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Design of a 4-DOF Robot Manipulator with Optimized Algorithm for Inverse Kinematics

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***Abstract*—**This paper shows in detail the mathematical model of direct and inverse kinematics for a robot manipulator (welding type) with four degrees of freedom. Using the D-H parameters, screw theory, numerical, geometric and interpolation methods, the theoretical and practical values of the position of robot were determined using an optimized algorithm for inverse kinematics obtaining the values of the particular joints in order to determine the virtual paths in a relatively short time.

***Keywords*—**Kinematics, degree of freedom, optimization, robot manipulator.

I. Introduction

At present, the area of industrial robotics is attracting the attention of various areas of research and technological development due to the rapid progress of the technology in different areas such as mechatronics, information technology, modern control systems and related technologies in the automotive and aerospace industries [1]-[3]. In addition, according to the process automation trends, the design of new robotic manipulators is the actual need, because with them is possible to ensure the integrity of various processes and eliminating operational risks to humans. Also, the manipulation of microscopic objects, especially biological objects using micro-electro-mechanical systems (MEMS) components, has become an important area of robotics research [4], [5]. Added to the above, the robotics every day reaches a greater degree of service against various circumstances, especially for human service [6]. Thus, various concepts and methods used for the design of a robot are important analyze and optimize, for example, the concepts and methods for the kinematics. Concerning to direct and inverse kinematics of the robot, several strategies has been proposed [7]-[10]. However, depending of the methods used to obtain the kinematic equations is possible to require more computationally power-efficient or the use of Lie and quatemions algebra [11], [12].

This paper describes the mechanical design and kinematic equations of a robotic manipulator with 4 degrees of freedom applicable to the development of industry in turn as a graduate research project. The kinematic analysis of the manipulator clearly was developed using direct and inverse kinematics, in order to determine the precise model that indicates the angular position is each joint. Both processes are described separately, and in turn the assembly mechanical design developed computer displays, identifying each of its links and the coordinate system for the joints. In the case of inverse kinematics, an optimized computational algorithm was implemented in order to obtain the values of the angular joints without using too much algebraic and computational processing.

II. Mechanical Design of the Prototype

The mechatronic system is an anthropomorphic robotic arm for industrial purpose. According to the stages of the overall project, the robot was initially designed to position points within a space in 3Dand after will be adding tools to act as an industrial welder. The robot has four degrees of freedom (DOF) considered sufficient for the end purpose. The first DOF has a rotational joint at the base, allowing movement in 360 degrees to increase the workspace, followed by three rotational joints. AllDOF will serve to positioning the robot at the desired points and using linear and nonlinear interpolation will be establishing paths for the robotic arm not considering obstacles. The mechanical design is show in Fig. 1.

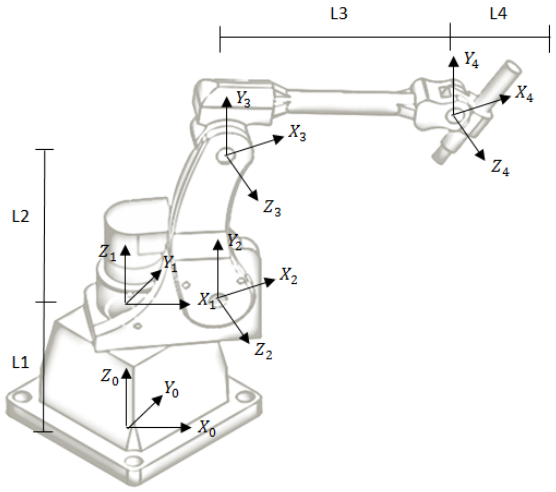


Fig. 1 Mechanical design and assignment of frames

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Convention for Assignation of Frames to Joints and D-H Parameters

The convention used to locate the frames in the joints is shown in Figs. 1 and 2. The axis Z of the frame 0 ({0}) and 1 ({1}) is coincident with the joint 1, while the frames 2, 3, 4 and 5 are out of the plane, axis Z, while the X and Y axes are formed according the right and rule on all frames. Fig. 2 shows the assignment of full frames and manipulator work space. By assigning frames is possible to obtain the Denavit-Hartenberg (*D-H*) parameters shown in Table I, which were used to calculate the homogeneous transformation matrix for each of the coordinate systems (or frame), following the general form:

$$ {}^{i-1}_{i}T = \begin{pmatrix} C\theta_i & -S\theta_i & 0 & a_{i-1} \\ S\theta_i C\alpha_{i-1} & C\theta_i C\alpha_{i-1} & -S\alpha_{i-1} & -S\alpha_{i-1}d_i \\ S\theta_i S\alpha_{i-1} & C\theta_i S\alpha_{i-1} & C\alpha_{i-1} & C\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1) $$

where the trigonometric functions, *sine* and *cosine* have been replaced by the letters "*S*" and "*C*" respectively for space considerations [13],[14].

As for the dimensions of the links, the lengths (*l1*, *l2*, *l3* and *l4*) of the links were established (15 cm). Table I shows the Denavit-Hartenberg parameters obtained from the mechanical design and configuration of the frames.

TABLE I
DENAVIT-HARTENBERG PARAMETERS

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	90	0	*l1*	θ_2
3	0	*l2*	0	θ_3
4	0	*l3*	0	θ_4
5	0	*l4*	0	0

In addition, Fig. 2 shows the assigned frames of the manipulator and the different references (work-table and object). Fig. 2 overlap frames 1 & 2 due to that the distance caused by motors dimension is not considered for the calculations.

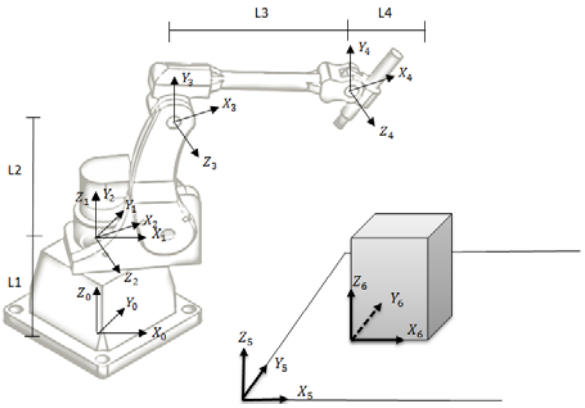


Fig. 2 Assignment of frames in the complete workspace

III. DIRECT KINEMATIC

Direct kinematics of a robot system is described by a transformation matrix *T*, which relates both the position and orientation of the endpoint (tool) of the robot with respect to a fixed reference (frame) coordinate system, which generally is the physical basis or frame {0}.This relationship is made using theparticular homogeneous transformations between joints, that involves translations and rotations. However, is possible to obtain the complete homogeneous transformations that involve all the joints in a general form. In our case:

$$ T = {}^{0}_{5}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T \quad (2) $$

Using the parameters of Table I and (1), the Denavit-Hartenberg parameters are assigned to the respective frames for each pair of joint, resulting in the following matrix.

$$ {}^{0}_{1}T = \begin{pmatrix} C\theta_1 & -S\theta_1 & 0 & 0 \\ S\theta_1 & C\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3) $$

$$ {}^{1}_{2}T = \begin{pmatrix} C\theta_2 & -S\theta_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S\theta_2 & C\theta_2 & 0 & l_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (4) $$

$$ {}^{2}_{3}T = \begin{pmatrix} C\theta_3 & -S\theta_3 & 0 & l_2 \\ S\theta_3 & C\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5) $$

$$ {}^{3}_{4}T = \begin{pmatrix} C\theta_4 & -S\theta_4 & 0 & l_3 \\ S\theta_4 & C\theta_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (6) $$

$$ {}^{4}_{5}T = \begin{pmatrix} 1 & 0 & 0 & l_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (7) $$

Equations (3)-(7) show the different homogeneous transformation for each pair of joints. Next, is necessary the algebraic development of (2). So, various matrixes resulting from the different components of (2) as shown:

$$ {}^{3}_{5}T = {}^{3}_{4}T\,{}^{4}_{5}T = \begin{pmatrix} C\theta_4 & -S\theta_4 & 0 & C\theta_4 l_4 + l_3 \\ S\theta_4 & C\theta_4 & 0 & S\theta_4 l_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (8) $$

$$ {}^{2}_{5}T = \begin{pmatrix} C\theta_3 C\theta_4 - S\theta_3 S\theta_4 & -C\theta_3 S\theta_4 - S\theta_3 C\theta_4 & 0 & C\theta_3(C\theta_4 l_4 + l_3) - S\theta_3(S\theta_4 l_4) + l_2 \\ S\theta_3 C\theta_4 + C\theta_3 S\theta_4 & -S\theta_3 S\theta_4 + C\theta_3 C\theta_4 & 0 & S\theta_3(C\theta_4 l_4 + l_3) + C\theta_3(S\theta_4 l_4) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (9) $$

In order to obtain a compact mathematical result, the following changes of variables and theorems were used: $C_{ij} = C\theta_i C\theta_j - S\theta_i S\theta_j$. $S_{ij} = S\theta_i C\theta_j + C\theta_i S\theta_j$, $a_1 = C\theta_3(C\theta_4 l_4 + l_3) - S\theta_3(S\theta_4 l_4) + l_2$, $a_2 = S\theta_3(C\theta_4 l_4 + l_3) + C\theta_3(S\theta_4 l_4)$

Applying these changes, the frames ${}^{2}_{5}T$ and ${}^{1}_{2}T$ are reduced to:

$$ {}^{2}_{5}T = \begin{pmatrix} C\theta_{34} & -S\theta_{34} & 0 & a_1 \\ S\theta_{34} & C\theta_{34} & 0 & a_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (10) $$

$$ {}^{1}_{5}T = {}^{1}_{2}T\,{}^{2}_{5}T = \begin{pmatrix} C\theta_{234} & -S\theta_{234} & 0 & b_1 \\ 0 & 0 & -1 & 0 \\ S\theta_{234} & C\theta_{234} & 0 & b_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (11) $$

In addition to the theorems of addition and subtraction of angles, the following variable changes were made:$b_1 = C\theta_2 a_1 - S\theta_2 a_2$ and $b_2 = S\theta_2 a_1 + C\theta_2 a_2 + l_1$

Finally, the complete homogeneous transform of our system is given by:

$$ {}^{0}_{5}T = {}^{0}_{1}T\,{}^{1}_{5}T = \begin{pmatrix} C\theta_1 C\theta_{234} & -C\theta_1 S\theta_{234} & S\theta_1 & C\theta_1 b_1 \\ S\theta_1 C\theta_{234} & -S\theta_1 S\theta_{234} & -C\theta_1 & S\theta_1 b_1 \\ S\theta_{234} & C\theta_{234} & 0 & b_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (12) $$

Next, the variables *b1* and *b2*were replaced in order to obtain the values for the various positions *px*, *py* and *pz* given by:

$$ p_x = C\theta_1(C\theta_{234}l_4 + C\theta_{23}l_3 + C\theta_2 l_2) \quad (13) $$

$$ p_y = S\theta_1(C\theta_{234}l_4 + C\theta_{23}l_3 + C\theta_2 l_2) \quad (14) $$

$$ p_z = S\theta_{234}l_4 + S\theta_{23}l_3 + S\theta_2 l_2 + l_1 \quad (15) $$

Finally, the positions in all axes, *px*,*py* and *pz* are given by (16)-(18) :

$$ p_x = C\theta_1(C(\theta_2+\theta_3+\theta_4)l_4 + C(\theta_2+\theta_3)l_3 + C\theta_2 l_2) \quad (16) $$

$$ p_y = S\theta_1(C(\theta_2+\theta_3+\theta_4)l_4 + C(\theta_2+\theta_3)l_3 + C\theta_2 l_2) \quad (17) $$

$$ p_z = S(\theta_2+\theta_3+\theta_4)l_4 + S(\theta_2+\theta_3)l_3 + S\theta_2 l_2 + l_1 \quad (18) $$

IV. Optimized Algorithm for Inverse Kinematics

Contrary to the case of direct kinematics, in the inverse kinematics is necessary to calculating the values that should have the joint according to an encoder (position sensor), in order to fix a specific position and orientation of the final tool. Although there are generic methods to carry out the inverse kinematics equations from the equations of direct kinematics; they are often iterative and with slow convergence or even no guarantee the results. Also, occurs the case that the solution is not unique, i.e. there are several solutions (configurations) of the same robot that allow a specific position and orientation. In these cases the solutions have to be restricted in order to use the best solution [15], [16]. In roughly speaking, there are three methods to solve this kind of problem: *a) Numerical Methods:* In most cases is necessary to solve a set of nonlinear equations, so that several iterative numerical methods are implemented to perform this task. Besides solving this problem can lead to multiple outcomes (different joint configurations that achieve the same configuration of the end effect or) or there may be no solution (position not reachable) [17], *b) Geometric methods:* This method is commonly used for robot with few degrees of freedom. The method is based on finding sufficient numbers of geometric relationships which will involve the coordinates of the end effector of the robot [18], *c) Algebraic methods:* In such methods is require the manipulation of the equations given in order to find a closed algebraic solution. It turns out that for much common geometry often arise various forms of transcendental equations [12].

In this paper, the combination of numerical and geometric methods in order to solve the inverse kinematics solutions was used, however there exist others hybrid methods [19]. This combination of methods is used to make more efficient and accurate the resolution of angles of each joint, because if only is used numerical methods, the number of operations increases exponentially using *Matlab*, so the method is inefficient. The inverse kinematics algorithm used in this work uses the geometric method to determine only the displacement angle of the joint 1 (or frame {1}) based on its mechanical configuration. This is done because the position of this joint only determines the position of the arm in the *XY*-plane and is independent of the other joints for calculating the value in the axis *Z*. This feature enables us to calculate the angle of the first joint in a geometrical way as follows:

Considering an imaginary unit vector in the X axis as a reference:

$$ \hat{X}i = (1,0) \quad (20) $$

And consider the desired points *pxi* and *pyi* to generate a displacement vector in the *XY*-plane:

$$ \hat{X}_{i+1} = (pxi, pyi) \quad (21) $$

Now, knowing the value of these two vectors is possible to calculate the angle β that exists between them as:

$$ \cos(\beta) = (u * v)/(|u| * |v|) \quad (22) $$

where *pxi*=*u* and *pyi*=*v*.

Fig. 3 shows the algorithm of the mathematical expression mentioned.

Fig. 3 shows the flow diagram of the algorithm used in this project for solving the inverse kinematic parameters, which begins by defining the variables to be used and then are need the desired position (*pxi, pyi, pzi*) in 3D space in order to be reached for the final tool of manipulator. With these data it is possible to determine the angle "θ_1" of the first joint using a geometric method, which uses the reference vector "*v1[1,0]*" and the position vector "*v2* [*pxi*,*pyi*]" to calculate the angle between them. Because this calculation gives us a pure positive angle, it is necessary to determine the sign of the angle through a decision function. After calculating the first angular position, is necessary to determine the others using a numerical method. So, the final result of the algorithm shown in Fig. 3 will be the incoming data for the algorithm shown in

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Fig. 4 that represent the optimized algorithm for complete inverse kinematic. For calculating the remaining angular positions (θ_2, θ_3, and θ_4), three "*for*" cycles functions were programmed in order to determine all the possible combinations of angles for the mentioned joints (or frames). Within the last cycle, the calculations of "*px, py, pz*" and the errors in the position *px* using *pxi* and *pz* with *pzi* were performed. Then, the decision function is performed, which required the parameters εtx and εty assigned to be lower than the margin of error value εs. If the calculated errors (εtxandεty) are greater than εs, the algorithm continues working within cycles, on the other hand, the final positions values of *X*, *Y* and *Z* are calculated. Finally, the values obtained are displayed and used for the configuration of the manipulator robot.

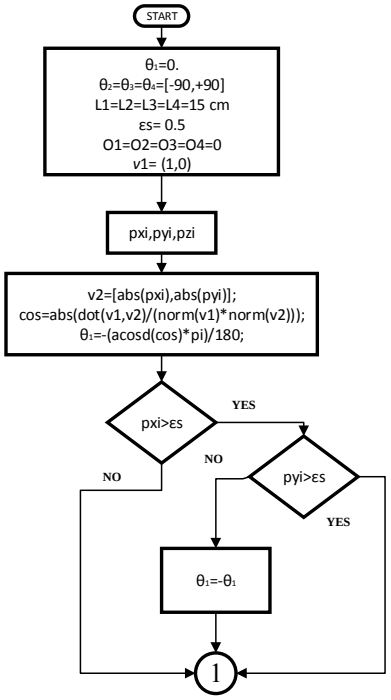


Fig. 3 Geometrical algorithm for calculate the angular position of {1}

TABLE II
PROPOSED AND PRACTICAL PARAMETERS

pxp	*pyp*	*pzp*	*pxc.*	*pyc*	*pzc*	Θ_1	Θ_2	Θ_3	Θ_4
30	20	20	29.85	19.90	20.09	33.69	-45.75	80.94	-6.53
40	20	20	39.80	19.90	19.97	26.56	-1.50	10.53	2.51
30	10	20	29.89	9.96	20.03	18.43	-58.83	87.92	15.58
40	10	20	39.80	9.95	19.92	14.03	-26.64	47.76	3.51
33.33	20	20	33.18	19.91	19.99	30.96	-34.69	57.82	10.55
36.66	20	20	36.54	19.93	19.90	28.61	-23.63	41.73	6.53
40	16.66	20	39.87	16.60	19.90	22.61	-14.58	28.65	5.53
40	13.33	20	39.90	13.26	19.90	18.43	-21.62	39.72	4.52
36.66	10	20	36.49	9.95	20.04	15.25	-38.71	61.84	11.56
33.33	10	20	33.19	9.95	20.03	16.70	-49.77	78.93	8.54
30	13.33	20	29.94	13.30	19.91	23.95	-55.81	85.97	10.55
30	16.66	20	29.87	16.58	19.95	29.04	-51.78	83.91	3.51

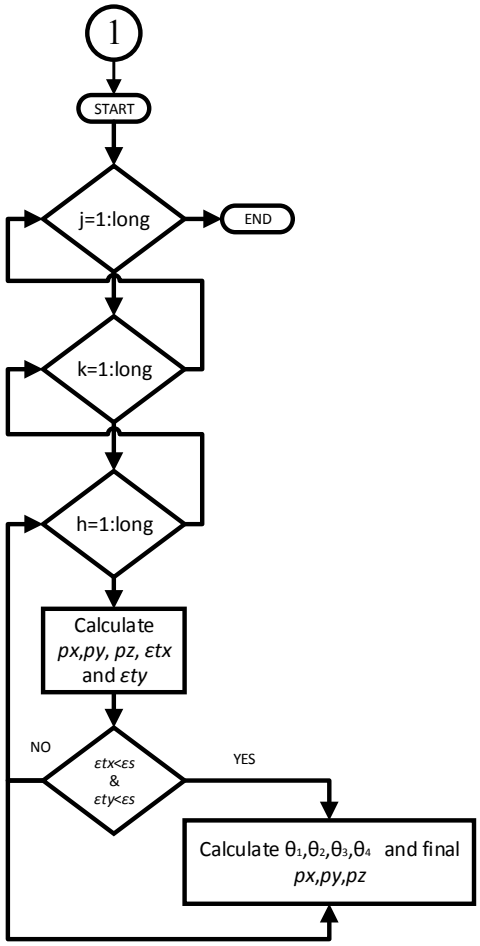


Fig. 4 Numerical algorithm for calculate the angular positions of inverse kinematic

As shown in Table II, the error between the proposed (*pxp*, *pyp* and *pzp*) and results points (*pxc*, *pyc* and *pzc*) are minimal using the optimized algorithm. In addition, the algorithm generates the angular values for each joint for each specific position. Also, due to the results obtained by the algorithm of inverse kinematics, is important to emphasizing the remarkable improvement in the response time (6 seconds) using a virtual encoder resolution of 1 degree. Fig. 5 shows different response time using different virtual encoder resolution. Obviously, while more resolution is used, the programmed algorithm increases the processing time.

V. ANALYTICAL AND SIMULATED RESULTS

Considering the results obtained by means of the equations and algorithms of direct and inverse kinematics, in this section the simulation results of the theoretical performance of the manipulator robot is shown. Fig. 6 shows the performance of the final tool changing the position (rotting each joint) of the manipulator of each degree of freedom.

The coordinate (44.99, -0.6725,15) was fixed for simulation purposes. Next. all the degrees of freedom was modified, so that were generated four paths in the *Z* axis corresponding to the last three joints, also is rotated the first joint generating a

path on the *XY*-plane. So, according to Fig. 6 is possible to determinate the workspace of the manipulator.

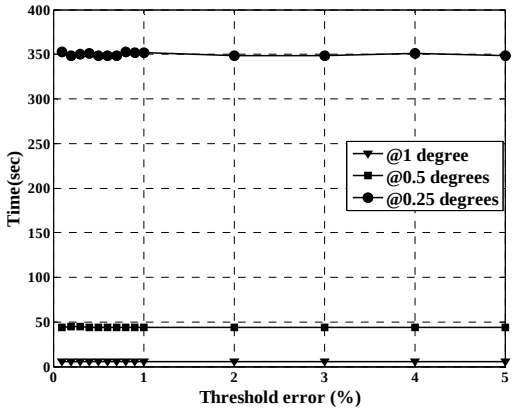


Fig. 5 Response time of the optimized algorithm using different virtual encoder resolution

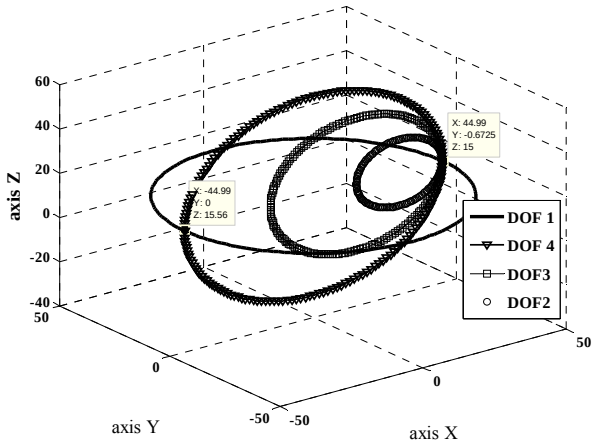


Fig. 6 Simulated results for different configuration of joints.

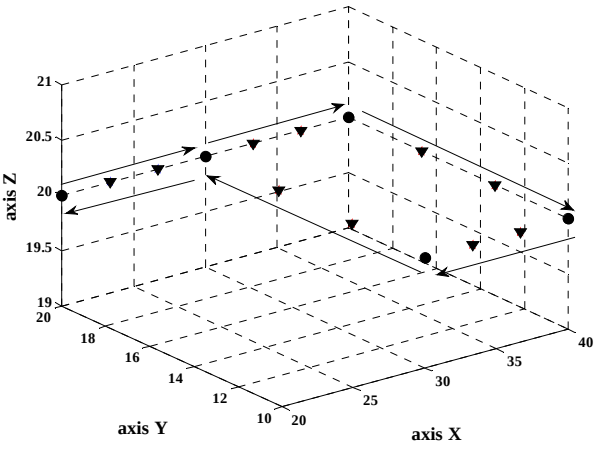


Fig. 7 Results of simulated work path manipulator robot

Finally, given the final purpose of the manipulator robot, was calculated a virtual path using linear interpolation as shown in Fig. 7. The aforementioned route was set up using the optimized algorithms programmed shown above. For the specific path shown in Fig. 7, the time required to calculate all the particular locations of the path was 1.66 minutes.

V. Conclusion

This article has shown the conceptual mechanical design of a manipulator robot with 4 DOF. Also has obtained the mathematical equations that describe the inverse and direct kinematics. Thus, using the equations of inverse kinematics, as well as a hybrid method, the angular values of individual joints were obtained to reach a specific point in the Cartesian plane. The hybrid method (or algorithm) for the inverse kinematics used is conformed for the combination of numerical and geometric methods. This combination of methods is used to make more efficient and accurate resolution of angles of each joint. The results show that the algorithm has appropriate performance with a relatively short computational time execution. Thus, using the algorithm is possible to obtain the set of angular values that place the end effector is a specific location resolution. Although it could be considered that the time required to generate the virtual path (Fig. 7) is large, it is possible to improve by using a digital processing system (or a computer systems with more computational power) such as an FPGA or microprocessor.

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