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DEVELOPMENT OF A MANIPULATOR AND KINEMATIC CONTROL SYSTEM WITH EMBEDDED CONTROL HMI FOR ACADEMIC PURPOSES FOR TECNOACADEMIA CÚCUTA

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ABSTRACT:

This research aims to develop an industrial manipulator, from its design stages to its physical creation using the embedded HMI kinematic control system, until its implementation and the selection of suitable electronic devices for its possible development. This project was designed for Tecnoacademia in Cucuta-Colombia for academic purposes, where the apprentice of this institution interacts directly with the manipulator, obtaining knowledge in robotics. Moreover, understanding the work through a graphical interface developed in the project is useful for knowing the basic concepts in robotics and the problem to be considered for understanding the work that was developed and his interface. Finally, a functional test and the teaching methodology for the apprentice are performed.

INTRODUCTION

Robotics is one of the main topics in industry 4.0 (Vaisi, 2022). Colombia has multiple entities that strengthen teaching in these areas, such as Tecnoacademia, where the knowledge of young people and students is strengthened through training. Tecnoacademia Cúcuta has two modalities, fixed Tecnoacademia and itinerant Tecnoacademia. Although this last modality tries to reduce the existing gaps in the education of young people between rural and urban areas, this one does not have a Robotic workbench at an easy-to-transport scale by which it is developed to strengthen learning by improving the conceptualization of rural youth. (Cruz+, 2016).

The development of the robotic bench at scale reflects the entire design methodology, from the conceptualization of selection criteria to the development, implementation, and validation of each component (Müller et al., 2017).

Mechanical design

The manipulator must be portable by providing it with a closed work environment in which there is no need to assemble or disassemble parts to be able to move the manipulator. The intervention of a person for the installation is minimized. In addition, by creating a closed environment where there is no possibility of disturbances when performing articular trajectories, the trajectories made will be more faithful to the trajectories generated.

Prototype

A concept to consider is the position of the manipulator. By positioning it vertically, as seen in Figure 1, we will take advantage of the closed workload, making it possible to position the end just below the base.

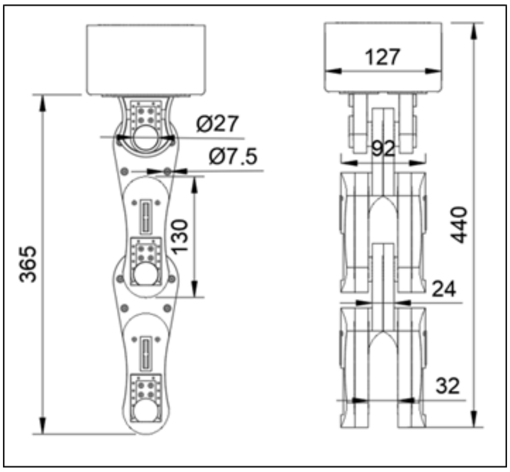


Figure 1. Dimensions of the Manipulator Prototype.

In detailing the prototype in Figure 1, an anthropomorphic design is developed in similarity to the sections of the human arm (Li et al., 2019). Furthermore, this prototype was designed in multiple parts for easy manufacturing and handling and subsequent replacements or complete or small adaptations for some specific parts, making it easier for the user.

To create the structure of the closed workload, the dimensions of the manipulator were analyzed, it must have sufficient space where interact with different elements within this workload, as seen in Figure 2.

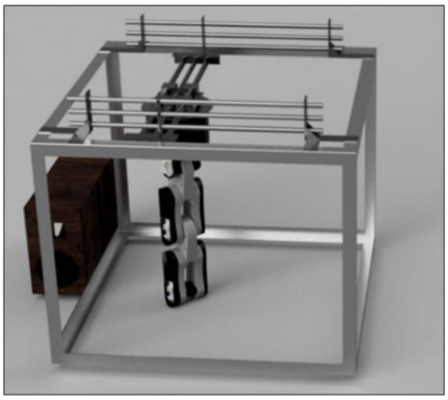


Figure 2. Prototype Rendering of Workload.

Kinematic Model

Al performs the kinematic model by means of the Denavit-Hartenberg convention (D-H), which allows for locating the points of each articulation, allowing the possibility to evaluate whether or not they are within the workload (Žlajpah & Petrič, 2023). On the other hand, the reference systems according to the D-H convention to the workload (Kalajahi et al., 2021), the representation is obtained in Figure 3 Obtaining the parameters presented in Table 1.

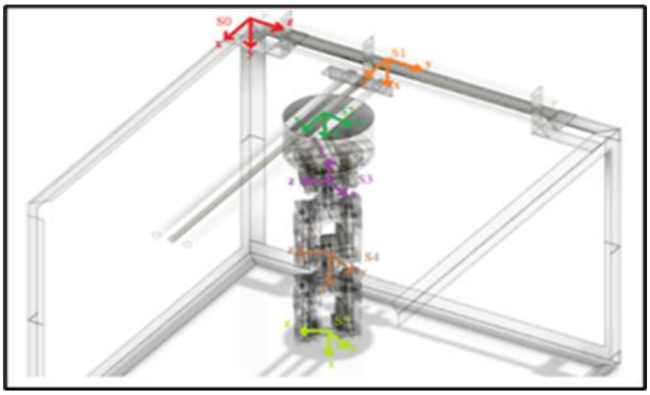


Figure 3. Representation of the systems in the manipulator.

Table 1: Denavit-Hartenberg parameters.

Articulation	**Angle**	**d**	**a**	**Alpha**
Art. 1	90	d	0	90
Art. 2	90	a+q1	0	90
Art. 3	q3	b+q2	0	-90
Art. 4	q4-90	c	d	0
Art. 5	q5	0	e	0
Art .6	q6	0	f	0

Solving the equations and considerations, was possible obtain the following relationships in Equation 1:

$$\mathrm{MTH_f} = \begin{bmatrix} \mathrm{Nx} & \mathrm{Ox} & \mathrm{Ax} & \mathrm{Px} \\ \mathrm{Ny} & \mathrm{Oy} & \mathrm{Ay} & \mathrm{Py} \\ \mathrm{Nz} & \mathrm{Oz} & \mathrm{Az} & \mathrm{Pz} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \mathrm{Eq.\,(1)}$$

Where: $\mathrm{Nx} = S_3S_{456}$, $\mathrm{Ox} = S_3C_{456}$, $\mathrm{Ax} = C_3$, $\mathrm{Px} = q2 + b + dS_3S_4 + eS_3S_{45} + fS_3S_{456}$, $\mathrm{Ny} = C_{456}$, $\mathrm{Oy} = -S_{456}$, $\mathrm{Ay} = 0$, $\mathrm{Py} = c + dC_4 + eC_{45} + fC_{456}$, $\mathrm{Nz} = C_3S_{456}$, $\mathrm{Oz} = C_3C_{456}$, $\mathrm{Az} = -S_3$, $\mathrm{Pz} = q1 + a + dC_3S_4 + eC_3S_{45} + fC_3S_{456}$ Con $h = dS_4 + eS_{45} + fS_{456}$

Reverse kinematics

For the case of the inverse kinematic model(Abdor-sierra et al., 2022), it can be found by the analytical method, using the formulas obtained from the homogeneous transformation matrix of Equation 1, which is obtained from article 3 based on Articles 1 and 2.

$$q2 = (\mathrm{Px} - b) - (\mathrm{Pz} - a)t_3 + q1t_3 \quad \mathrm{Art.\,1\ y\ 2:}$$

$$\theta_3 = \mathrm{ArcTan}\left(-\frac{\mathrm{Az}}{\mathrm{Ax}}\right) \quad \mathrm{Art.\,3.}$$

Considering the above articles, articles 4 to 6 were found:

$$\theta_4 = \mathrm{Arctan}\left(\frac{x}{y}\right) \pm \mathrm{Arctan}\left(\frac{\sqrt{x^2 + y^2 - z^2}}{z}\right) \quad \mathrm{Art.\,4.}$$

$$\theta_5 = \theta_4 \pm \mathrm{Arctan}\left(\frac{x}{y}\right) \pm \mathrm{Arctan}\left(\frac{\sqrt{x^2 + y^2 - z^2}}{z}\right) \quad \mathrm{Art.\,5.}$$

$$\theta_6 = \mathrm{Arctan}\left(\frac{-\mathrm{Oy}}{\mathrm{Ny}}\right) - \theta_4 - \theta_5 \quad \mathrm{Art.\,6.}$$

Development of the system

The arm consists of two assemblies, which were analyzed, identifying the parts that will withstand greater stresses. Although this analysis was done employing a simulation of static loads to make more evident the fracture points and the stresses of the parts, it was decided to increase the load.

Table 2. Load simulation results.

Name	Basic Assembly I		Basic Assembly II	
	Minimum	**Maximum**	**Minimum**	**Maximum**
Tension				
Von Mises	0.001158 MPa	1.141 MPa	3.963e-04 MPa	0.7656 MPa
Dispacement				
Total	0 Mm	0.04189 Mm	0 Mm	0.01919 Mm
Reaction force				
Total	0 N	1.986 N	0 N	9.661 N

Deformation				
Equivalent	8.06e-07	8.875e-04	2.41e-07	4.357e-04
Contact pressure				
Total	0 MPa	0.7684 MPa	0 MPa	0.5621 MPa

Material Selection

With the help of programs, multiple materials were compared, used in engineering, and some background. As a result, they obtained the three most used for this purpose, as specified in Table 3.

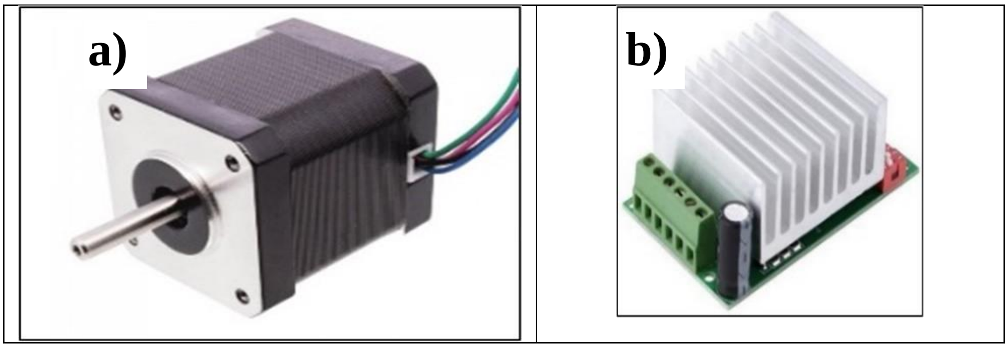
Table 3. Suitable materials

Number	Name
1	Polylactic acid (PLA)
2	Polyethylene terephthalate (PET)
3	Acrylonitrile butadiene styrene (ABS)

According to (Morales & Estephan, 2021), this bioplastic is one of the mainly used raw materials for 3D printing. Based on these results and analysis, it is possible to opt for a filling density of 40% since, even so, with such resistance to tensile stress, taking the lowest average, the material would manage to withstand loads of 10kg, although not knowing the real safety factor.

Design of the control system

Joints 1 and 2, being a prismatic movement, have step-by-step motors NEMA 17, illustrated in Figure 4a, of which it is necessary to have a controller observed in Figure 4b. For articulation 3, 4, 5, and 6, rotational joints, it becomes more practical to have servo motors, which by default for this project were selected servo motors from Figure 4c.



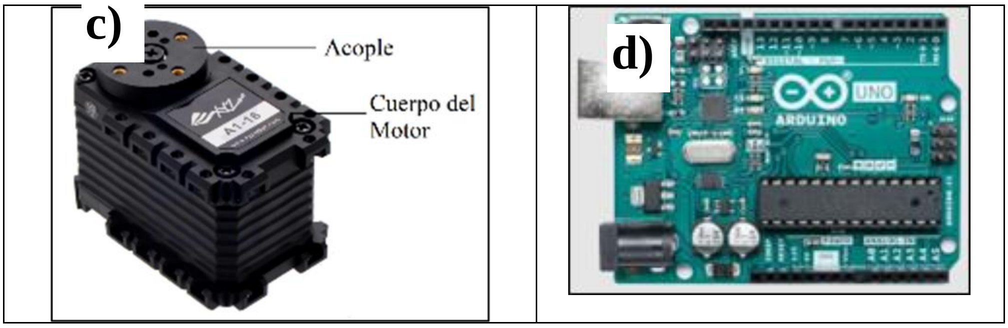


Figure 4. a) Stepper motors NEMA 17, b) Passthrough driver image tb6600, c) image and parts of the XYZ Robot a1-16, and d) Image of Arduino One.

The signals required for the joints will be sent by a slave controller, given in Figure 4d, which will process the master controller's information. For the selection of the master controller, we opted for a raspberry pi 4, given in Figure 5. A great advantage is that it has a large academy-oriented community, as well as several users who have used this card to develop various similar projects.

Figure 5. Raspberry pi development card 4 model b.

Kinematic Control

On the other hand, was defined those four types of possible trajectories in Cartesian space (Axis-to-axis trajectories, Simultaneous trajectories, Coordinated trajectories, and Analytical trajectories).

Interpolators

Only two types of interpolators, Cubic and Trapezoidal, will be used, with some differences. With the trapezoidal interpolator, three types of trajectories will be executed because, by its nature, it is not feasible to create straight-line trajectories, so only develop axis-to-axis trajectories, simultaneous and coordinated, whose difference lies in the execution times of each. This interpolator joins two points creating trajectories with a trapezoidal velocity profile, from which its name is derived.

With the type of Cubic interpolator, it is possible to run all four types of trajectories. It is based on a 3rd-degree polynomial. The initial process of this cubic interpolator is somewhat like the process of the trapezoidal interpolator. For its execution, the function must first be called, which reads the parameters, just like the previous interpolated call returns a vector with the articular trajectories of position, speed, and runtime, sampled at desired intervals, which for this case are 100 m.

Concatenation of Trajectories

When talking about concatenation of trajectories, it is to be able to join multiple trajectories in one, without this implying a zero speed at the end of the manipulator on the passage of the desired points, making the speed over its entire trajectory continuous, reducing runtimes. The cubic interpolator does not need to change mathematical formulas to concatenate trajectories.

In the case of the Trapezoidal interpolator, two solutions are proposed: The first solution is proposed (Biagiotti, L. & Melchiorri, 2008), where it states that the braking times of point q (i-1) can be added with the starting times of point q i. The second solution is proposed (Peñín L, 2007), where was changed the mathematical formulas to determine the start and stop of each point, anticipating the movement.

Design of the control interface

Based on the rules above, some principles were adapted to comply with them as criteria for the development of the interface. It establishes three principles, the first as general principles are the scope and restrictions in general way on the development of the interface. The second principle, principles for the screen display, are a gamma of suggestions that designers should consider for optimal ergonomics in different areas, such as visual and mental. The third and final principle, principles for control and interaction, establishes the restrictions.

Basic structure

To meet all the criteria previously set, an interface with two pages were designed as shown in Figure 6. The first page will be developed related to the control of the manipulator, with 4 windows where the information is divided by its thematic. The second page will facilitate the configuration or utilities of the system and will be divided into three windows.

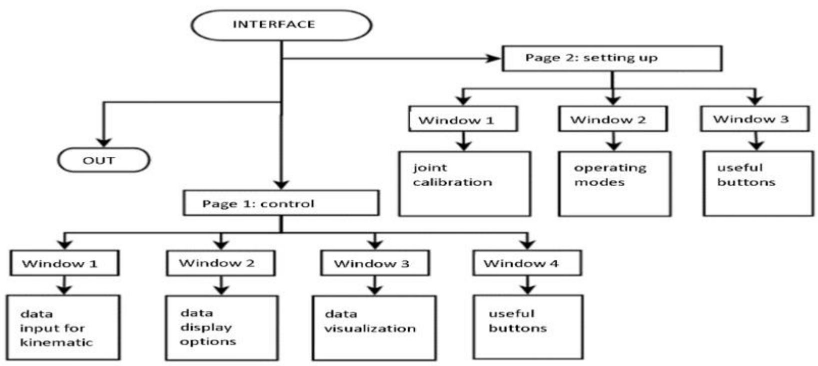


Figure 6. Basic structure for the interface design.

Basic Interface Design

When starting the program, the interface will be in the main panel, where the user can only run one section at a time. This design was achieved in a very interactive way through dynamic elements, as shown in Figure 7, where it can be observed that the elements to be selected make a movement allusive to their functionality, making them very striking.

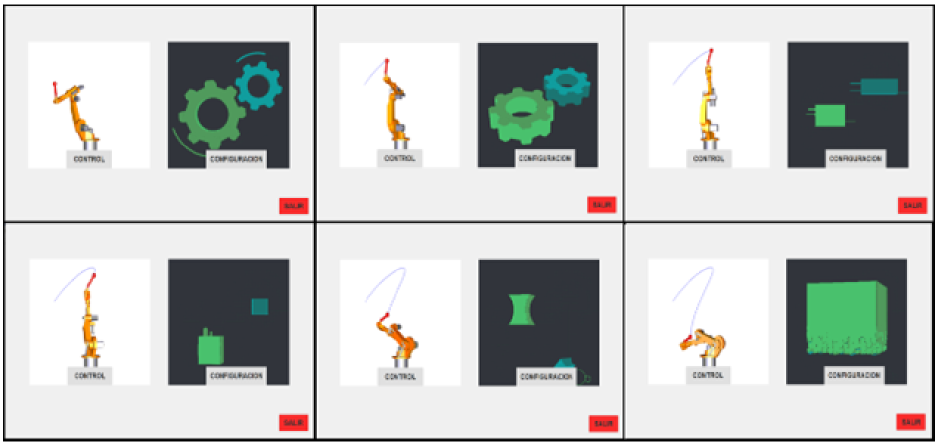


Figure 7. Dynamic elements of the main interface panel

Design of the Handheld and Implementation

To comply with the regulations (ISA 101, ISO 11064-5) in terms of visual ergonomics, positioning the control screen in a fixed location could occasion weariness to users. Therefore, it was decided that the user can manipulate the screen by means of a structure that helps him to hold it with one hand or with two hands, moving it freely. For its design, the ergonomics were emphasized, in terms of the position of the flexion of the wrist of the hand, the weight of the structure-screen assembly, and the resistance of the part.

Implementation of the Interface

In order to implement the interface, it will be exported as a program, which starts every time the Raspberry pi is turned on, as seen in Figure 8, without the possibility of the user leaving the program, and only when pressing "exit" will be given the order to shut down the device.

Figure 8. Image of the implementation of the interface

Implementation and validation

As the system is not equipped with dynamic control, which guarantees the correct positioning of the articular value, it is necessary to protect the trajectories made by the manipulator generated by the kinematic control in an open control loop. For your protection, it is only to avoid disturbances that divert the end of the manipulator. This is very simple since there is a bucket, which can be lined with a transparent material that does not pose a danger to the apprentices, as seen in Figure 9.

Figure 9. Robotized Work Bench at Scale.

Safety System for Users

It has three switches, and one is for the restart of the motors of the arm, which, if they hit an obstacle, will be turned off, so they must be restarted. The second power switch is for the general shutdown of the system by disconnecting the power directly. Finally, the last pushbutton, which can be displayed in Figure 9, is the emergency one, which decouples the power from all actuators.

Methodology for the evaluation

Having cleared the process to perform the trajectories, was proceeded to establish the methodology used for the validation of the entire control system, which we can see in Figure 10, a brief description of the process carried out in each item.

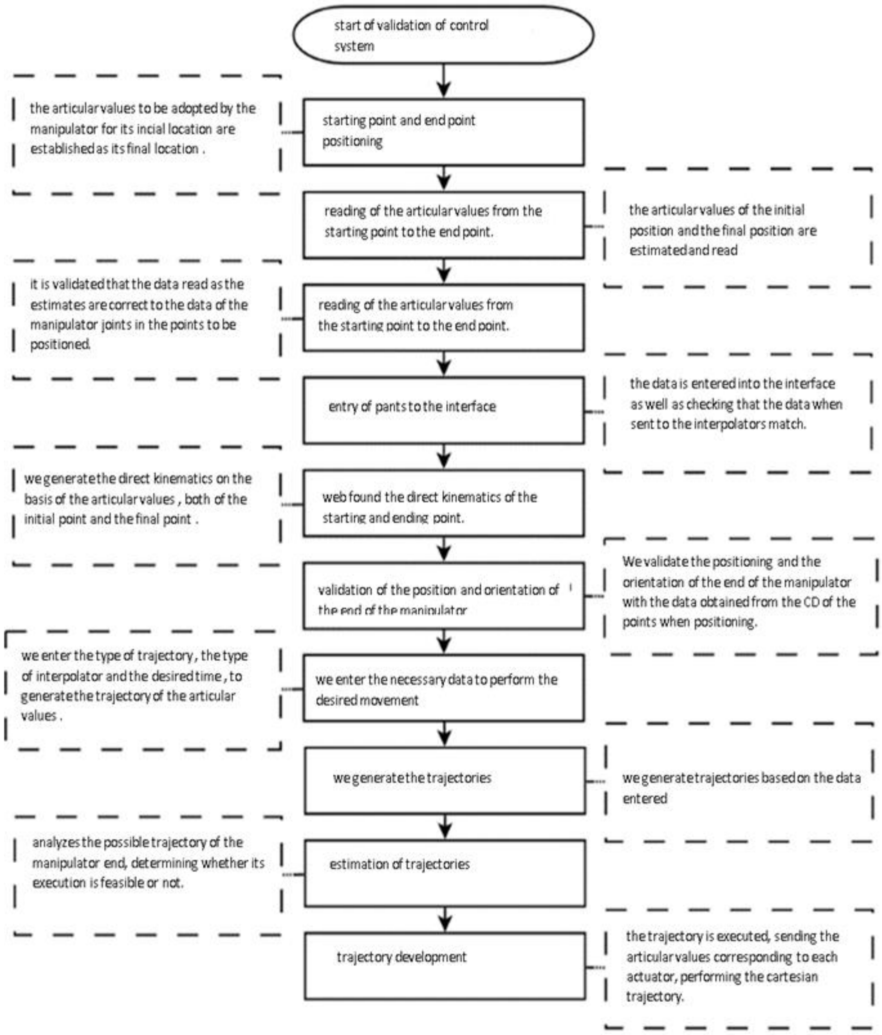


Figure 10. methodology for the validation of the control system

Tests and Validation

For the development of the tests, 4 points were predetermined within the workload, named a, b, c, and d, as shown in Figure 11, each of which has a specific articulation position, defined below: Art. 1, Art. 2, Art. 3, Art. 4, Art. 5, Art. 6, based on a) 0, 0, 8, -30, 30, 90; b) 14, 11.5, -35, -20, 70, 80 and c) 28, 16, 80, 40, 80, -90, 13, 13, 105, 20, 70, -30

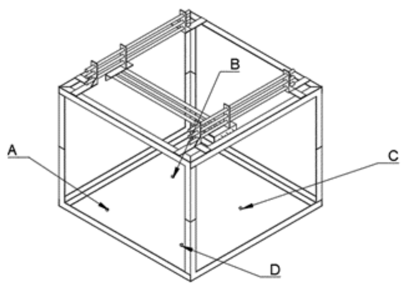


Figure 11. Joint values.

For practicality, only one test is documented, obtaining the results in Table 4, la Figure 12, and Figure 13:

Table 4. Results of the error rate of the test

Extreme Location and Starting point		
Desired value	**Real value**	**Relative error**
px = 16.26 py = 34.59 pz = 39.19	px = 15.5 py = 35.8 pz = 40.8	ex = 4.6% ey = 3.5% ez = 4.1%
Final point		
Desired value	**Real value**	**Relative error**
px = 57.94 **py = 35.11** **pz = 44.93**	px = 56 py = 36 pz = 43.6	ex = 3.3% ey = 2.5% ez = 2.9%

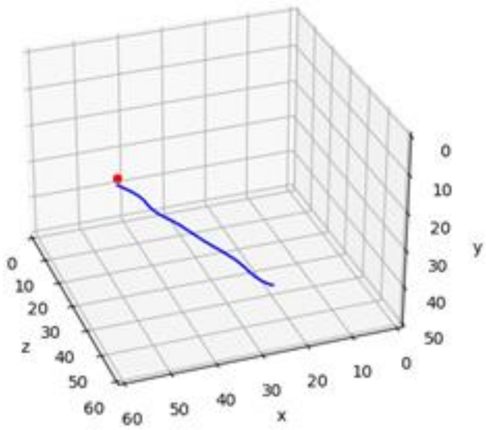


Figure 12. Emulation of the manipulator end movement within the workload.

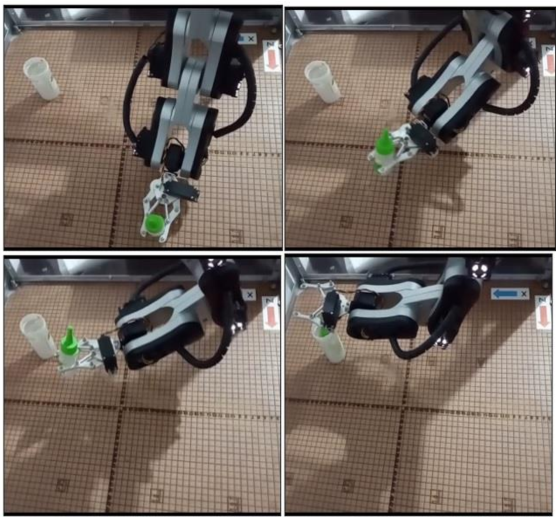


Figure 13. Capture images of the movement of the proof

Learning Methodology

In order to develop activities in which the apprentice interacts directly with the manipulator, acquiring learning directly with the workbench, a series of activities described in Figure 14 is proposed, in which the facilitator will have to deepen, or if for his considerations, may change. Before teaching in robotics, the apprentice must have basic knowledge of electronics and mechanics since they are the basis for understanding the workbench's operation.

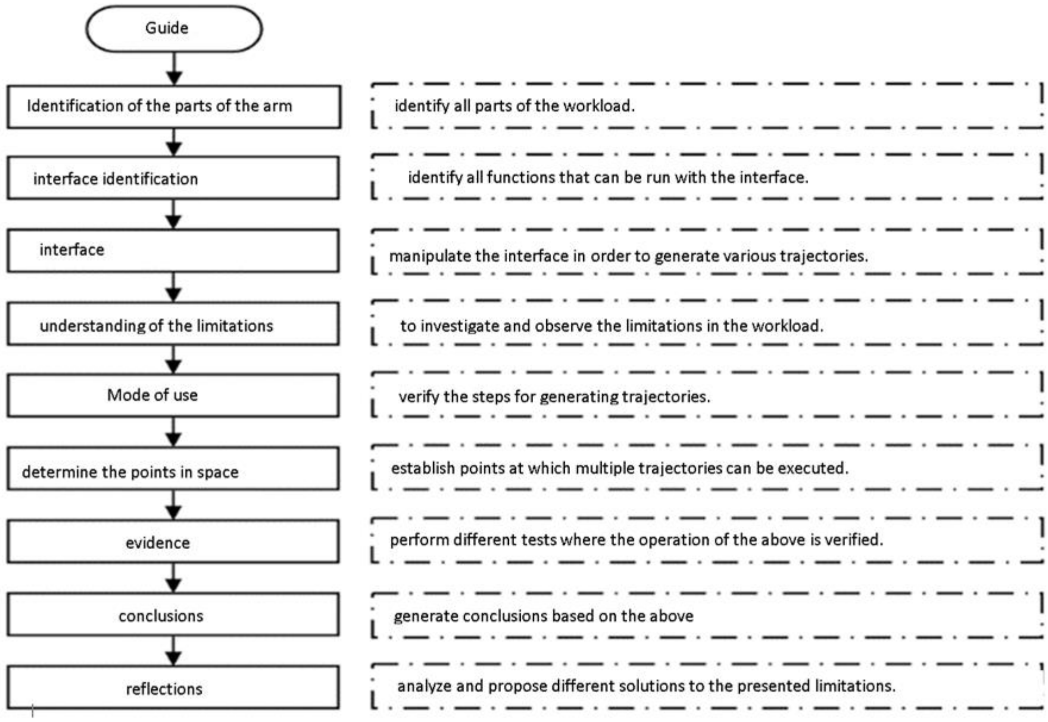


Figure 14. Learning methodology flow diagram with robotic workbench

CONCLUSIONS

Obtaining the manipulator kinematic model can be validated, based on the accuracy of the manipulator end location in the tests, by checking the similarity of the model with the actual system.

Based on the generation of trajectories given by the images of the tests and on the emulation of the test, it can be observed that the answers are very similar, sustained by their low percentage of error between the initial and final points. Also, the execution times correspond in remarkably like the real to the desired ones, which can be concluded that there is a great similarity between the trajectory generated and the desired trajectory.

When comparing the error rate of the starting point with the endpoint of the test performed, it can be observed that in this first one, there is a higher error rate, indicating that there is a factor that generates a higher error rate when analyzing each of the images of the actual trajectory. Also was observed that the highest percentage of error is found when the arm is more extended, generating higher torques and although the motors try to position themselves in their desired articular values with a very high degree of accuracy, concluding that that slightly higher error percentage, can be avoided by strengthening the system with dynamic control.

Creating the prototype and providing it with a protection system so that it does not encounter disturbances within its workload guarantees a generation of trajectories more in line with the desired ones. Furthermore, as well as implementing a safety system such as emergency buttons and isolation of some sections, possible accidents are mitigated when handling the workbench.

In general, the error percentage exists due to the clearances of the different elements that make up the engine in Figure 6, which, for the most part, have a greater tolerance, that by adding all these chain tolerances, we have an error rate of around 2.5%.

In the absence of feedback on the closure of the grippers, the user must specify the correct dimensions of the element to be taken since if the engine is closed too much, it begins to be forced, or if it is not closed properly, the part will not be fastened properly.

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