Modelling and simulation of trajectories for hydraulic robot applied to assembly functions in a flexible manufacturing system

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Abstract

In this document the modelling and simulation of trajectories for a robot applied to hydraulic assembly functions in a flexible manufacturing system are presented. This project is part of the robotic manufacturing system of the laboratory of the University of La Salle. The methodology used to develop the project involves modelling with direct cinematic with the Denavit - Hartenber parameters, dynamic modelling with Lagrange - Euler equations and simulation and programming of manipulator trajectories applying interpolation of intermediate points and of starting point and end point. As a result, is obtained the matrix linking the position of the tip to the base of manipulator and the equations of torque variation depending on the speed and acceleration profiles in the paths taken.

Keywords: assembly, simulation, modelling, robot.

Modelamiento y simulación de trayectorias para un robot hidráulico aplicado a funciones de ensamblaje en un sistema flexible de manufactura

Resumen

En este documento se presenta el modelamiento y simulación de trayectorias para un robot hidráulico aplicado a funciones de ensamblaje en un sistema flexible de manufactura. Este proyecto está integrado en el sistema de manufactura del Laboratorio de Robótica de la Universidad de La Salle. La metodología empleada para el desarrollo del proyecto involucra el modelamiento cinemático directo con parámetros de Denavit-Hartenberg, modelamiento dinámico con ecuaciones de Lagrange–Euler y simulación y programación de trayectorias del manipulador que aplican la interpolación de puntos intermedios y de punto de inicio y punto final. Como resultado se obtiene la matriz que relaciona la posición del extremo con la base del manipulador y las ecuaciones de variación de torque según los perfiles de velocidad y aceleración en las trayectorias realizadas.

Palabras clave: ensamblaje, simulación, modelamiento, robot.

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Introduction

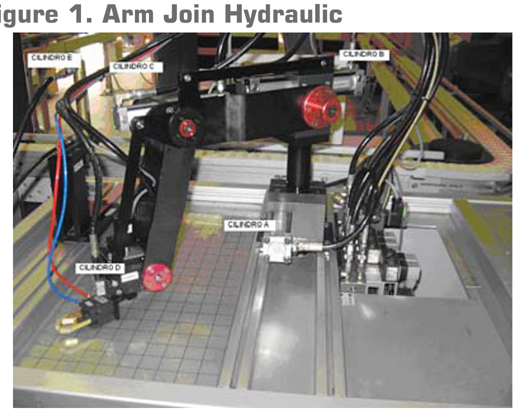
In modern industry where it is implementing automation, generally used with power-operated robots because of their low weight and rapid response to the demands made on them. However, are limiting their low ability to manipulate large loads, a situation which opens a space for the implementation of hydraulic robots in cases where the requirements of handling heavy loads are the daily requirement.

This work is a study on the applicability of the simulation trajectories of a hydraulic robot and its validation by the scheduling of trajectories in the manipulator.

Metodology

Through modelling with matrix and differential equations, the cinematic and dynamic model of the robot is shown as can seen in figure 1. These models allow obtaining variables: position, velocity and acceleration, angle of every link and the entire package, to obtain the torque and power drive of the whole.

Figure 1. Arm Join Hydraulic



Model cinematic robot

The model for determining the position of the end of the manipulator regarding its base, apply the methodology Denavit-Hartenberger (DH). With this, with a Homogeneous Transformation Matrix (HTM), in function of the angles and lengths of each link with respect to the previous link (D-H parameters, table 1), the position is determined.

Table 1. Parameters Denavith-Hartenberger.

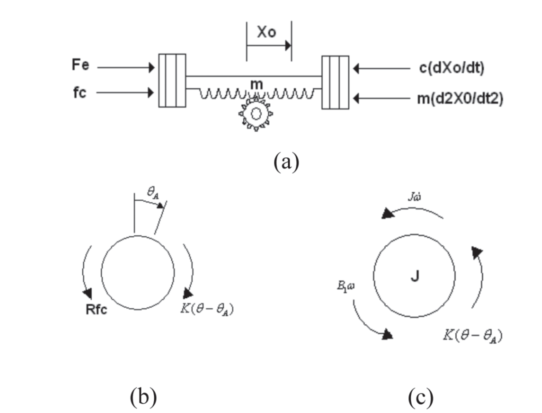
LINK	Θ_i DEGREE	d_i mm	a_i mm	α_i DEGREE
1	q_1	L_1	0	0
2	q_2	d_1	0	90
3	q_3	0	d_2	0
4	q_4	$-d_3$	d_4	-90

After obtaining the relationship between the links through the previous matrix, you can get the final position of the end of the robot varying the angle of the joints.

Hydraulic System Model

This model includes a hydraulic cylinder, a rack, a pinion gear and a shaft which supports the hydraulic arm (figure 2). With these elements, and working in the state variables space, the following model (equation 1), for the kinematics of the link 1 is obtained, with its rotational axis perpendicular to the horizontal plane:

Figure 2. Hydraulic Mechanic System



$$\dot{\theta} = \omega$$
$$\dot{\omega} = \frac{1}{J}\left[-K_{tor}\theta - B_1\omega + \frac{K}{R}Xo\right]$$
$$\dot{X}o = Vo \qquad \text{Eq. (1)}$$
$$\dot{V}o = \frac{1}{m}\left[\frac{K}{R}\theta - \frac{K}{R^2}Xo - CVo + Fe\right]$$

Solving this set of equations in Matlab Simulink, are obtained responses from angular position, angular velocity, linear position and linear velocity in function of time (figures 3, 4, 5 and 6).

Figure 3. Position of the robot vs. time

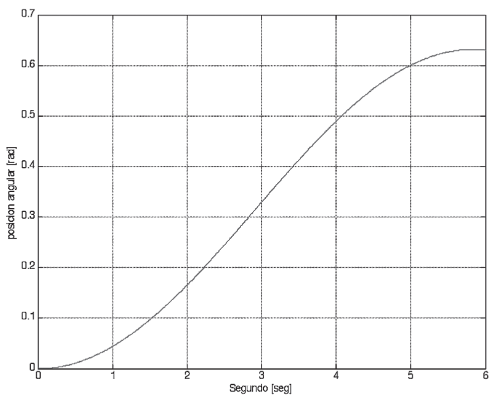


Figure 3, shows the changing of the trajectory in function of the time, when the robot turns from zero to 37°, during approximately 6 s. Analyzing this figure, the first two and last two grids, we can notice that it has a relatively smooth slope, indicative of how it starts and ends the movement slowly. The two central grids show how the robot has a linear behaviour with maximum slope, indicative of the high speed of the mechanism during the middle of the path.

Figure 4 shows that the movement of the link begins with a zero speed and should end with a zero speed once it reaches the desired position. The maximum speed reached by the mechanism is due to the requirement, to sweep the path in the specified time. The model developed shows how one considers that the mechanism can not achieve the maximum speed at a time zero, but follows a parabolic profile.

Figure 4. Angular speed of the robot vs. time

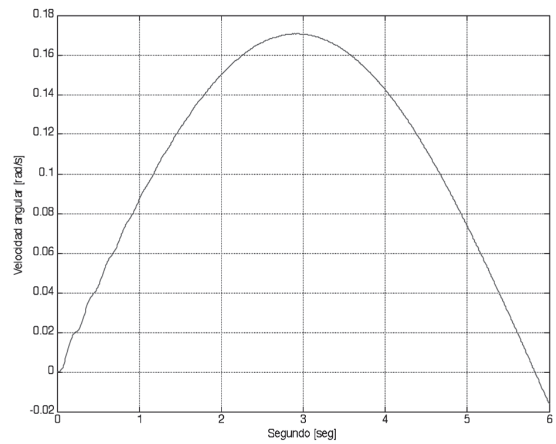
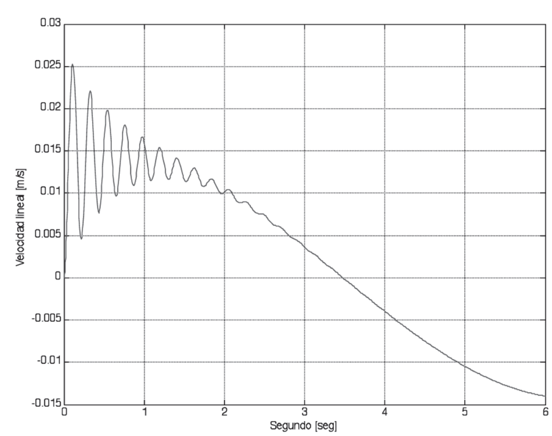


Figure 6 shows the change in the position of the rack driven by a hydraulic cylinder. This shows that during the first two seconds there are fluctuations in the system possibly due to inertia of the whole, the elasticity of the components of the manipulator and friction between elements of the system.

Just as this analysis is done for the link 1, with the same mathematical model, this analysis can be done for the other links. The only data to change are the mass and inertia and eventually the diameter of pinion actuator, to adapt the model to new conditions desired.

Figure 5. Linear Speed of the actuator link 1



Lagrange calculations for the hydraulic robot (dynamic model)

Applying the formulation of Lagrange, the equation 2 is gotten, for calculating the torques in each link.

$$\tau_1 = m_{ec} l^2 Cos^2(\varphi)\ddot{q}_1 \qquad \text{Eq. (2)}$$

$$\tau_2 = \begin{bmatrix} m_2 lc_2^2 + m_2 l_2^2 + m_3\, lc_2^2 \\ -2 m_3\, l_2 lc_3\ Cos\ (q_3)\ \left(1 - 2Cos^2\ (q_2)\right) \\ + I_2 + I_3 \end{bmatrix} \ddot{q}_2 - \begin{bmatrix} m_3 lc_2^2 + m_3 l_2 lc_3\, Cos\ (q_3)* \\ \left(1 - 2Cos^2\ (q_2)\right) - I_3 \end{bmatrix} \ddot{q}_3$$

$$+ 2m_3 l_2 lc_3\ Sen(q_3)\,\dot{q}_2\dot{q}_3 - m_3 l_2 lc_3\ Sen(q_3)\,\dot{q}_3$$

$$+ \left[m_2 lc_2 + m_3 l_2\right] g\ Cos\,(q_2) - m_3 lc_3 g\ Cos(q_2 - q_3)$$

$$\tau_3 = \left[-m_3 lc_3^2 + m_3 l_2 lc_3 Cos(q_3) + I_3\right]\ddot{q}_2 + \left[m_3 lc_3^2 + I_3\right]\ddot{q}_3 - 2m_3 l_2 lc_3 Sen(q_3)\dot{q}_2\dot{q}_3 - m_3 l_2 lc_3 Sen(q_3)\dot{q}_2^2$$
$$+ m_3 lc_3 g Sen(q_2 - q_3)$$

To evaluate the torques, it is necessary to calculate the position of center of mass, because the torque varies with the position. The equation that determines this variation is the next (equation 3).

$$l = \frac{m_2 l_{2cm} + m_3 l_{3cm} + m_c l_{ccm}}{m_2 + m_3 + m_c} \qquad \text{Eq. (3)}$$

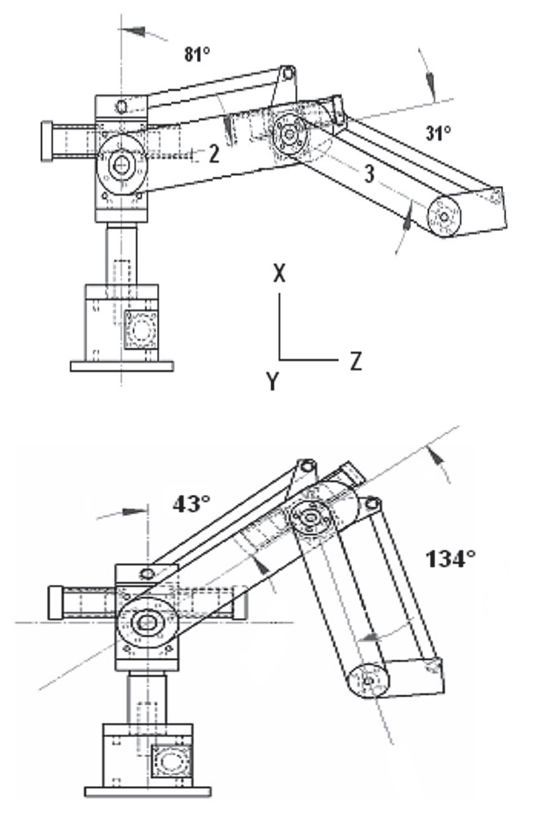
The angle between the center of mass of the links 2 and 3, is given by the equation 4.

$$\phi = Arc\tan\left(\frac{l_{2-3cmX}}{l_{2-3cmZ}}\right) \qquad \text{Ec. (4)}$$

Obtaining of the torque to the link 1

The torque required to operate the link 1, is a function of the horizontal position of center mass of the links 2 and 3 and the load. The movement happens at Z-Y plane (figure 6).

Figure 6. Extreme positions of the links 2 and 3



The equation 2 can be assessed in two ways: (a) center of mass of the links 2 and 3, at a fixed distance from the axis of rotation of the link 1, and rotation of this center of mass on the horizontal plane, (b) center of mass of the links 2 and 3 varying its distance from the rotation axis of the link 1 and the rotation of this center of mass on the horizontal plane. The most critical case is the (a), because of the requirement for a higher torque to the drive of the entire robot. This is the case to be analyzed.

Additionally, there are two possibilities: that the center of mass is as far as possible to the axis of rotation or as close as possible. The first case is the most critical and will be analyzed (figure 7). Finally, the manipulator can work with or without load cargo. The first case is the most critical and will be analyzed.

In figure 7, you see the result of simulating the behaviour of torque 1 when the hydraulic arm is manipulating a load of 0.5 kg, with maximum extension link from 2 to 81 degrees and change the angle of link 3 from 134 to 31° (to see figure 6). The link one rotates on the Z-Y plane.

With positions before specified, it appears as the center of mass of the whole goes from minimum to the maximum distances from the axis of rotation of the link 1, then the moment of inertia makes maximum when the position of the link 3 is 31°, it implies that torque 1 required to turn the entire robot, must be maximum to moved in such a manner as to fulfil the conditions for the border conditions.

On-line programming for home positioning

To locate the manipulator in a desired position, because it do not have the appropriate electronic means to process the signals emitted by the position sensors (potentiometers), it is necessary to define a benchmark for the manipulator (called Home). So that the manipulator must be always taken at this point of reference, so that the control system, starting from this position, could lead precisely to the desired point to the manipulator.

To determine where the robot is, the PLC makes a reading of the value of the signal from a potentiometer. This value identifies the position of each of its links in the real environment. Depending on the position in which the manipulator is, automatically runs a routine for position at home.

Off-line programming trajectories

For the programming of the assembly trajectories, a set of functions was made, giving a profile of, position, speed and acceleration depending on the time to follow a certain trajectory. For this, the simulation software, in this case Matlab, it needs the following input:

Initial point.
Final point.
initial velocity.
constant increase.
constant decrease.

The function performs a calculation between the start and end points to increase or decrease the opening of the proportional valve depending on the evolution of the trajectory.

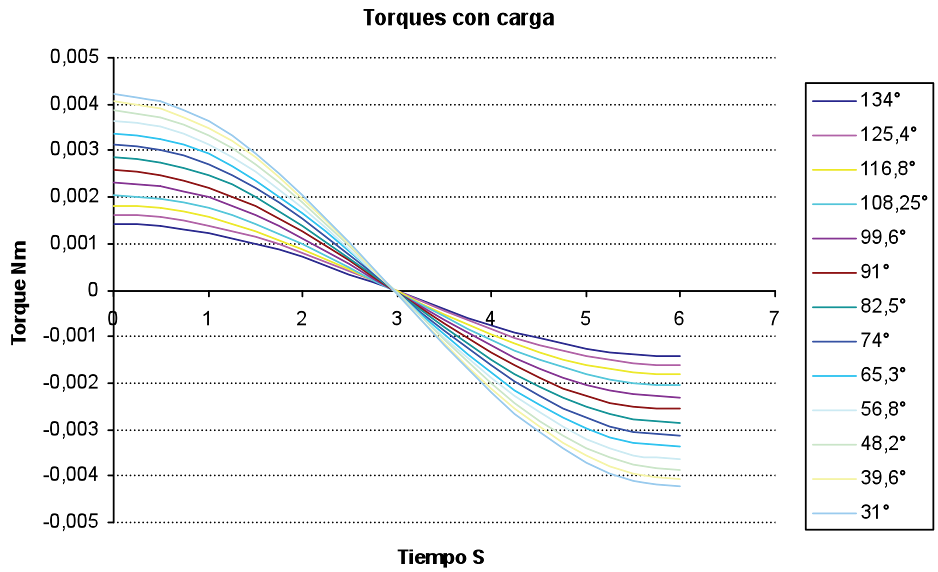
Matlab trajectories simulation

To describe the position of each joint, the polynomial used is shown in equation 5.

$$p(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \qquad \text{Eq. (5)}$$

Where:

Figure 7. Variation of torque 1, loaded and fixed position link 3. Link 2 in total length



p (t) = angular position (radians) of articulation, as a function of time.

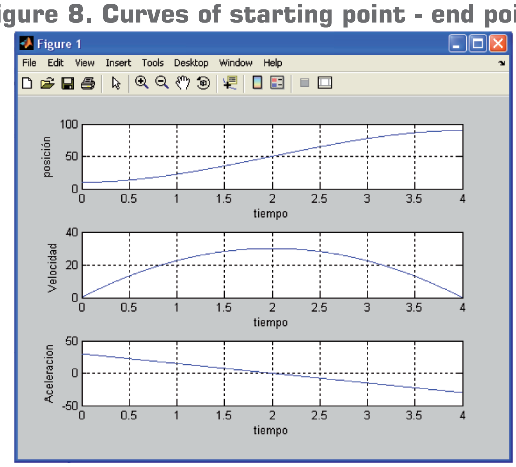
ai = coefficients to estimate, depending on initial conditions.

t = time, in seconds.

The coefficients of this polynomial, four in this case, where obtained with the border conditions.

The trajectory simulation results with start point - endpoint, are shown in figure 8.

Figure 8. Curves of starting point - end point

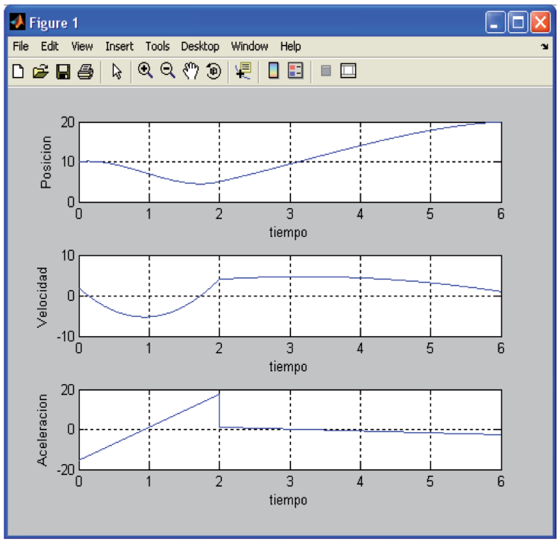


In figure 8, you can see that the angular position has an initial value of 10° and a final value of 90°, coinciding with the initial conditions laid down. The graph shows a rate of speed, starting and ending in zero, met with the values of speed to be taken into the starting point and destination. Lastly, the acceleration graphic, in the corresponding points at the beginning and the arrival, is the maximum to overcome inertia of the whole robot or link. At half time, the acceleration is zero, point where the speed is the highest and is a turning point where there is a change in the direction of speed.

Figures obtained from angular position, angular velocity and acceleration angle, for the simulation of intermediate points, are shown in Figure 9.

You can see in the position graphic (to see figure 9), it appears that part of a starting position equal to 10°, an intermediate passes of 5°, and finally reaches a final position of 20°, indicating that the basis of the position 10° moves in one direction to attain the position of 5°, and then goes in the opposite direction to reach the position of 20°.

Figure 9. Representation of curves points to a single point

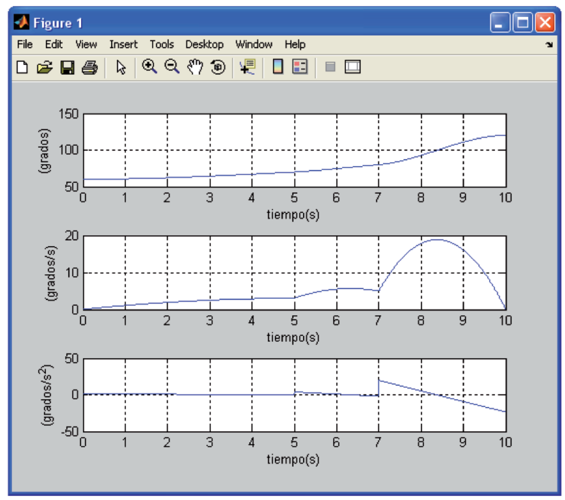


To speed profile in the first branch, describe a parable concave upwards, indicating that the rate becomes negative in the first part of the parable (indicative that the joint is moving in the opposite direction as the assumed positive) and positive in the second branch (movement in the positive direction); everything to get to this point to the desired speed. From this point, the curve reaches the desired final speed. The analysis of the acceleration profile in the first branch, between zero and two seconds, is identical to what has been done in the case of the trajectory with starting point and end point; for the second branch, between 2 and 6 seconds back, the analysis is similar. It is noteworthy that in the profile of accelerations to the point, there is a sudden change in acceleration, which can lead to a more coarse movement of the joint, leading to a possible generation of errors when the physical element will be positioned.

The results for this example, are shown as can see in Figure 10.

In the graph of angular position, it can be seen as the articulation is located at the desired angles for specified times. The angular velocity graph shows a mild variation of speed until the second branch, but in the third branch there is a sudden change of this. In the graph of angular acceleration, for times of 5 and 7 seconds there is a leap of acceleration. This sudden change, leading to proportional variations in the speed.

Figure 10. Representation of curves for two points



Results

Once developed the mathematical model of kinematics of the robot, you get the matrix equation, which relates developments in the movement of the links of the robot, and also it facilitates routines programming to the manipulator.

As a result, a mathematical model in state variables of the hydraulic system was obtained. This model allows generate the movement of the mechanical structure of the robot, and the simulation of its movements. With this simulation it can be obtained the behaviour of the position, velocity and acceleration of the links when they must move from one point to another.

The dynamic model shows an equation with which you can obtain the torques required to implement in each articulation of the robot. See equations 2. Obtaining the behaviour of torque in time, to meet conditions given, makes it possible to calculate the power required in the actuator that will do that movement.

By scheduling the trajectories of assembly, there is an application in Matlab, which can simulate the behaviour of the robot when it has to move from one place to another, and in which the condition borders may be changed as are: time movement, start point, endpoint and initial, middle and end velocity.

Additionally, we found a flow chart that takes into account when scheduling trajectories, because it is necessary, before initiating any movement, that the robot reaches the Home position; with this reference will begin to develop assembly trajectories.

Discussion

For modelling, simulation and robot programming paths for hydraulic assembly functions, it was used the cinematic modelling, to know mathematically, with geometric and matrix patterns, the position of the end effector. This position can be known by defining the intervals between which can move each of the segments in both rotation and in translation. This variation, does not have a predefined strategy for variation of such rotations and translations, and simply is related to specific values of rotation and translation, to determine the position of the end effector according to the values given. If you want to generate a specific trajectory of this effector, it is necessary to resort to any procedure that alters the values of rotation and translation of each of the joints, in a such way that follows approximately the path desired. To accomplish this, there are programming trajectories. This programming includes several strategies to generate trajectories, each of which allows achieve different paths so that the developer can choose the method that best fits their requirements.

Because the cinematic model allows determine the position of the end effector excluding the effects of inertia, it is not possible to determine the torques required to move the effector from one position to another. For this reason, it is necessary to develop a dynamic model to determine the required torques in the actuators, depending on the cargo handled, in order to meet the power required in the hydraulic system. This model does not allow to know the structure dynamic behaviour, during its operation from one point to another, so it requires another kind of model to learn this behaviour. This model is the dynamic model of vibrational hydraulic system, which involves properties of the material with which the system is built, such as modulus of elasticity or stiffness and viscous friction always present in such mechanisms.

Conclusions

It was obtained the Homogeneous Transformation Matrix that relates the different parts of the robot, to eventually establish a relationship between the end of the robot and its base. With this model can be obtained for any moment, the end of the robot's position regarding its base.

With the use paths programming strategies by start point - endpoint interpolation and intermediate points interpolation, for trajectories programming, and their comparison with the trajectories generated by the manipulator, it was determined that the models are adjusted quite well as expected for both types of simulations. However, it was observed in the intermediate points simulation, that the obtained speeds are greater than in the start point and end point simulation, which makes it advisable strategy for programming trajectories assembly by a lower trend to the presence of instabilities or inaccuracies in the positioning.

It is possible the control of a hydraulic arm through a PLC, but the programming of the arm becomes rigid (it's possible to use a program at once). An option to provide flexibility to the module, can be implementing a data acquisition card and a PC.

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