AUTOMATION OF MANUFACTURING CELL USING AN INDUSTRIAL ROBOT AND CONTROLLED BY P.L.C.

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Abstract
This work consists of a previous study to automate and to implement a manufacturing cell. The process proposed consists of the manipulation of an object on a transport system operated by an electric engine. The automation system is composed by frequencies converter, three degrees of freedom robotic manipulator with cylindrical coordinates, Programmable Logic Controller (PLC), pneumatic system and sensors. The sensors are used to monitor the process and the PLC makes the control of the whole system. The PLC is programmed in LADDER. The robotic arm starts from an initial position (P0) and it moves the object, through a linear trajectory, from position P1 up to position P2, certain on the transport system. The linear trajectory is adopted to reduce time in the process. These trajectories are programmed in language "C" program, according to Denavit-Hartenberg (D-H) parameters for the evaluation of the Direct and Inverse Kinematics. It is used as end-effector a pneumatic system and sucker to pick the object up. The process cycle is concluded when the object arrives at the end of the transport system (position P3). The final result is a fully automated transport robotic system for industrial application.

1 Introduction

1.1 Automation and Robots
[3] Automation has not only led to improve productivity but has also helped minimize variations in manufactured components, thereby raising quality standards. Flexible and agile manufacturing concepts by integrating imaging and motion using industrial robots provide an excellent teaching tool to the field of "Mechatronics" which integrates mechanism design and analysis, soft computing, sensing and electronics.

[4] An automated manufacturing system usually consists of a collection of material-processing and handling devices. Developments in order to improve agility and flexibility in automated manufacturing systems provide advantage in the areas of cost, product architecture and product development using a component-based technology robot workcell that can be rapidly configured to perform a specific manufacturing task. The workcell is conceived with standard and inter-operable components including actuator modules, rigid link connectors and tools that can be assembled into robots with arbitrary geometry and degrees of freedom.

[6] Flexible manufacturing systems are essential for small or medium batch and job shop manufacturing. These types of production systems are used to manufacture a considerable variety of products with medium or small volumes. Therefore, the manufacturing platforms supporting these types of production must be flexible and organized in flexible manufacturing cells.

[7] To position and orient the hand of an industrial robot to perform a particular manufacturing process, the joints are commanded to assume certain angles and/or displacements. However, due to position errors at joints, the assumed positions are almost always different from those commanded. These deviations induce a random error to the position and orientation of the hand. The ability

of the hand to perform according to the required accuracy depends, among other things, on the extent of joint position errors. [5] Taguchi Methods are used to conduct parameter design to improve the accuracy of the Cartesian positions of the end-effector within the robot workspace, subject to spatial considerations of the manufacturing process and required boundary conditions.

[2] Mass-production assembly lines were first introduced at the beginning of the twentieth century (1905) by the Ford Motor Company. Over the ensuing decades, specialized machines have been designed and developed for high-volume production of mechanical and electrical parts. However, when each yearly production cycle ends and new models of the parts are to be introduced, the specialized machines have to be shut down and the hardware *retooled* for the next generation of models.

Commonly are used in industrial robots only two basic types of robot joints, as listed in Tab. (1).

Table 1. Types of robot joints

Type	Notation	Symbol	Description
Revolute	R		Rotary motion about an axis
Prismatic	P		Linear motion along an axis

Revolute joints (R) exhibit rotary motion about an axis. They are the most common type of joint. The next most common type is a prismatic joint (P), which exhibits sliding or linear motion along an axis. The particular combination of revolute and prismatic joints for the three major axes determines the geometry of the work envelope, as summarized in Tab. (2).

Table 2. Robot work envelopes based on major axes

Robot	Axis 1	Axis 2	Axis 3	Total Revolute
Cartesian	P	P	P	0
Cylindrical	R	P	P	1

Table 2. Robot work envelopes based on major axes (continuation)

Robot	Axis 1	Axis 2	Axis 3	Total Revolute
Spherical	R	R	P	2
SCARA	R	R	P	2
Articulated	R	R	R	3

1.2 Robot Arm Kinematics

[1] A mechanical manipulator can be modeled as an open-loop articulated chain with several rigid bodies (links) connected in series by either revolute or prismatic joints driven by actuators. One end of the chain is attached to a supporting base while the other end is free and attached with a tool (the end-effector) to manipulate objects or perform assembly tasks. The relative motion of the joints results in the motion of the links that positions the hand in a desired orientation.

Robot arm kinematics deals with the analytical study of the geometry of motion of a robot arm with respect to a fixed reference coordinate system as a function of time without regard to the forces or moments that cause the motion. Denavit and Hartenberg (1955) proposed a systematic and generalized approach of utilizing matrix algebra to describe and represent the spatial geometry of the links of a robot arm with respect to a fixed reference frame. This method uses 4 X 4 homogeneous transformation matrix to describe the spatial relationship between two adjacent rigid mechanical links and reduces the direct kinematics problem to finding an equivalent 4 X 4 homogeneous transformation matrix.

In general, the inverse kinematics problem can be solved by several techniques. Most commonly used methods are the matrix algebraic, iterative, or geometric approaches.

1.3 The Denavit-Hartenberg Representation

[1] The Denavit-Hartenberg representation results in a 4 X 4 homogeneous transformation matrix representing each link's coordinate system at the joint with respect to the previous link's coordinate system.

Every coordinate frame is determined and established on the basis of three rules:

- the z_{i-1} axis lies along the axis of motion of the *i*th joint;
- the x_i axis is normal to the z_{i-1} axis, and pointing away from it;
- the y_i axis completes the right-handed coordinate system as required.

The Denavit-Hartenberg representation of a rigid link depends on four geometric parameters associated with each link. These four parameters completely describe any revolute or prismatic joint. Referring to Fig. (1), these four parameters are defined as follows:

θ_i is the joint angle from the x_{i-1} axis to the x_i axis about z_{i-1} axis (using the right-hand rule);
d_i is the distance from the origin of the (*i*-1)th coordinate frame to the intersection of the z_{i-1} axis with the x_i axis along the z_{i-1} axis;
a_i is the offset distance from the intersection of the z_{i-1} axis with the x_i axis to the origin of the *i*th frame along the x_i axis (or the shortest distance between the z_{i-1} and z_i axes);
α_i is the offset angle from the z_{i-1} axis to the z_i axis about the x_i axis (using the right-hand rule).

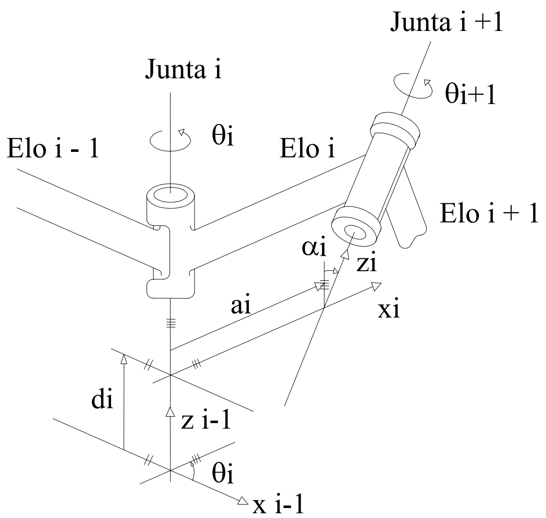

Figure 1. Link coordinate system and its parameters.

Once the Denavit-Hartenberg coordinate system has been established for each link, a homogeneous transformation matrix can easily be developed relating the *i*th coordinate frame to the (*i*-1)th coordinate frame. This matrix is the resultant of the product of the transformation matrices for adjacent coordinate frames, as shown in Eq. (1).

$$ {}^{i-1}A_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i\cdot\operatorname{sen}\theta_i & \operatorname{sen}\alpha_i\cdot\operatorname{sen}\theta_i & a_i\cdot\cos\theta_i \\ \operatorname{sen}\theta_i & \cos\alpha_i\cdot\cos\theta_i & -\operatorname{sen}\alpha_i\cdot\cos\theta_i & a_i\cdot\operatorname{sen}\theta_i \\ 0 & \operatorname{sen}\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

A homogeneous transformation matrix can be considered to consist of four sub matrices, as shown in Eq. (2).

$$ {}^{0}T_n = \begin{bmatrix} R_{3x3} & p_{3x1} \\ f_{1x3} & 1x1 \end{bmatrix} = \left[\begin{array}{c:c} \text{rotation matrix} & \text{position vector} \\ \hdashline \text{perspective transformation} & \text{scaling} \end{array}\right] \quad (2) $$

The upper right 3 X 1 sub matrix represents the position vector of the origin (dx, dy, dz) of the rotated coordinate system with respect to the reference system.

2 Method

The manufacturing cell proposed is fairly flexible, therefore it was adopted as a study the manipulation of an object on a transport system.

The interface of the manufacturing cell is illustrated in Fig. (2). An electric sensor indicates the robot's initial position. At the position P1, a sensor of presence installed on the transport system detects the object, which it sends a signal to the Programmable Logic Controller (PLC) and, this sends a signal to the frequencies converter to stop the transport system's motion and, a second signal to the robot to pick the object up. According to the time programmed, the robot executes the trajectories from P0 up to P1, P1 up to P2 and, P2 up to P0. The end-effector is a pneumatic cylinder and sucker to pick the object up. There are two magnetic sensors installed in the cylinder to indicate the superior and inferior positions. At the position P1, by the computer, the robot sends a signal to the PLC and, this sends three signals, the first to start the sucker's vacuum valve, the second to start the down motion of the cylinder and, the third to start the up motion of the cylinder after having picked the object up. The robot arm moves the object, through a linear trajectory, from position P1 up to position P2, certain on the transport system. At the position P2, by the computer, the robot sends a signal to the PLC and, this sends four signals, the first to start the down motion of the cylinder, the second to turn off the vacuum valve, the third to start the up motion of the cylinder and, the fourth to the frequencies converter to start the transport system's motion. After that, the robot arm comes back to the initial position and, the object is moved to the position P3, where a sensor detects its presence and sends a signal to the PLC and, this sends a signal to the converter to stop the transport system's motion, concluding the process cycle.

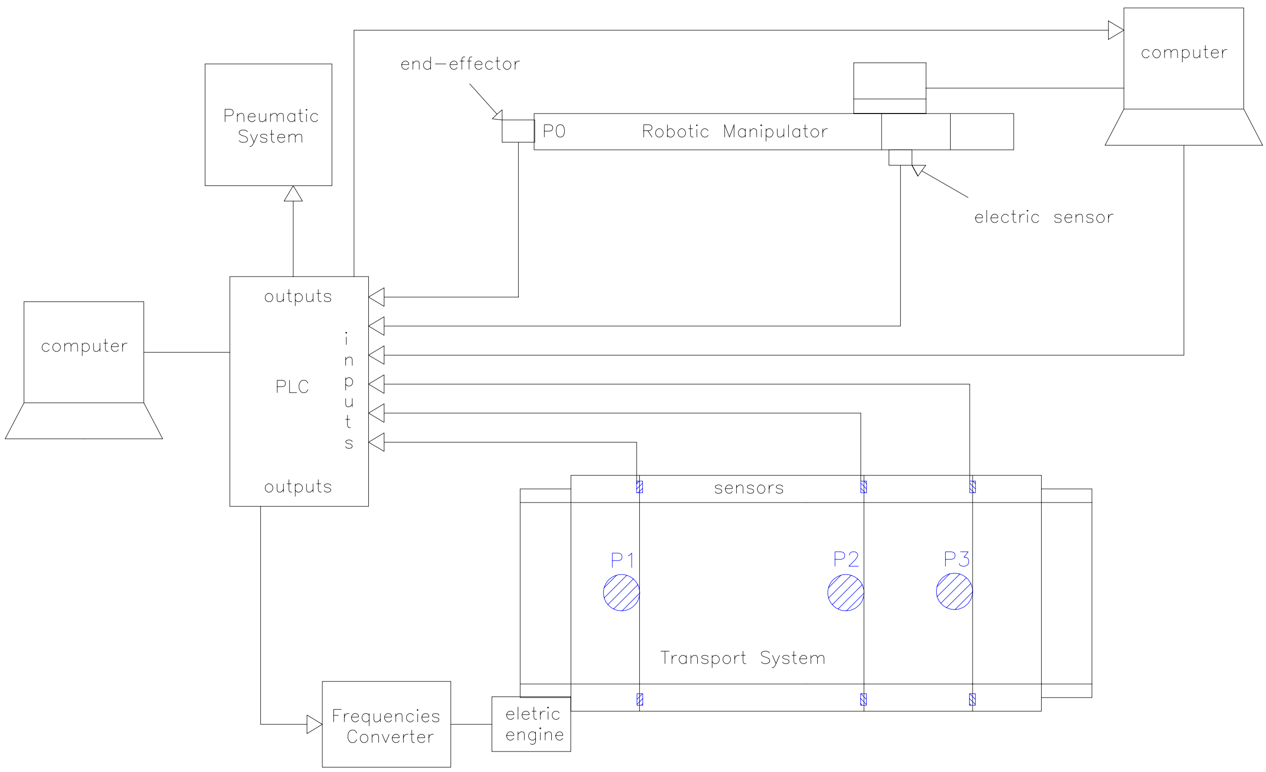

Fig. 2. Interface of the manufacturing cell.

The robot program is done in "C" programming language, where it is inserted the equations of the Inverse Kinematics. The PLC programming is done in "LADDER".

3 Results

3.1 Calculation of the Direct Kinematics for the Robot

The robotic manipulator has three degrees of freedom and cylindrical coordinates with a revolute joint and two prismatic joints. The link coordinate system for this robot is illustrated in Fig. (3).

The joint and link parameters are defined according to link coordinate systems adopted for the robotic manipulator using the Denavit-Hartenberg method. These parameters are presented in Tab. (3).

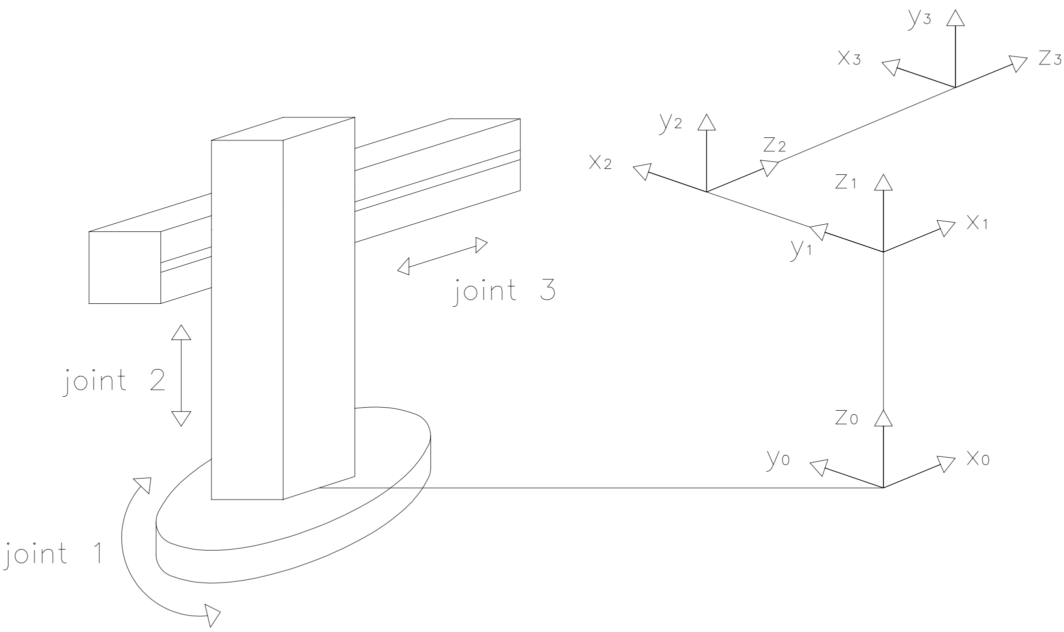

Fig. 3. Link coordinate system for the robotic manipulator.

Table 3. Joint and link coordinate parameters for the robotic manipulator.

Joint i	θi	αi	a_i	d_i
1	θ_1	0	0	d_1
2	90º	90º	a_2	0
3	0	0	0	d_3

The homogeneous transformation matrix ($^0T_3$) is shown in Eq. (3) as the resultant of the product of the transformation matrices for adjacent coordinate frames ($^0A_1$; $^1A_2$; $^2A_3$), respectively for each joint substituting the joint and link coordinate parameters in Eq. (3).

$$^0T_3 = \begin{bmatrix} -\operatorname{sen}\theta_1 & 0 & \cos\theta_1 & d_3\cdot\cos\theta_1 - a_2\cdot\operatorname{sen}\theta_1 \\ \cos\theta_1 & 0 & \operatorname{sen}\theta_1 & d_3\cdot\operatorname{sen}\theta_1 + a_2\cdot\cos\theta_1 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Therefore, the position vector from the homogeneous transformation matrix ($^0T_3$) represents the Direct Kinematics (Px, Py e Pz) of the robotic manipulator, as shown in Eq. (4), Eq. (5) and Eq. (6), respectively.

$$Px = d_3\cdot\cos\theta_1 - a_2\cdot\operatorname{sen}\theta_1 \quad (4)$$

$$Py = d_3\cdot\operatorname{sen}\theta_1 + a_2\cdot\cos\theta_1 \quad (5)$$

$$Pz = d_1 \quad (6)$$

3.2 Calculation of the Inverse Kinematics for the Robot

The method used to solve the Inverse Kinematics problem of the robot was geometric approaches and trigonometry. Therefore, the result of the Inverse Kinematics equations (d_1; d_3; θ_1) is shown in Eq. (7), Eq. (8) and Eq. (9), respectively.

$$d_1 = Pz \quad (7)$$

$$d_3 = \sqrt{P_x^2 + P_y^2 - a_2^2} \quad (8)$$

$$\theta_1 = \arccos\left(\frac{P_x}{\sqrt{P_x^2 + P_y^2}}\right) - \arccos\left(\frac{d_3}{\sqrt{d_3^2 + a_2^2}}\right) \quad (9)$$

3.3 Calculation of the Motion Positions of the Robot

The joint and link coordinate parameters determine the limits of motion for the robotic manipulator. According to the robot used as illustrated in Fig. (4), these limits are shown in Fig. (6). The minimum and maximum ranges of the robotic arm about of the vertical axis determine its work area. Therefore, observing the limits and work area of the robot, the layout for the manufacturing cell is illustrated in Fig. (5).

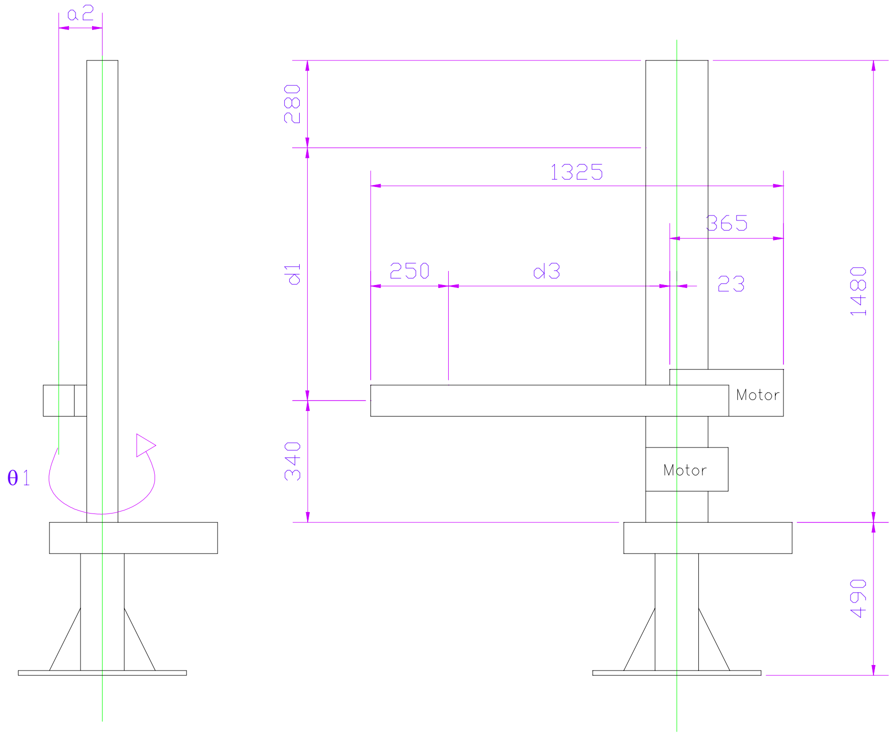

Fig. 4. Dimensions of the robot and its parameters.

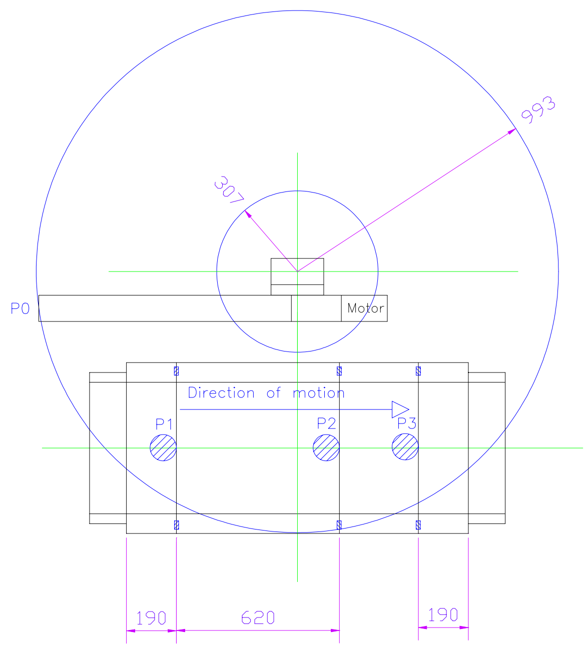

Fig. 5. Layout for the manufacturing cell.

$$\boxed{\begin{array}{l} 0 \le d_1 \le 860mm \\ 0 \le d_3 \le 710mm \\ 0 \le \theta_1 \le 360^\circ \\ a_2 = 140mm \end{array}}$$

Fig. 6. Limits of motion for the robotic manipulator.

3.4 Control of the Manufacturing Cell

The control of the manufacturing cell is done using a S7-200 Programmable Logic Controller (PLC) made by Siemens, which it has eight digital inputs (0-7) and six digital outputs (0-5) linked to the sensors, frequencies converter, robotic manipulator and, pneumatic system. The sequence of control is presented in Tab. (4).

Table 4. Sequence of control of the manufacturing cell.

Sequence	Description
1	The Process starts with the robotic arm at the initial position, indicated by the electric sensor. The transport system is turned on by the frequencies converter and the sensors at the positions P1, P2 and, P3 are not detecting any presence of an object.
2	When the sensor of presence at the position P1 detects the object, the transport system stops the motion and, the robot starts the motion to pick the object up describing a linear trajectory from P0 up to P1, after that from P1 up to P2 and, P2 up to P0, according to the time programmed.
3	The sucker picks the object up when the robotic arm arrives at the position P1 and stops for a time.
4	After the sucker picks the object up, the robot arm moves it up to position P2.
5	At the position P2, the robotic arm stops its motion for a time and the end-effector put the object on the transport system.
6	When the sensor of presence at the position P2 detects the object, the robotic arm comes back to the initial position (P0) and the frequencies converter starts the transport system's motion.
7	The converter stops the transport system's motion when the object arrives at the position P3, where a sensor detects its presence, concluding the process cycle.

4 Discussion

The calculation of the Direct Kinematics for the robotic manipulator was used Denavit-Hartenberg method determining the joint and link coordinate parameters and, the homogeneous transformation matrix. However, the calculation of the Inverse Kinematics was used, among other methods, geometric approaches and trigonometry.

The layout for the manufacturing cell was established according to the work area of the robotic arm and, the best position of the transport system to execute the task. The Programmable Logic Controller (PLC) makes the control of the whole manufacturing cell. The linear trajectories of the robotic arm are to reduce the process time.

5 Conclusions

This work presents the automation of a manufacturing cell using a industrial robot to manipulate an object on a transport system making the cell's control by PLC. To achieve this goal it was used some technologies as robotic, pneumatic system and programmable logic controller and, some devices as transport system, frequencies converter and sensors. For being of a manufacturing cell quite flexible, it was proposed the manipulation of an object on a transport system by the robotic arm describing a linear trajectory. It is possible to check in this work Denavit-Hartenberg method to determine the link coordinate systems and joint coordinate parameters for the robotic manipulator and, the Direct Kinematics by the homogeneous transformation matrix. The Inverse Kinematics is determined starting from Direct Kinematics using geometric approaches and trigonometry. The manufacturing cell's assembling was according to the robotic manipulator's limits of motion and, consequently, its work area, so that could have the best layout for the foreseen task. Therefore, the final result is a fully automated transport robotic system for industrial application.

References

[1] Fu, K. S., Gonzalez, R. C. and Lee, C. S. G. *Robotics: control, sensing, vision, and intelligence*, McGraw-Hill, pp. 12 – 40, 1987.

[2] Schilling, Robert J. *Fundamentals of robotics analysis & control*, Prentice-Hall, pp. 1, 4 – 5, 1990.

[3] Nagchaudhuri A, Kuruganty S and Shakur A. *Introduction of mechatronics concepts in a robotics course using an industrial SCARA robot equipped with a vision sensor,* Elsevier Science Ltd. – Mechatronics, 2002, v. 12, p. 183 – 193.

[4] Chen I-Ming. *Rapid response manufacturing through a rapidly reconfigurable robotic workcell*, Elsevier Science Ltd. – Robotics and Computer Integrated Manufacturing , 2001, v. 17, p. 199 – 213.

[5] Kao I and Gong C. *Robot-based computer-integrated manufecturing as applied in manufacturing automation*, Elsevier Science Ltd. – Robotics and Computer Integrated Manufacturing , 1997, v. 13, p. 157 – 167.

[6] Pires J and Costa J. *Object-oriented and distributed approach for programming robotic manufacturing cells*, Elsevier Science Ltd. – Robotics and

Computer Integrated Manufacturing, 2000, v.16, p. 29 – 42.

[7] Azadivar F. *The effect of joint position errors of industrial robots on their performance in manufacturing operations*, IEEE Journal of Robotics and Automation, 1987, v. RA-3, p. 109 – 114.