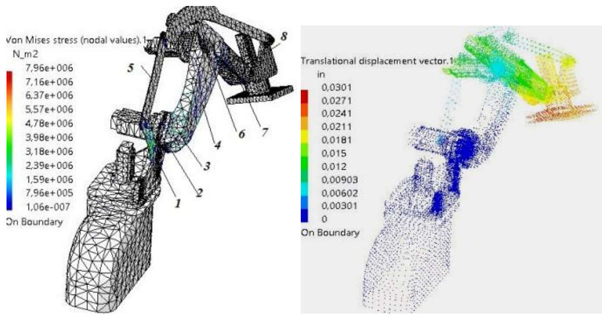

Fig. 7. Exaggerated deformation of the structure to highlight critical points (left side) and unaccepted maximum translational displacements (right side).

Structural deformations in the J2 joint area are the most unfavorable because they cause the greatest system control problems: 1) produce the largest TCP point trajectory positioning errors; 2) creates the highest vibrations in the system, especially at high speeds and accelerations; 3) system stabilization becomes difficult to optimize the parameters of each servo system of each axis. In these conditions, through successive tests performed in practice, we noticed that as a matter of fact, we cannot stabilize the system, even if the PID parameter changes are modified with great accuracy for each axis. Improving the mechanical stiffness of the structure is absolutely necessary.

IV. Analysis of Results and Proposing Solutions for Improvement

As can be seen in the simulation of Fig. 7, deformations of the structure are very high. If stress values are within the breaking limit, 0.0301 inch (0.0765 mm) displacement values can't be accepted. This is the reason why we have proceeded to successively improve the rigidity of the mechanical structure [8].

Several successive modifications were made at the places shown in Fig. 7, in particular on the following elements: 1 - supporting rod of the deformable parallelogram mechanism; 2 - the arm attachment of the robot body; 3 - the shape and size of the lower part of the arm, where the structure is most affected by the forces applied; 4 - the shape and thickness of the arm; 5 - Parallelogram mechanism rods; 6 - the forearm Ze places where the biggest errors of the mathematical model are found. These errors are very small, as presented in the table in the figure, which leads us to the conclusion that the choice of the mathematical modeling method through finite element analysis has led us to very good results.

VI. Conclusion and Future Work

This scientific paper highlights the way in which it was possible to design a new industrial robot structure with 5 degrees of freedom through mathematical modeling and finite element analysis. Mathematical algorithms of direct and inverse kinematics are easy to implement in the robot controller, due to the simple form of motion equations, especially in the case of inverse kinematics. They make it easy to determine the speeds and accelerations in the couplings and better mechanical positioning precision.

Finite Element Analysis allowed us to optimize component parts and ensured a maximum deformation of 0.0063 inches, which is a very good accuracy for 10 Kg payload. What remains to be done is the effective realization of the structure, the implementation of mathematical algorithms in the controller and practical laboratory tests. The next step is to improve the mechanical structure of the robot to reduce the positioning errors on the trajectory and for better stability of travel for high speeds and accelerations. One of the solutions is to change the material, instead of aluminum to use carbon fiber, as robot material construction.

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