

24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1655

DESIGN, ANALYSIS AND SOFTWARE CORRECTION FOR THE PERFORMANCE OF A SCARA ROBOT

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Abstract. *The industrial robotic manipulators have become popular in industries, requiring qualified professionals to operate them. The teaching of industrial robotics has employed didactic robots. Commercially available robots are usually imported and expensive, this situation has led to the development of models in the educational institutions themselves. Regardless of the design methodology employed, the project has its potential limited by the manufacturing resources available in the educational institutions. One possible way to correct the performance of the robotic manipulator due to manufacturing failures is through a correction by software. The article presents a robot design systematic, prototype performance analysis and a correction by software of the manufacturing problems.*

Keywords: *robotics, design, performance, correction, adjustment.*

1. INTRODUCTION

The increasing diffusion of robotics teaching in university courses, motivated by the increasing use of robots in the industries, demanded the use of didactic robots with open architecture. The teaching kits with characteristics similar to the industrial robots are mostly imported and expensive (Reis and Vidal Filho, 2016; Vidal Filho, 2012). This situation motivated the development of didactic manipulators in educational institutions, but economic restrictions in educational institutions difficult the manufacturing process, taking into account that there is no specialized machinery or skilled workers to manufacture robotic manipulators with the same precision of commercial robots. One way to remedy the effects of manufacturing quality problems in the performance of didactic robots is to employ a correction through control software. When a divergence occurs between the design measures and the measurements of the manufactured robot, a positioning error can be perceived. This fact occurs when the robot is programmed offline or when it has to follow a trajectory, because in offline programming the robot controller uses a mathematical model with parameters derived from the design measures. This article presents the design of a SCARA (Selective Compliance Assembly Robot Arm) robot, the prototype performance analysis methodology and the systematic to reduce the errors of positioning by software.

2. DESIGN METHODOLOGY

Choosing a good systematic is the first step to ensure the success of a project. Reviewing the literature, several articles on design, modeling and controlling manipulator robots are observed (Shariatee, *et al.*, 2014; Urrea, *et al.*, 2016). Most do not detail all the systematics used. In Vidal Filho *et al.* (2001), a system is presented which divides the robot design into the development of three systems: mechanical, electro-electronic and control. The first two are subdivided into three subsystems: structure, actuators and transmission. The control system is subdivided into a control system and a safety system. Initially the complete set of the conceptual design is made and then each subsystem is designed according to the flowchart shown in fig.1. There is a great emphasis on translating specifications from needs.

Vidal Filho *et al.* (2001) focused on the design of the mechanical system and provided guidelines for the design of each subsystem.

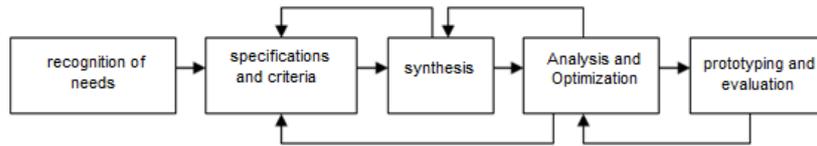


Figure 1. Systematic design of each subsystem (Vidal Filho, 2001)

In Diaz *et al.* (2007), the design of a SCARA manipulator was presented. The project was divided in simulation using CAD/CAE software, geometric modeling, kinematics and dynamics. Nevertheless the design specifications are not informed. Santos *et al.* (2012) developed a systematic implemented in software with the objective of assisting in the mechanical design. The desired requirements were established and the architecture of the mechanism was synthesized. Subsequently, starting from the payload, length of the necessary displacements and working times, the dimensions of the links were calculated and the strategy of the trajectory generation was chosen. After that, the kinematic modeling of the manipulator was made, maximum speeds and accelerations were identified and the torques at the joints were calculated. Finally the moments of inertia of the links were calculated, the resistance of the materials was analyzed and the sections of the links were dimensioned.

2.1 Mechanical design

The project starts with the specifications obtained from the requirement analysis. The desired robot has the objective of being employed in didactic activities, therefore it has to have a dimension that is compatible with a laboratory table and a must be low cost. The robot should have a payload of 250 g and reach between 250 and 300 mm. In Reis and Vidal Filho (2016) a market research was made on didactic robots and this analysis was used to complete the design specifications. The structural configuration chosen was the SCARA type. Aluminum alloy tubes with square cross-section were chosen instead of choosing plates to build the robot, as in Reis and Vidal Filho (2016). The main advantage of this assembly is to simplify manufacturing and reduce cost. Static calculations are initially made to determine the tube wall thickness and the cross-sectional area. The larger the section area, the smaller the required wall thickness of the pipe to tolerate the same load. The mathematical model choose to analyze the mechanical resistance of the arm considers the arm as a crimped beam. The failure criterion used in engineering design is the maximum material flow stress, however a robot must have a high rigidity that does not produce elastic deformations that could affect the desired accuracy. In this way, the failure criterion choose is associated with a maximum elastic deformation for the specified payload. As there are a small number of square section pipe options, the 50x50 mm section was chosen and analyzed for its deformation with an operating load. The equation (1) was used.

$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI} \quad (1)$$

Where, M is the moment of flexion due to external loads, E is the modulus of elasticity and I is the moment of inertia of the area. A deformation of 0.06 mm was calculated, which was acceptable. Subsequently the dynamic modeling was done using the Euler-Lagrange equation below.

$$T_i = \frac{\partial}{\partial t} \left(\frac{\partial L}{\partial \dot{\theta}_i} \right) - \frac{\partial L}{\partial \theta_i} \quad (2)$$

Where L is the Lagrangian, the difference of kinetic energy and gravitational potential, T is the torque and θ is the angle of the joint.

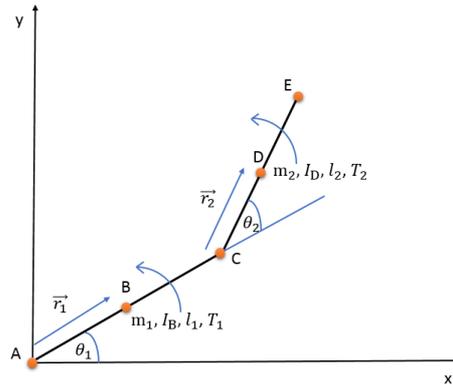


Figure 2. Dinamic model(Mello,2016)

In the graph shown in figure 2, θ_1 and θ_2 are the angular displacements of the joints, l_1 and l_2 are the length of the links, r_1 is the distance between points A and B, r_2 is distance between points C and D, points B and D are the center of mass, I_B is the moment of inertia of the first link in relation to point B, I_D is the moment of inertia of the second link in relation to point D, m_1 and m_2 are the mass of the links plus the motors mass, and T_1 and T_2 are the torques in the joints. Using equation (2), equation (3) can be obtained:

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = A \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + B \begin{bmatrix} \dot{\theta}_1 \dot{\theta}_2 \\ \dot{\theta}_2 \dot{\theta}_1 \end{bmatrix} + C \begin{bmatrix} \dot{\theta}_1^2 \\ \dot{\theta}_2^2 \end{bmatrix} + D \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \quad (3)$$

where,

$$A = \begin{bmatrix} I_A + I_D + m_2 l_1 + m_2 r_2^2 + 2m_2 l_1 r_2 \cos \theta_2 & m_2 r_2^2 + m_2 l_1 r_2 \cos \theta_2 + I_D \\ m_2 r_2^2 + m_2 l_1 r_2 \cos \theta_2 + I_D & m_2 r_2^2 + I_D \end{bmatrix} \quad (4)$$

$$B = \begin{bmatrix} -m_2 l_1 r_2 \sin \theta_2 & -m_2 l_1 r_2 \sin \theta_2 \\ -m_2 l_1 r_2 \sin \theta_2 & 0 \end{bmatrix} \quad (5)$$

$$C = \begin{bmatrix} 0 & -m_2 l_1 r_2 \sin \theta_2 \\ 0 & 0 \end{bmatrix} \quad (6)$$

$$D = \begin{bmatrix} 0 & 0 \\ m_2 l_1 r_2 \sin \theta_2 & m_2 l_1 r_2 \sin \theta_2 \end{bmatrix} \quad (7)$$

By replacing the values of A, B, C, D, angular velocities and accelerations by the calculated values, shown in the following table, the torques are obtained.

Table 1. Torques parameters

Variable	Value	Measure unit
I_A	0,0001772	kg.m ²
I_D	0,0573374	kg.m ²
m_2	2,56	kg
l_1	0,168	m
r_2	0,1014	m
$\dot{\theta}_1$	0,52	rad/s
$\dot{\theta}_2$	0,52	rad/s
$\ddot{\theta}_1$	0,52	rad/s
$\ddot{\theta}_2$	0,52	rad/s

The calculated torque values are $T_1 = 0.39$, Nm and $T_2 = 0.13$ Nm.

Knowing the torques and the maximum angular speeds, the required power is obtained and the motors can be selected. Stepper motors have been chosen because they are cheaper than servomotors. A 3D CAD drawing was developed (Fig.3). This allowed a geometric analysis of the interferences between components and the detailing of the parts. The motors were placed directly in the joints of the manipulator. The last link corresponds to a linear guide with vertical displacement driven by a screw. Figure 3 (a) shows the CAD model and (b) the built prototype.

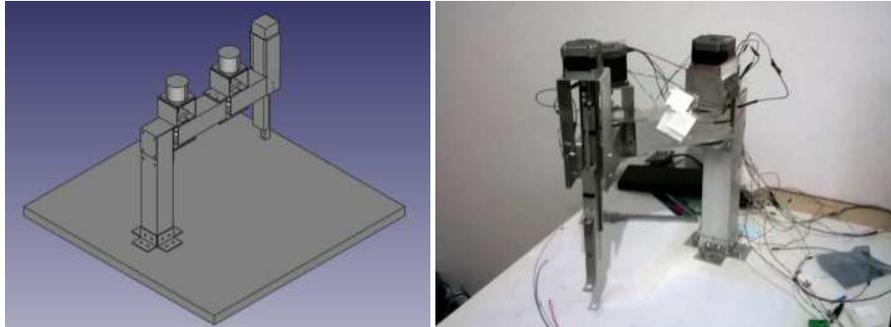


Figure 3. a) CAD model of robot. b) The built prototype

2.2 Electric and electronic design

The system design starts by analyzing the parameters obtained from the design of the mechanical system, such as the required power, torques and maximum angular velocities, with this information it is possible to specify the motors. Step motors can be classified in unipolar and bipolar. Bipolar step motors were chosen because they provide more torque. When selecting the motor, it should be noted that the torque decreases while increasing the motor coils drive frequency. It is necessary to analyze the motor torque curve related to the frequency and select which allows the desired torque at the maximum frequency. Later, the command architecture was determined, in other words, the type of control unit and the way of communication with the motor drivers. A personal computer (PC) was chosen as control unit, which allowed a flexible system for teaching. The PC communicates via USB with the Arduino as it commands the motors driver.

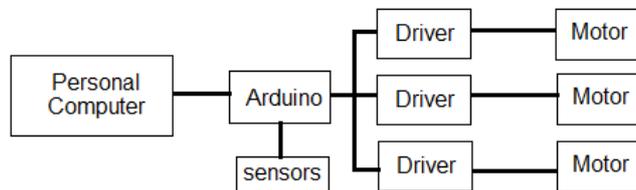


Figure 4. Electronic systems

A commercial motor driver with the L298 CI was chosen and can be seen in figure 5.

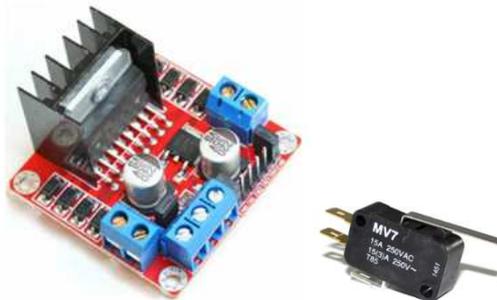


Figure 5. Motor driver and end of stroke sensor

There was no need for angular position sensors, such as encoder, because the stepper motor has been chosen as actuator. It has a constant angular displacement for each step. If the torque disturbances due to the work loads are within the torque limits of the step motor to the desired speed, it ensures the accuracy of the number of steps given. However, as the system needs to start counting the steps of a reference point, end of stroke sensors are required. Mechanical, optical and magnetic sensors can be used, but mechanical sensors were chosen for their low cost (fig.5).

2.3 Software design

This phase of the project corresponds to the development of the program that controls the robot. An open platform is a system specification, so the program will run on a PC and communicate with a microcontroller type Arduino board. In the Arduino there will be a program responsible for controlling the step motor with the step numbers and speed sent by the main program.

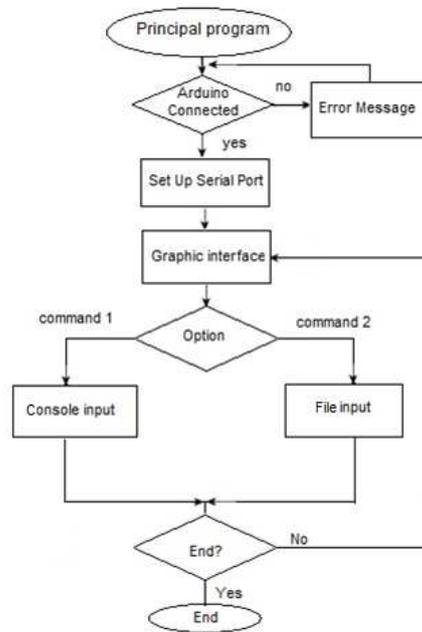


Figure 6- Flow diagram of the main robot control program

The program starts by establishing serial connection with the Arduino. After the graphical interface is available, it can be selected if the trajectory points data will be inserted via file or keyboard. A module corresponding to this option is activated.

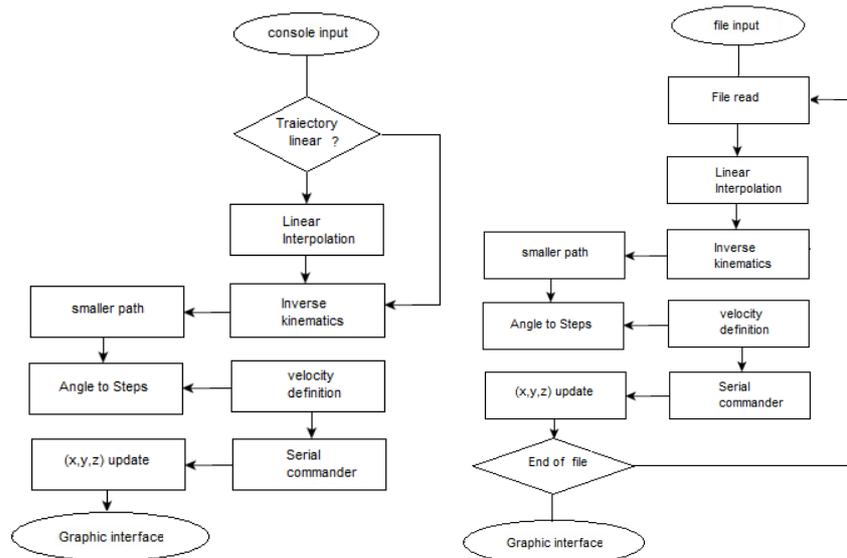


Figure 7. Data input modules

The Figure 7 shows that the difference between the modules is the input of the data. The modules have the same functions for calculating joint variables, such as calculating inverse kinematics, the smallest path between two given points, and converting the angle in steps.

3. PERFORMANCE ANALYSIS

Systematics using coordinate measuring machines to assess manipulator performance have already been used (Costa Neto et al., 2012). These machines facilitate the process of collecting points in three-dimensional space. Dec et al. (2016) developed a systematic using a standard block, a measuring machine and a coordinate measuring arm to evaluate a 3D printer prototype. It is observed that the coordinate measuring arm has more flexibility to reach measuring points than cartesian measuring machines.



Figure 8. Coordinate measuring arm Romer Arm100

A methodology was developed in order to analyze the performance of the developed SCARA robot. It combines the requirements of the manipulators performance standard [ISO 9283] with a systematic using a ROMER Arm 100 and a coordinate measuring arm from UnB Metrology Laboratory, which has an uncertainty of volumetric measurement of the order of $\pm 60 \mu\text{m}$. The uncertainty due to the arm probing error is $16 \mu\text{m}$.

Geometric measurements of the robotic manipulator parts, measures of parallelism, perpendicularity and distance between axes were made. It was measured whether the vertical link was perpendicular to the base at point (1) of Fig. 9. It was also checked whether the vertical link was perpendicular to the arm link Fig. 9 (2). It was measured if the joint axes were parallel to each other and perpendicular to the base, Fig. 9 (3). The distance between axes and arm height to the base was measured.

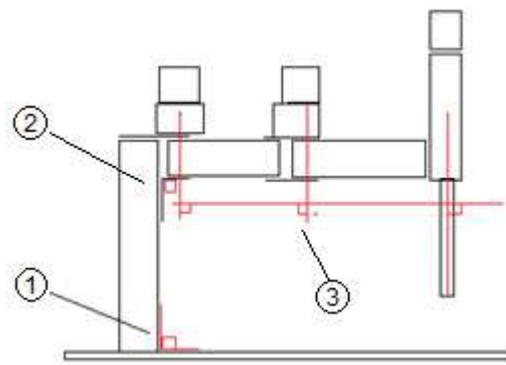


Figure 9. SCARA manipulator and measures evaluated

It is important to compare the deviations in measurements with the acceptable error value. This value is related to the positioning precision specified in the project. The influence of each geometric parameter and the error associated with it in the accuracy of the end effector position must be determined. Table 2 details the joint axes inclinations in relation to the director vector of the base plane. The design specification asks for perpendicular axes, in other words, it should have a slope close to 0° in relation to the director vector. Table 3 shows the inclination and distance between the axes.

Table 2. Axis inclination relative to the base.

PLAN	LINE	MEASURED ANGULE
Base	Joint 1	0.5825°
Base	Joint 2	0.5131°
Base	Joint 3	0.9012°

Table 3. Axis to axis inclination.

LINE 1	LINE 2	MEASURED ANGLE	PLANE DISTANCE (mm)
Junta 1	Junta 2	0.6592°	169.6193
Junta 2	Junta 3	1.4140°	114.1769

By design specification, the axes should be parallel, i.e., the angles between them should be close to 0°. The distances between axes should be 168 mm between joint 1 and 2 and 112 mm between joint 2 and 3, which is not verified in the measurements, as can be seeing in Tab. 3.

4. SOFTWARE ADJUSTMENT METHODOLOGY

The mathematical model applied in the kinematic controller of the manipulator is affected by the identified manufacturing deviations. If the manipulator was used only for “Pick-and-place” tasks and was programmed by the “online” systematics, the task would not be compromised, because in this systematics the end effector of the robot is positioned at the points of interest to store values of the joint coordinates, not needing an internal kinematic model. However, when the task trajectory is important or the “offline” programming is used, the mathematical model becomes fundamental. Some articles have studied the effect of manufacturing deviations on the mathematical model that controls the manipulator kinematics and its effects on precision (Ginani and Motta, 2011). In this paper it has been observed that even in industrial robots there may be manufacturing deviations that can affect the precision of the desired positioning in design. In the case of the didactic robot, usually manufactured in the teaching institutions themselves, the deviations are greater and the challenge is to verify if these deviations can be compensated at a low cost.

One way is to use software to compensate manufacturing errors in the robot kinematic model. A direct and inverse kinematic model is developed using the actual measurements of the robot considering manufacturing errors related to the design. The Denavi-Hartenberg (DH) convention was used to develop the direct kinematic model (Craig, 2013). The DH model uses 4 parameters for each coordinate system transformation. The measurements made by the coordinate measuring arm are replaced in the model and the coordinate transformation matrices are created. These matrices are shown below.

$$H_1^0 = \begin{bmatrix} 0.1191 & -0.9928 & 0.0101 & 0 \\ 0.9929 & 0.1191 & -0.0012 & 0 \\ 0 & 0.0102 & 0.9999 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

$$H_2^1 = \begin{bmatrix} \cos(\theta_1 + 0.57) & -0.9999 * \sin(\theta_1 + 0.57) & -0.01151 * \sin(\theta_1 + 0.57) & 108.2 * \cos(\theta_1 + 0.57) \\ \sin(\theta_1 + 0.57) & 0.9999 * \cos(\theta_1 + 0.57) & 0.01151 * \cos(\theta_1 + 0.57) & 108.2 * \sin(\theta_1 + 0.57) \\ 0 & -0.01151 & 0.9999 & 11366.0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

$$H_3^2 = \begin{bmatrix} \cos(\theta_2 + 0.25) & -0.9997 * \sin(\theta_2 + 0.25) & -0.02468 * \sin(\theta_2 + 0.25) & 48.43 * \cos(\theta_2 + 0.25) \\ \sin(\theta_2 + 0.25) & 0.9997 * \cos(\theta_2 + 0.25) & 0.02468 * \cos(\theta_2 + 0.25) & 48.43 * \sin(\theta_2 + 0.25) \\ 0 & -0.02468 & 0.9997 & -7165.0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

$$H_e^3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -4190.1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

The homogeneous matrices represent sequentially each transformation of the robot coordinate systems. Multiplying all the matrices the direct kinematics relating the coordinate system of the base to the end effector are obtained:

$$H_e^0 = H_1^0 * H_2^1 * H_3^2 * H_e^3 \quad (12)$$

The theoretical model of a SCARA robot direct kinematics can be seen below:

$$x = l_1 * \cos(\theta_1) + l_2 * \cos(\theta_1 + \theta_2) \quad (13)$$

$$y = l_1 * \sin(\theta_1) + l_2 * \sin(\theta_1 + \theta_2) \quad (14)$$

$$z = D - d_3 \quad (15)$$

A simulation was performed in order to analyze the errors generated due to the manufacturing deviations by the theoretical model in the positioning of the terminal effector, considering design values $l_1 = 168$ and $l_2 = 112$ and angular increments of 1.8° pitch motors. A grid of robot reachable points was generated in the workload for the real and for the theoretical model. The graph below compares the errors between them in the xy plane, the vertical axis z, and the xyz space (total error).

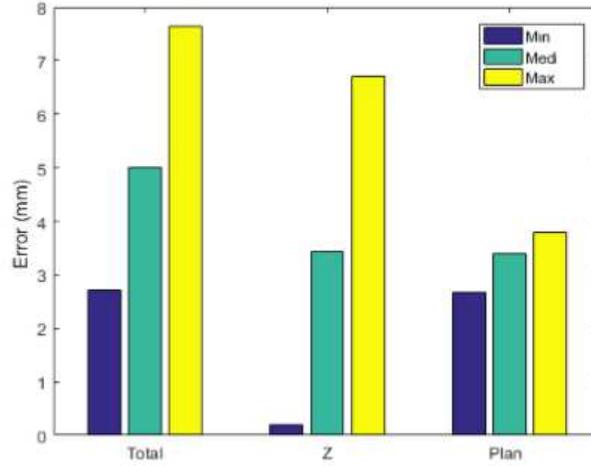


Figure 10. Error between the theoretical model and the real model

In order to perform kinematic control of the robot arm, it is necessary to obtain the inverse kinematic model which, from the end effector desired position (x, y, z) , computes the values of the joint variables $(\theta_1, \theta_2, d_3)$. The inverse analytical model is not trivial when the SCARA robot has deviations of parallelism in the joint axes. The theoretical model of the inverse kinematics of the robot, considering the parallel axes, is seen below:

$$\theta_2 = \pm \cos^{-1} \left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2 * l_1 * l_2} \right). \quad (16)$$

$$\theta_1 = \tan^{-1} \left(\frac{y}{x} \right) - \tan^{-1} \left(\frac{l_2 * \sin(\theta_2)}{l_1 + l_2 * \cos(\theta_2)} \right). \quad (17)$$

$$d_3 = D - z \quad (18)$$

A numerical solution can be used to solve the inverse kinematics of the real model when the joint axes are not parallel. In Rosario (2005) it is proposed a systematic trajectory generation using the manipulator Jacobian. The Jacobian is the matrix obtained from the direct kinematic model, the elements of the matrix are the partial derivatives for each axis of the function that calculates the end effector cartesian coordinates as a function of the joint variables (eq.19).

$$J = \begin{bmatrix} \frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} & \frac{\partial x}{\partial d_3} \\ \frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_2} & \frac{\partial y}{\partial d_3} \\ \frac{\partial z}{\partial \theta_1} & \frac{\partial z}{\partial \theta_2} & \frac{\partial z}{\partial d_3} \end{bmatrix} \quad (19)$$

It is known that the cartesian velocities of the end effector can be obtained by multiplying the Jacobian by the angular velocities of the joints, $[\dot{x}] = J \cdot [\dot{\theta}]$ (Craig, 2013). The infinitesimal displacements can be calculate by the equation (20):

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \approx J * \begin{bmatrix} \Delta \theta_1 \\ \Delta \theta_2 \\ \Delta d_3 \end{bmatrix} \quad (20)$$

To obtain the joint variables increments related to the variations of the end effector position, the inverse of the Jacobian is calculated.

$$\begin{bmatrix} \Delta \theta_1 \\ \Delta \theta_2 \\ \Delta d_3 \end{bmatrix} \approx J^{-1} * \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \quad (21)$$

The systematic observed in Rosário (2015) is used to calculate the inverse kinematics and, at the same time, generate the trajectory between two points. A systematic combination was made using the inverse Jacobian and the inverse theoretical model of a SCARA robot (eq. 16, 17, 18). In the inverse theoretical model, the lengths values of the projected links are replaced by the measured values, $l_1 = 169.62$ and $l_2 = 114.18$. Compensation was made in Z with the mean error obtained in the graph available in fig.6. The proposed method starts with the calculation of the joint variables (θ_1, θ_2, d_3) for a desired point $P_f(x_f, y_f, z_f)$ using the compensated theoretical model. Substituting these values into the real direct kinematic model, Eq.(12), the values (x_p, y_p, z_p) are obtained. By calculating the distance between this point and the desired one the positioning error is obtained. If the error is greater than an acceptable value, points are interpolated between this position and the desired position Pf. Subsequently it is necessary to calculate ($\Delta x, \Delta y, \Delta z$) for the first point and the inverse Jacobian for this position. Using Eq. (21), the increments ($\Delta \theta_1, \Delta \theta_2, \Delta d_3$) are calculated to reach this position. Adding these increments to the joint variables of the previous position (θ_1, θ_2, d_3), the values of the current position can be obtained. The next cartesian point in the interpolation is selected and the procedure is repeated until the error is acceptable.

Analyzing Table 4, it is observed that the errors were reduced significantly in the average and the maximum error is less than 1.1 mm.

Table 4. Error analysis using the method.

	Total error	Plan error	Z error	Y error	X error
Minimum	0.0000	0.0000	0.0000	0.0000	0.0000
Average	0.0029	0.0029	0.0000	0.0019	0.0017
Maximum	1.0922	1.0920	0.0202	0.9596	0.5212

5. CONCLUSION

This paper presents a systematic design of a SCARA robot and a systematic approach to reduce design deviation errors by making a software adjustment. It has been demonstrated that it is possible to significantly reduce the errors caused in the manufacturing process by measuring the prototype and introducing the design deviation values in the kinematic model of the robot control program. This allowed achieving positioning precision without increasing the manufacturing process costs. The manufacturing problems resulted in average positioning errors of 5 mm and a maximum error of 8 mm. Using the software adjustment the maximum error reduced to 1.1 mm, without changing the low manufacturing cost. The cost of material used in the manufacture of the robot was estimated at R \$ 754.00 (US \$ 237.00). The cost of the service (man-machine / hour) was not calculated because it employed only the institution's internal workforce.

6. ACKNOWLEDGEMENTS

The authors would like to thank the UnB Laboratory of Metrology for the support in the measurements of the robot and the University of Brasília for the financial support.

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