Palestine Polytechnic University
College of engineering
Mechanical & Electrical Engineering Departments

Graduation Project

Automatic Wood Plates Painting Machine

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Submitted to the College of Engineering

In partial fulfillment of the requirements for the

Bachelor's degree in engineering

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....

2019 - May

محاولة اهداء

ولاءً لعهد الصداقة الأول...ووفاءً لحق الاخوة

إلى الصديق الأول,الشقيق الذي لم تنجبه أمي, إلى رفيق الطفولة والشباب، نديم الدرب والقلم والعلم

إلى الغائب الحاضر أبدا بقلوبنا وعقولنا

ألى الروح الجميلة التي غادرت هذا الحياة بدون وداع تاركة خلفها احلامنا المنتظر تحقيقها

إليك يا من رحلت مبكراً قبل نهاية الطريق

حاضرٌ دائما بالذاكرة والوجدان

صوتك وضحكاتك عالقة هاهنا إلى الأبد

هذا العمل ما كان سيرى النور لولا روحك التي تطوف بسلام حولنا لنصل آخر الدرب

كنت أجملهم

وخفيف أنت كنسمة

الان أنت حيٌ فينا ما حيينا

فرغ منك المكان وما زال كل شيء ينتقص منك

باق أنت بقلوبنا فالرجال أمثالك لا يموتون بتقليدية،

رجلٌ مثلك يظل على رؤوس الأشهاد.. لا يُنسى ولا يرحل، ولا يموت كباقي البشر

إلى **إياد**، علك تسمعني الان أو تجد من يقرأ لك هذا هناك

الملخص

يهدف المشروع الى إنشاء آلة تقوم بطلاء الالواح الخشبية بطريقة اوتماتيكية وذلك بهدف تقديم منتج ذو كفائة عالية وتحسين عملية الانتاج وإبعاد العامل البشري عن مخاطر عملية الطلاء واثارها السلبية على الصحة . وذلك بالتخلص من بعض المشاكل التي كانت تواجههم في عملية الطلاء اليدوي , مثل : عدم كفائة المنتج المتمثلة بسوء توزيع الطلاء على الاوجه الخشبية و الوقت الكبير الذي كانت تستغرقه عملية الطلاء اليدوية . وفي نهاية المشروع تم انشاء نموذج عملي مصغر عن الآلة يحاكي طريقة عملها وقد ادى الاهداف المطلوبة على اكمل وجه .

Abstract:

The purpose of this project is to design and produce a machine that can paint any type of wooden plates using spray painting technique.

The wooden piece is inserted, and the paint type is specified, the machine is painted according to the dimension of this piece based on certain equations previously entered.

What is expected of the machine to do, possibility to paint three types of paint on all surfaces of the wooden piece with high accuracy.

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Chapter1

Introduction

1.1. Overview of the project

The need to save time and effort and get the highest possible quality led us to produce a machine to paint the wood panels automatically using spraying technique, this machine is very important for every carpenter to enhance his current status and grow up the manufacturing sector in the country. This machine produces a sensible difference between the manual and automatic painting; it produces a very beautiful product with high quality. The process of the machine is to move the spray gun above the moving plate to make such a path to cover the whole plate homogeneously.

1.2. The need of the project

Painting is one of the most important things in industrial life. The process of painting wood and home furniture is very important for the beauty and protection of the product. In the process of manual painting there are many problems facing workers, the most important of which is the health of the worker, in the spraying process of paint, workers may suffer from many lung diseases. And other reasons related to the quality of the product and the speed of production and the provision of effort.

1.3. Requirements

- Capability to paint the wood plates using spray technique.
- Capability to paint the wood plates with dimensions the does not exceed (220*120) cm.
- Produce high quality product with homogeneously distributed paint material.
- Production rate of the machine is (30-40) square meter of wood plates per one hour.
- Capability to diagnose the errors by HMI “touch screen’.
- Capability to measure the dimensions of the product and process the data to determine the long of the path automatically.

1.4. Description of the project

The purpose of this project is to design and produce an automatic machine that can paint any type of wooden plates" interior doors, kitchen cabinet and furniture panels" using spray painting technique, also to build an integrated diagnostic system using Scada technology. We have asked some carpenters and wood painters who use the traditional way that is gun spray, we found that all of them suffer from diseases and slow production rate and low quality of products, and they supported the idea. This machine only needs 2 normal workers to load the wood plates and discharge the painted wood plates. At the end of the project we will implement a small-scale prototype to determine the operation of the machine.

1.5. Literature review:

1.5.1. Painting:

Painting is an important process in the industrial sector, such that wood painting, walls, iron, aluminum, Stainless steel, furniture, etc...Painting is used for these major reasons, first for protect the painted piece "from corrosion, form scratches…".Or it used to Give an aesthetic view for the surfaces that are painted or to make the cleaning process of these surfaces easy. Methods of painting the surfaces:

1- Painting using brush paint: this is the traditional method for paint, it used widely for painting walls and sometimes iron, as shown in Figure 1.

Figure 1: Traditional painting ways.

2- Paint using ionized paint grains:

This method is used to paint the sheet metals, this can be done using the charged sheet metal with an opposite charged paint grains then it enters into a thermal oven to change the paint material to its final shape, as shown in Figure 2.

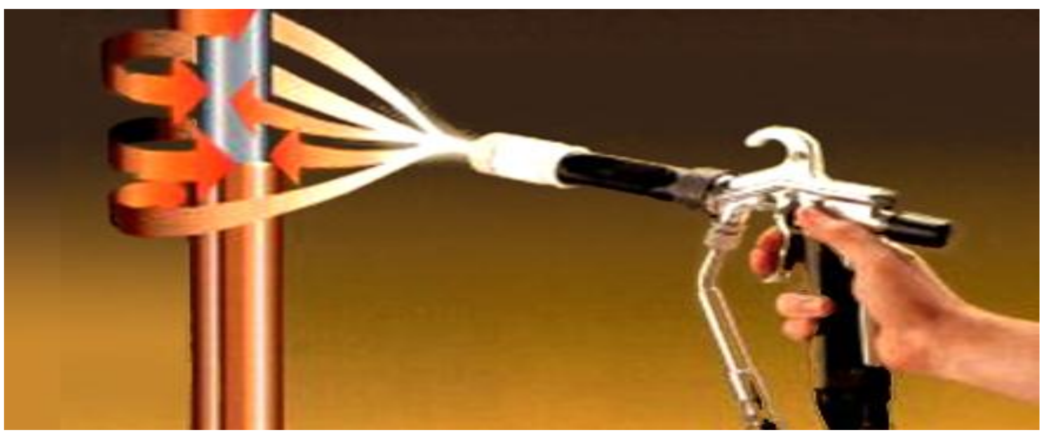

Figure 2: Paint using ionized paint grains.

3- Spraying: this method used to paint woods, iron, sheet metals, furniture etc.…

In this method, worker uses spraying gun to paint the piece as desired, as shown in Figure 3.

Figure 3:Spray painting technique.

Wood plates painting:

Painting wooden doors or kitchen cabinet or other types of wooden furniture plates passes through three stages, in other word three layers of painting:

1- Color layer.
2- Base layer.
3- Lacquer.

The color layer is optional here, the customer may like the normal color of wood, then the base layer comes to protect the color. Then the lacquer layer to give a bright to the piece of work.

Between each stage there must be some time to dry up the paint material.

1.5.2. CNC Machine

Computerized Numerical Control (Computer + Numerical Control)

• Numerical control is a programmable automation in which process is controlled by Numbers, Letters, and symbols.

• CNC Machining is a process used in the manufacturing sector that involves the use of computers to control machine tools like lathes, mills and grinders[1].

1.5.3. CNC Machine necessary

• To manufacture complex curved geometries in 2D or 3D was extremely expensive by mechanical means (which usually would require complex jigs to control the cutter motions)

• Increased productivity: Due to low cycle time achieved through higher material removal rates and low set up times achieved by faster tool positioning, changing, automated material handling etc.

• Improved quality: Due to accurate part dimensions and excellent surface finish that can be achieved due to precision motion control and improved thermal control by automatic control of coolant flow[2].

1.5.4. Servo Motor

Figure 4: servo motor.

A servomotor is a rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity and acceleration It consists of a suitable motor coupled to a sensor for position feedback. It also requires a relatively sophisticated controller, often a dedicated module designed specifically for use with servomotor[1].

1.5.5. Stepper motor

Figure 5: Stepper motor

A stepper motor is an electromechanical device it converts electrical power into mechanical power. Also, it is a brushless, synchronous electric motor that can divide a full rotation into an expansive number of steps. The motor's position can be controlled accurately without any feedback mechanism, as long as the motor is carefully sized to the application. Stepper motors are similar to switched reluctance motor[2].

Stepper motor or Servo motor

Figure 6: Stepper Vs Servo.

stepper motors are good solutions for applications with low speed, low acceleration, and low accuracy requirements. Stepper motors also tend to be compact and inexpensive. This makes these motors a good fit for medical, biotech, security and defense, and semiconductor manufacturing applications. Servo motors are a better choice for systems requiring high speed, high acceleration, and high accuracy. The trade-off is a higher cost and complexity. Servo motors are typically used in packaging, converting, web processing, and similar application[3].

Servo or stepper

In our project we will use stepper motor because it has a less cost than servo motor and the stepper can done the work we need in our project, but servo is proffered to use because it has more accuracy.

We will use stepper motor to control the spray guns move and the wood piece moves.

1.5.6. HMI

Figure 7: HMI “Touch Screen”.

A human-machine interface (HMI) is the user interface that connects an operator to the controller for an industrial system.

Industrial control systems (ICS) are integrated hardware and software designed to monitor and control the operation of machinery and associated devices in industrial environments, including those that are designated critical infrastructure. An HMI includes electronic components for signaling and controlling automation system[4].

How we use HMI?

In our system permits remote user to make modifications to the HMI, and to the control status of the machine. Any subsequent modifications are transmitted to the machine and remote user in real time. Thus, the system and method allow a remote user to effectively monitor and control machines and processes without the need for the operator to be physically present at the location where the machine or process is located or being performed.

1.5.7. PLC:

A Programmable Logic Controller, or PLC for short, is simply a special computer device used for industrial control systems. They are used in many industries such as oil refineries, manufacturing lines, conveyor systems and so on. Where ever there is a need to control devices, the PLC provides a flexible way to "soft wire" the components together. The basic units have a CPU (a computer processor) that is dedicated to run one program that monitors a series of different inputs and logically manipulates the outputs for the desired control. They are meant to be very flexible in how they can be programmed while also providing the advantages of high reliability (no program crashes or mechanical failures), compact and economical over traditional control systems[5].

1.6. Motivation and solving the problem

We have chosen this project to solve the problems mentioned in section 1.2, so:

-The worker will keep his lung in a good health because he will be away from work area.

-The machine will move in homogeneous movement, so the paint material will be distributed on all parts of the piece of work.

- This machine can paint about 150-200 pieces of interior doors per shift (8 working hour/shift), can paint about 350-500 square meters of furniture panels, or kitchen cabinet doors “in full scale”, so the production rate is very high, this will save time and money.

-From the fault diagnostic system, we can able to explore the error easily on the HMI screen of the machine, so the worker may be able to fix the error.

1.7. Overall cost

The following table shows the project cost.

Item Name	*Number of items*	*Cost (NIS)*
Plc control system	*1*	*1000*
HMI	*1*	*1250*
Light sensor	*2*	*350*
Stepper Motors	*2*	*400*
Stepper Motors Driver	*2*	*500*
Frequency Converter	*1*	*800*
1-phase AC motor	*1*	*200*
valves	-	*100*
Level sensor	*1*	*100*

Relays	-	*250*
Contactors	-	*300*
Air switch	*4*	*150*
Spraying gun	*4*	*1500*
Air compressor	*1*	*500*
Body	-	*2000*
Total Cost		*9400*

Table 1: Overall cost.

Chapter 2

Conceptual design & Machine description

In this chapter we describe the general operation of the machine, then talk about each component in details.

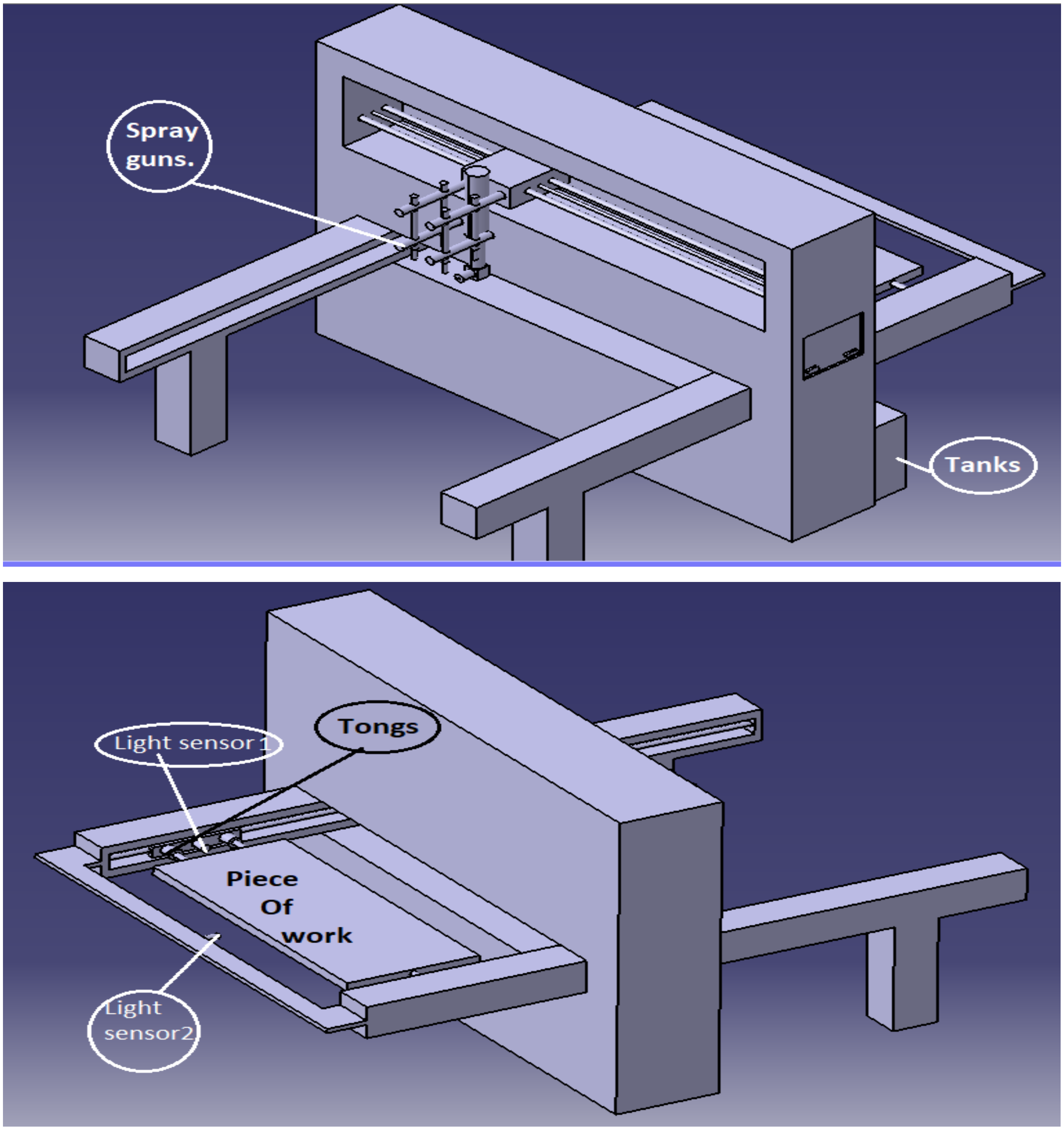

Figure 8: Machine configuration.

2.1. Block diagram

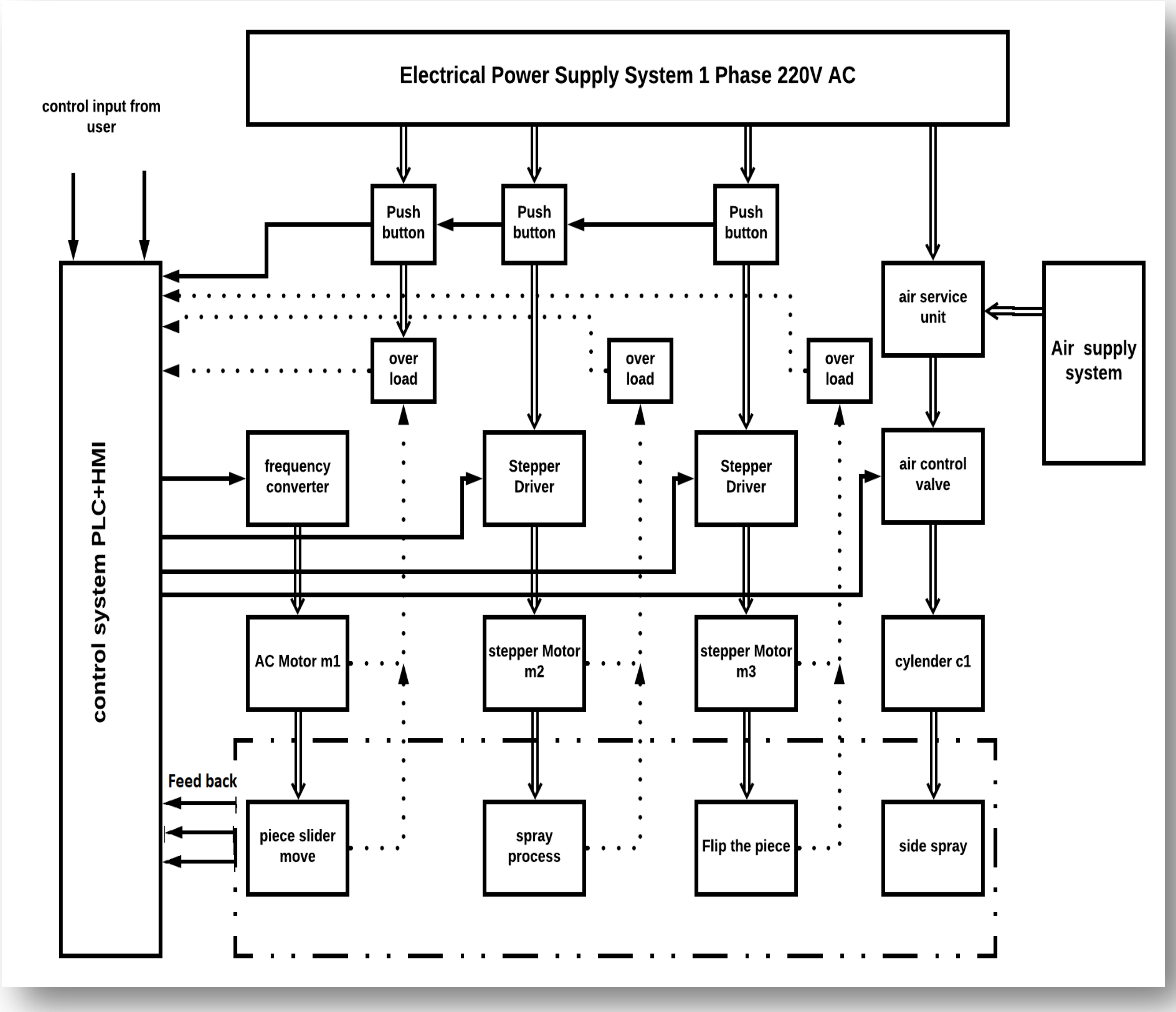

Figure 9: block diagram.

2.1.1. Piece paint cycle:

At the begging two workers insert the piece to the machine on the carrier pins , then the sensors take the dimension of the piece to derive the painting area , then the slider start moving inside the machine and when they reach under spray guns , that detected via PLC program , then the spray gun process start since the spray guns slider start to move ,and when the first side of the piece done , then cylinder of edge spray gun stroke to paint the edge , when they finished the first edge, the peace flipped via flip motor , to paint the next edge , then the piece move backward to paint the other side until reach the home position that detected via limit switch.

Note, the upper and lower edges will be painted by the same spray guns that paint the surfaces, the spray guns must be inclined to cover all surfaces.

2.1.2. Fault diagnostic:

- Motor status detected via sensor & drivers and compares it with normal values and show error if there is mismatch between reading & normal values.
- Level sensor in paint tank show the quantity of painting material in it to the user on the touch screen and show error if they become low.

2.2. Machine description

The operation of painting contains four main sections:

1. Loading and unloading the piece.
2. Measuring the dimensions of the piece.
3. Motion of piece.
4. Spray gun movement.

2.2.1. Loading and unloading the piece

- At the beginning the pieces should be drilled, three rods will be fixed in these holes as shown in Figure 10, the goal of these rods is to fix the piece and to allow rotation of piece.

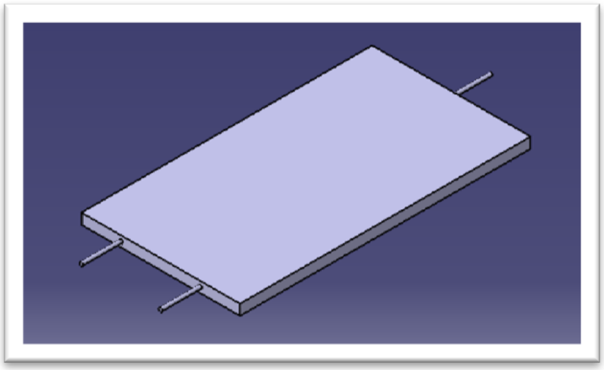

Figure 10: Piece of work with fixed rods.

- The piece will be fixed by two workers manually on special tong to fix it as shown in Figure 11&Figure 12.

Figure 11: tong

- After finishing the painting operation, workers carry the piece from the rods without touch the painted area, then put it on a special stand to dry.

2.2.2. Measuring the dimensions of the piece

After loading piece, the worker presses on start button on touch screen, two light sensors will measure the dimensions" Length & Width".

- Light sensor #1" Ls1": the sensor must be fixed on the edge of the side of machine as shown Figure 12, Ls1 function is to measure the Length piece and to check the existence of the piece.

- Light sensor #2" Ls2": the sensor must be fixed on special stand as shown Figure 12, Ls2 function is to measure the Width of piece.

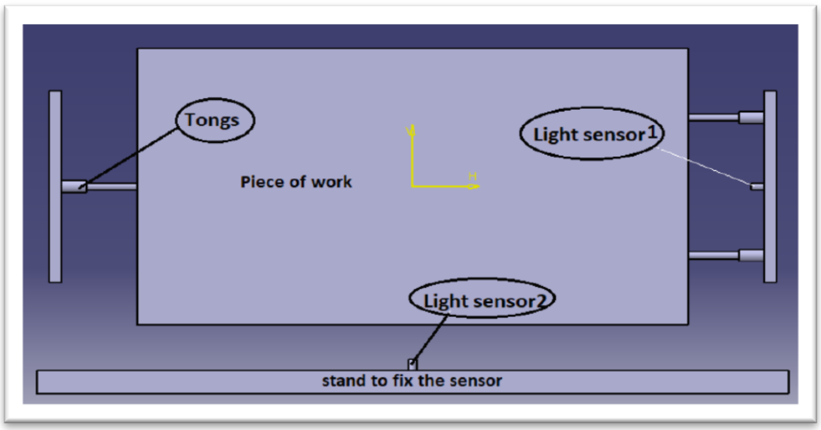

Figure 12: Sensors location & tongs.

2.2.3. Motion of piece

After taking the dimensions of piece, the Ac motor that moves the door in x-axis will start up, the motor tied with power screw by motor coupler to move the piece of work as shown in Figure 13.

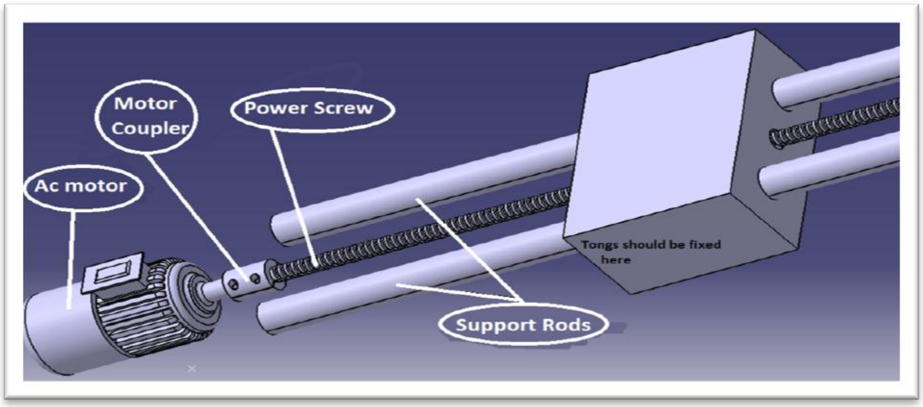

Figure 13: motion technique of piece

2.2.4. Motion of spray guns

There are five spray guns, four to paint the surfaces, one to paint the sides as shown in Figure 14, fixed on support beam and support rods, the beam can be moved by power screw that the stepper motor rotate it “convert rotational motion to linear motion” as shown in Figure 14.

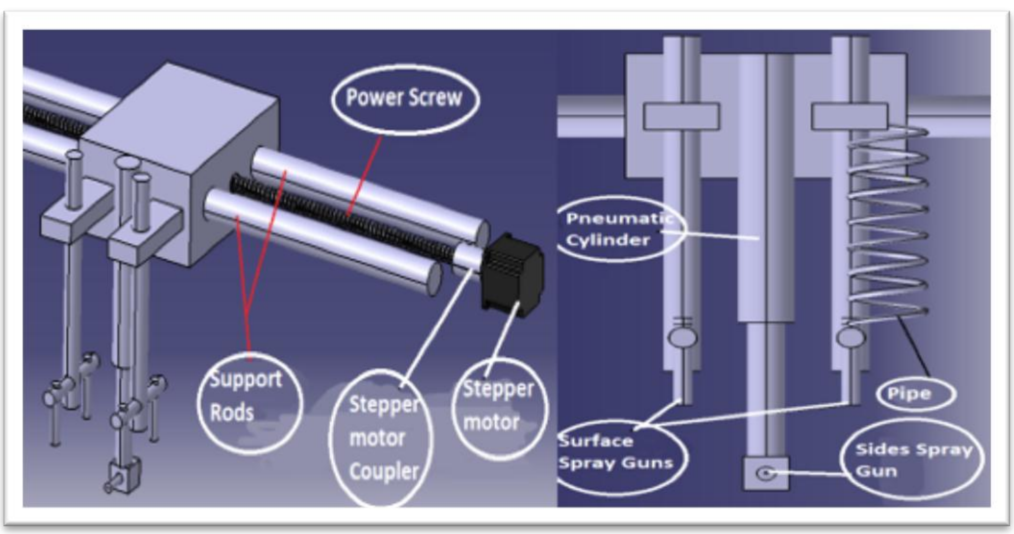

Figure 14: Spray gun motion & and spray component.

After finishing painting process of the first surface, pneumatic cylinder will extend until reach the mid thickness of the piece, then side spray gun will jet paint material with movement the slider in y-axis, pneumatic cylinder shown in Figure 14.

2.2.5. Flipping piece of work

After finishing painting process of the first surface and first side, flipping stepper motor flips the piece 180 degree to paint the other side and surface as shown in Figure 15.

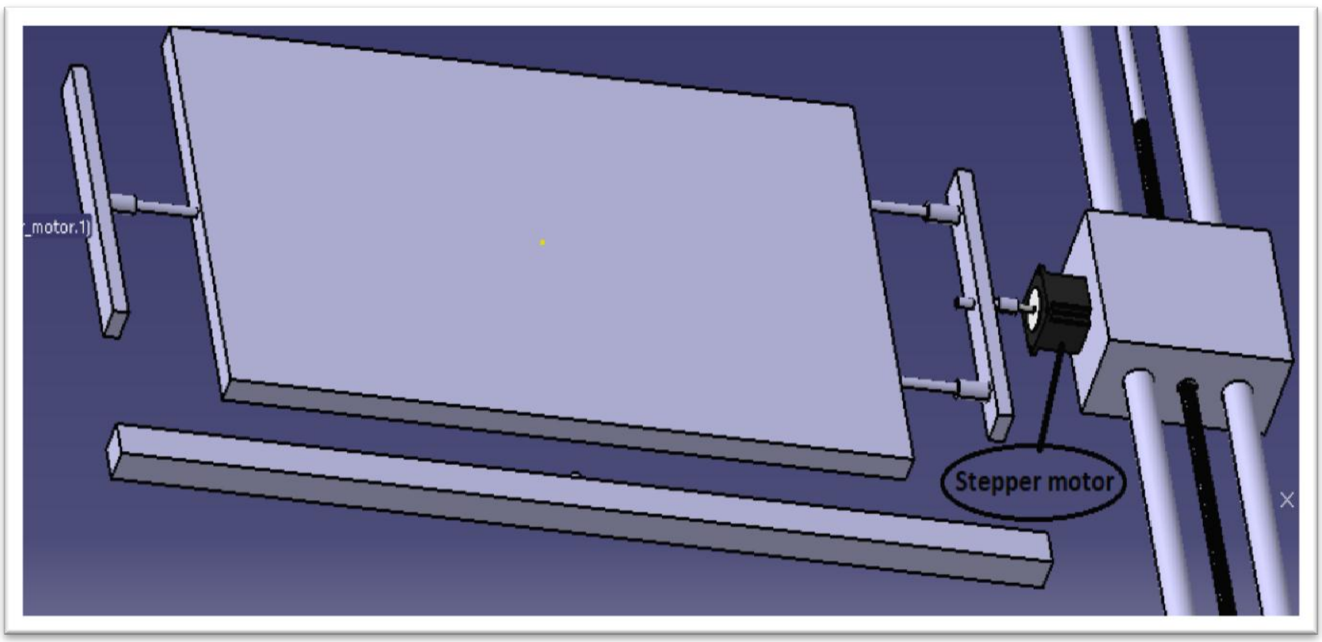

Figure 15: Flipping stepper motor

Chapter 3

Mathematical model

In this chapter we will talk about coordinate system, kinematic, kinetic and modeling the machine.

3.1. Coordinate System

Machine can be considered 4 axis machines:

1) Movement in x-axis: piece of work moves from the loading point until reach the final painted point, then return to unload it, as shown in Figure 16.
2) Movement in y-axis: spray guns moves to paint piece in y axis as shown in Figure 16.
3) Movement in z-axis: after finish painting the first surface, hydraulic pump extends in z-axis until reach the midpoint of thickness of piece, as shown in Figure 16.
4) Rotation about y-axis: after finish painting the first surface and the firs side, a stepper motor flips the door 180^o , as shown in Figure 16.

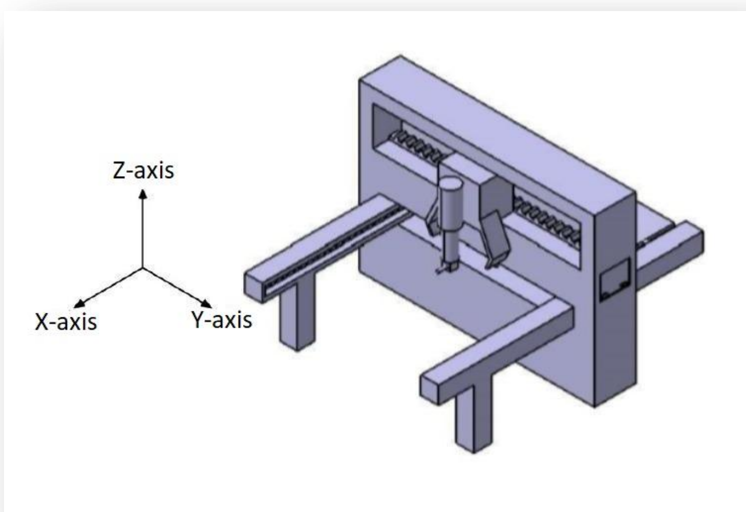

Figure 16: Coordinate system.

Technical parameters:

- Dimensions of work piece can be paint: L, W and t; this represents the dimensions of piece (Length, Width and thickness respectively).
- Feeding speed "V_f": it's the speed of the piece in x-axis.
- Surface painting Spray gun speed "V_s": it's the speed of the Spray gun in y-axis.
- Side painting spray gun: After 1st surface painted the hydraulic cylinder extends in z-axis until reach the midpoint of the thickness "t/2", then it moves with speed of V_s.

3.2. Feeding dynamic:

To move the piece of work in x-axis, we used Ac motor coupled with power screw to convert the rotational motion to linear motion.

The velocity of the piece of work has to increase from "V_o"until reach to reach steady state speed"$V_f = V_{max}$", then keep its speed until reach the end of the piece "$t_f - t_2$" as shown in Figure 16.

Due to this deference in the velocity, so there are acceleration "a_{max}" at the beginning of motion" $0 - t_1$" ,then the acceleration will be zero when the velocity is constant "$t_1 - t_2$", then before reaching the end of the path "t_2" there is deceleration equals "-a_{max}". As shown in Figure 17.

The position at the 1st interval "$0 - t_1$" increased non-linearly until t_1, then it increased linearly until t_2, then non-linearly until t_f as shown in Figure 17.

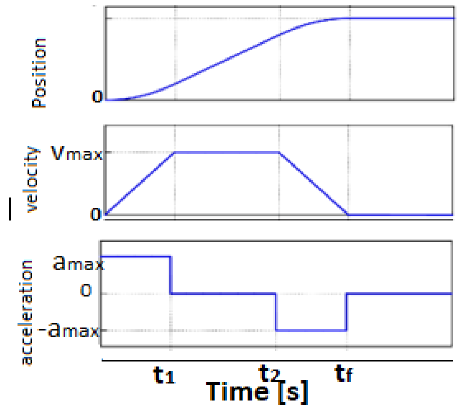

Figure 17: Trapezoidal velocity profile of feeding dynamic “a, b and c respectively”

Now, at the interval” $0-t_1$ ”:

$$V_f = V_0 + a_{\max} * t \quad (3.2.1)$$

But $V_0 = 0$ then:

$$V_f = a_{\max} * t$$

(3.2.2)

At $t = t_1$ velocity:

$$V_f = a_{\max} * t_1$$

(3.2.3)

Then the acceleration can be found by equation (3.2.4):

$$a_{\max} = \frac{V_f}{t_1}$$

(3.2.4)

This velocity in equation (3.2.2) represents the integral of acceleration in Figure 17 “a”, and the integral of this equation represents the position of the piece as in equation(3.2.6)

$$d = V_o^2 * t + \frac{1}{2} * a_{\max} * t^2$$

(3.2.5)

But $V_0 = 0$, then:

$$d = \frac{1}{2} * a_{\max} * t^2$$

(3.2.6)

where:

t_1 : the time required to reach steady state speed, we choose it 0.1 sec.

t_2 : the time required to start deceleration.

t_f : is the time of one path painting.

x_f : the total length of the piece.

d : the distance that the piece passes it at any time.

V_o : initial velocity=0.

V_f : steady state velocity.

$a_{\max}$: maximum acceleration.

3.3. Spray gun dynamic:

Spray gun dynamic follows the dynamic of feeding and the equations of both is the same.

3.4. Flip motor dynamic

Piece of work have to flip 180 degree using flip motor, the velocity starts from zero and increase until reach the midpoint (90 degree), then falls down again as shown in Figure 18.

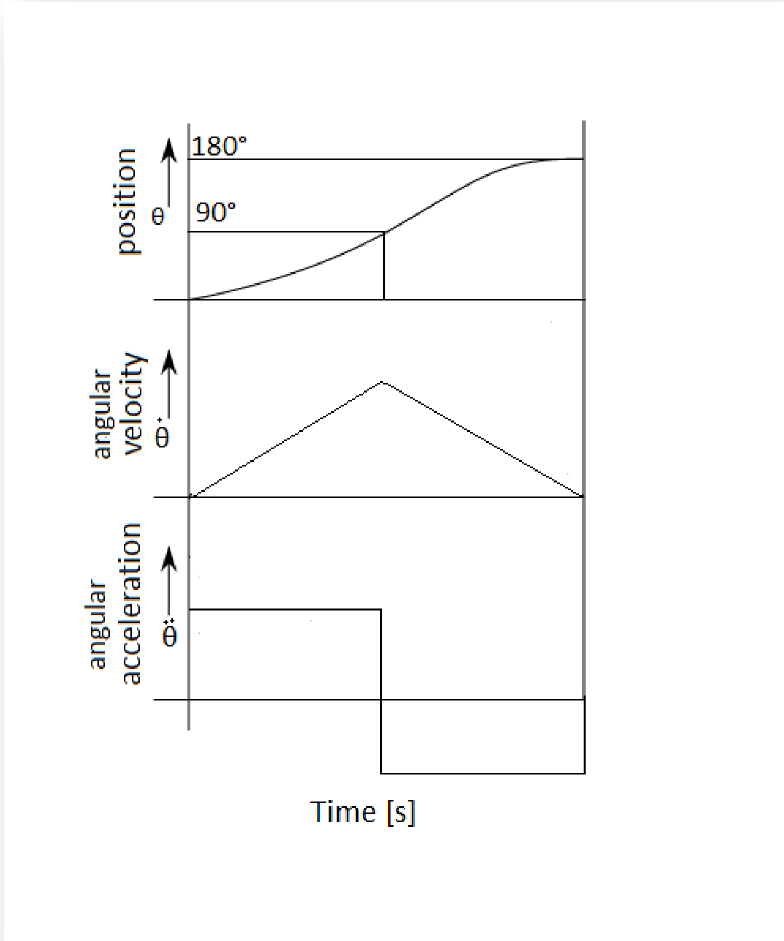

Figure 18: Trapezoidal velocity profile of flip motor.

3.5. Modeling

We have three motors to control their output:

1-slider motor “carries spray guns”.

2-conveyor motor “carries piece of work”.

3-flip motor “flip the piece”.

We control the motor that carry one mass, so the system is 2nd order system as shown in Figure 19

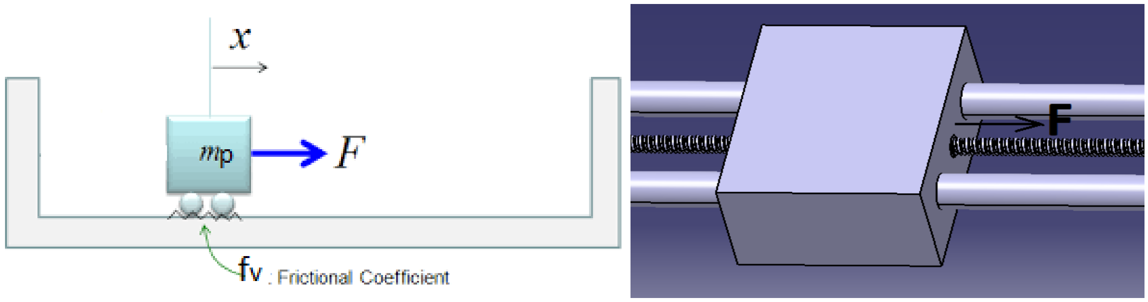

Figure 19: physical representaion

Differential equations:

$$m_p \ddot{x} + f_v \dot{x} = F \qquad (3.5.1)$$

where:

m_p : total mass of piece and the stand that carries the piece.

f_v : friction coefficient between mass and rods.

F : input force" motor output"

Now, to get the state space representation for system:

Let:

$q_1 = x$

$q_2 = \dot{x}$

Then the state space model is:

$$\dot{q} = \begin{bmatrix} 0 & 1 \\ \frac{-f_v}{m_p} & 0 \end{bmatrix} * x + \begin{bmatrix} 0 \\ -\frac{1}{m_p} \end{bmatrix} * F$$

(3.5.2)

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} * q$$

(3.5.3)

Now, to get the transfer function:

Take Laplace transform for equation (3.5.1):

$$m_p s^2 X(s) + f_v s X(s) = F(s)$$

(3.5.4)

$$X(s)(m_p s^2 + f_v s) = F(s)$$

(3.5.5)

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{(m_p s^2 + f_v s)}$$

(3.5.6)

Equation (3.5.6) represents the transfer function that will be used in control chapter to design the controller.

Chapter 4

Mechanical Design

Introduction:

In this chapter we will design the painting machine and we calculate the torque on the motor and the deflection on structure machine.

4.1. Support rods design:

In this section we will calculate the diameter of Rods:

4.1.1. Rods of piece of work

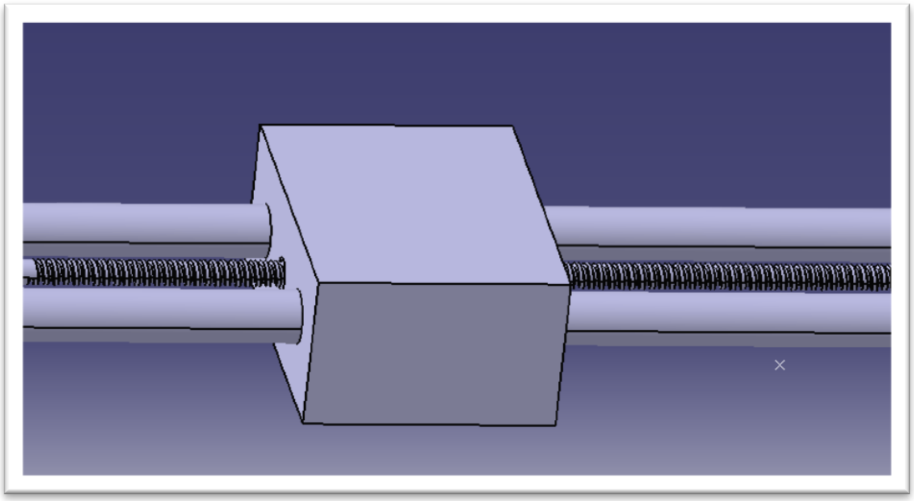

Figure 20: support rods with power screw.

At the beginning we have to design support rod that carries piece of work to prevent any deflection in rods, so we assumed that the maximum allowable deflection is 1mm.

Here, we have distributed load that comes from the weight of the rod and concentrated loud that come from piece of work this will be calculated as follow:

$$w_p = m_p g \quad (4.1.1)$$

$$m_R = \frac{\pi}{4} * D^2 * \rho * L \quad (4.1.2)$$

$$w_R = m_R * g \quad (4.1.3)$$

Where:

w_p : is the weight of the piece of work.

m_p :is the mass of piece of work.

g : gravitational acceleration $= 9.81 m/s^2$.

m_R : Rod's mass.

w_R : Rod's weight.

D : Rod's diameter.

ρ : Density of rod's material.

L : Length of the rod $L = 1m$.

Substituting in equation (4.1.1), got:

$w_p = 40Kg * 9.81 m/s^2 = 392.4N$

To find rod's weight we assumed that the material is stainless steel, which it's density $\rho = 7700 Kg/m^3$.

Now, substitute in equation (4.1.2) that represents cross sectional area multiplied by density and length of rod:

$$m_R = \rho \times v = 7700 \times \frac{\pi}{4} D^2 \times L$$

$$w_R = \frac{\pi}{4} * D^2 * 7700 * 1 * 9.81 = 6047.56 * D^2$$

(4.1.4)

Now, maximum deflection is assumed to be **1mm** at the midpoint of the rod, so the distributed loud and concentrated load effect on the deflection, so:

$$Y_{\max} = Y_1 + Y_2$$

Where**:**

$Y_{\max}$: maximum deflection on the rod.

Y_1 : deflection due to concentrated load.

Y_2 : deflection due to distributed load as shown in Figure 21.

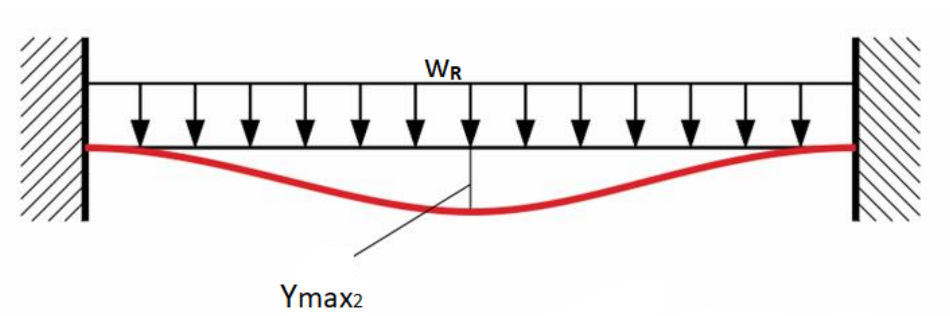

Figure 21: Deflection of distributed load.

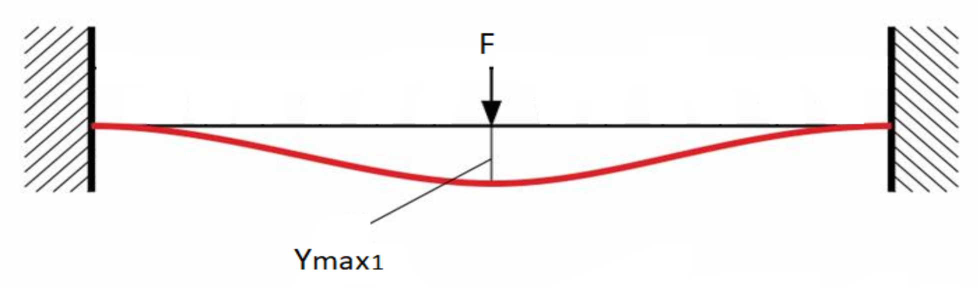

Figure 22: Deflection due to piece of work Weight.

$$Y_1 = -\frac{w_p L^3}{192EI}$$

(4.1.5)

$$Y_2 = -\frac{w_R L^4}{384EI}$$

(4.1.6)

Where:

E : is the modulus of elasticity of steel $= 207 * 10^9 GPa$

I : is the area moment of inertia, for circular section given by equation

$$I = \frac{\pi}{64} * D^4$$

(4.1.7)

Now, substituting in equation(4.1.5):

$$Y_1 = -\frac{392.4 * 3^3}{192 * 207 * 10^9 \frac{\pi}{4} * D^4}$$

$$Y_1 = 0.543 \times 10^{-8} D^{-4}$$

(4.1.8)

substituting in equation(4.1.6), got:

$$Y_2 = \frac{6047.565 \times 3^4 \times D^2}{384 \times 207 \times 10^9 \times \frac{\pi}{64} D^4}$$

$$Y_2 = 12.31 \times 10^{-7} D^{-2}$$

(4.1.9)

Now, adding equation(4.1.8) & equation (4.1.9) and assuming that $Y_{\max} = 1mm$:

$$0.001D^4 - 12.31 \times 10^{-7} D^2 - 0.543 \times 10^{-8} = 0 \qquad (4.1.10)$$

Solving equation (4.1.10) we got:

$D = 5.5cm$

For safety let choose $\underline{D = 6cm}$.

4.1.2. Rods of spray guns

As calculated in last section and previous equations we got:

$$Y_1 = \frac{7.5 \times 2.7^3 \times 9.81 \times D^2}{192 \times 207 \times 10^9 \times \frac{\pi}{64} D^4}$$

$$Y_1 = 7.42 \times 10^{-10} \times D^{-4}$$

(4.1.1)

$$Y_2 = \frac{6047.56 \times 9.81 \times 2.7^4 \times D^2}{384 \times 207 \times 10^9 \times \frac{\pi}{64} D^4}$$

$$Y_2 = 8.069 \times 10^{-7} \times D^{-2}$$

(4.1.2)

Now, add equation (4.1.1) & equation (4.1.2), summation equals **1mm:**

$$D^4 - 80.8 \times 10^{-5} D^2 - 7.42 \times 10^{-7} = 0$$

(4.1.3)

After solving equation (4.1.3), we got:

$D = 3.6cm$

For safety let choose $\underline{D = 4cm}$.

4.2. Torque & power calculation:

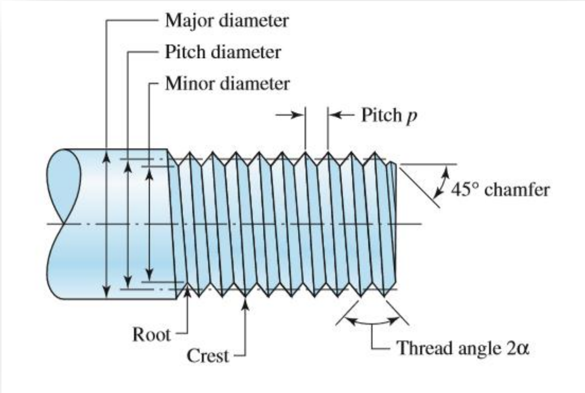

Figure 23: power screw.

The technique we used to move the piece of work and spray guns is power screw technique, as mentioned in machine description, the motor is coupled with power screw, and when the motor rotates, power screw will rotate and push or pull the piece of work using power screw that shown in Figure 23. Torque calculation as follow:

4.2.1. Power screw of piece of work

Torque needed calculated by equation(4.2.1):

$$T_m = \frac{Fd_m}{2}\left(\frac{L + \pi f d_m \sec\alpha}{\pi d_m - fL\sec\alpha}\right)$$

(4.2.1)

Where:

$\alpha =$ thread angle 14.5°

d_m : main diameter of power screw =2cm

f : friction coefficient =0.1 “by assumption”.

F : force needed to push or pull piece of work.

P : pitch =4mm.

L : distance that piece of work pass through one revolution.

$L = n * P = 4*10^{-3} mm$.

where:

n : is the number of threads, here we have single threaded power screw so $n = 1$.

To calculate the force needed we have to apply the equation of motion on the system, equation(4.2.2):

$$F = m_p \ddot{x} + f_v \dot{x}$$

(4.2.2)

$$v_f = \dot{x} = v_o + a_{\max} \times t$$

(4.2.3)

$$a_{\max} = \ddot{x} = \frac{8_{(m/\min)}}{60_{(\sec)} \times 0.1_{(\sec)}} = 1.33 m/s^2$$

Now, substitute in equation(4.2.2)

$$F = 80 \times 1.33 + 0.1 \times 0.133 = 106.413 [N]$$

After substituting in equation(4.2.1), we got:

$$T_m = \frac{106.413 \times 0.02}{2} \left(\frac{0.004 + \pi \times 0.1 \times 0.02 \times \sec 14.5^\circ}{\pi \times 0.02 - 0.1 \times 0.004 \times \sec 14.5^\circ} \right) = 0.1788 [N.m]$$

Now, to calculate the power needed:

$$P = T * w$$

Where:

P : power [watt]

T : Torque $[N.m]$

w : angular velocity [rad/s].

Now we have to calculate angular velocity:

Where:

v_f : Steady state velocity=8 m/min.

$$v_f = l \times N$$

(4.2.4)

where:

N : Number of revolutions per second.

l : Distance that piece of work pass through one revolution.

So,

$$N = \frac{V}{l} = \frac{8}{4 \times 10^{-3}} = 2000 rpm$$

(4.2.5)

$$w = \frac{2\pi}{60} N = 209.33 (rad/s)$$

Power needed of conveyor motor:

$$P = T \times w = 37.42 [watt]$$

4.2.2. Power screw of spray guns

Here, calculation is the same as in previous section:

$$F = m_p \ddot{x} + f_v \dot{x}$$

$$F = 15 \times 1.33 + 0.1 \times \frac{100}{60} = 20.11 [N]$$

$$T_m = \frac{20.11 \times 0.02}{2} \left(\frac{0.004 + \pi \times 0.1 \times 0.02 \times \sec 14.5^\circ}{\pi \times 0.02 - 0.1 \times 0.004 \times \sec 14.5^\circ}\right)$$

$$T_m = 0.033 [N.m]$$

V: Velocity =100m/min.

$$V = L \times N$$

$$N = \frac{V}{L} = \frac{100}{4 \times 10^{-3}} = 416 rpm$$

Power needed of slider motor:

$$P = T \times w = 1.4[watt]$$

4.2.3. Power of Flip motor

After finishing paint process of the first face and first edge, flip motor has to rotate 180 degrees to paint the other face and edge. The piece has to flip in slow velocity to keep the quality of paint before dry, so the velocity is said to be 10 rpm.

So, $N = 10 rpm$

The equation of motion of the system is:

$$T = J\ddot{\theta} + c\dot{\theta}$$

(4.2.6)

$\theta_0 = 0$, $\theta_f = \pi$

$\dot{\theta}_0 = 0$, $\dot{\theta}_f = 0$

$$\dot{\theta} = \dot{\theta}_0 + \ddot{\theta} t$$

(4.2.7)

$$\dot{\theta}_{\max} = w = \frac{2\pi}{60} * N = 1.04 rad / s$$

in mathematical model chapter we assumed that the velocity starts from zero increasing until the midpoint, here the midpoint is at $t = 1.5[\sec]$.

So,

$$\ddot{\theta} = \frac{\dot{\theta}}{t} = \frac{1.04}{1.5} = 0.69[rad/s^2]$$

Now, we have to calculate the mass moment of inertia "J":

$$J = \frac{1}{12} m_p (a^2)$$

(4.2.8)

Where a is the width of piece of work =1.2 m.

So,

$$T = \frac{1}{12}(70)(1.2)^2(0.67) + (0.1)(1) = 5.7 N.m$$

$$P = T \times \dot{\theta}_{\max} = 5.7[watt]$$

Chapter 5

Electrical Design

5.1. Introduction

In this chapter, we will design the Protection circuits. Power circuit and control circuit will be explained in this chapter.

5.2. Equipment

- **Electrical Equipment**

Motors:

3phase motor:

This motor will be used to move the move the wood piece. Figure 24 shows the 3phase motor.

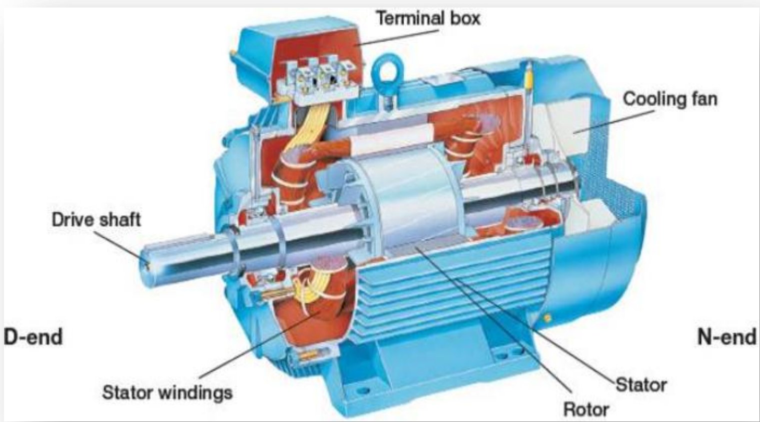

Figure 24 3phase motor

Stepper motors:

We have two stepper motors, one to move the spray guns, the other one to flip the wood piece. Figure 25 shows the stepper motor.

Figure 25 stepper motor

Frequency converter:

The frequency converter “Inverter” used to control the speed and direction of 3phase motor. Figure 26 shows the frequency converter.

Figure 26 frequency converter

Stepper motor driver:

We used two stepper motor drivers to control the speed, position and direction of stepper motor. Figure 27 shows the stepper motor driver.

Figure 27 stepper motor driver.

Sensors:

We have two kinds of sensors, light sensors and limit switches, light sensor used to detect the wood piece, when the wood piece arrives under the light sensor, it will send signal to PLC, to determine the start and end of path. Figure 28 shows the light sensor. Limit switches used

Figure 28 light sensor

Figure 29 limit switch

- **Pneumatic equipment**

Cylinder:

We have Pneumatic cylinder for extending the side spray gun until reach the edge of the wood piece. Figure 30 shows the double acting cylinder.

Figure 30: Double acting cylinder.

Directional control valve:

We have the directional control valve to control the extension and retraction of double acting cylinder via PLC signal. Figure 31 shows the directional control valve.

Figure 31: Directional control valve

Compressor:

Compressors supply the air flow for all equipment in a system as shown in Figure 32.

Figure 32: Air compressor.

Spray gun:

We have three spray guns, two of them to paint the surfaces, the other one to paint the edges. Figure 33 shows the Spray gun**.**

Figure 33: Spray gun.

On/off control valve:

We have three on/off control valve to control the operation of spray guns. Figure 34 shows the on/off control valve.

Figure 34: On/off control valve.

5.3. Protection Circuit Sizing

The following table describes selected loads for least next standard specifications.

name	Ac or dc	P/KW	V	I(A)	T(N.m)
M1	3Φ AC	0.12	380	0.51	0.85
M2	DC	0.096	24	4	0.3
M3	DC	0.063	24	2.6	0.2

Table 2: Motors specifications.

Protection Circuit for motors:

the over load for the 3Φ AC motor protection is programmable via the frequency converter, and for stepper motors, the current will be determined from drivers.

5.4. PLC control circuit

PLC Control circuit for all the machine is shown below.

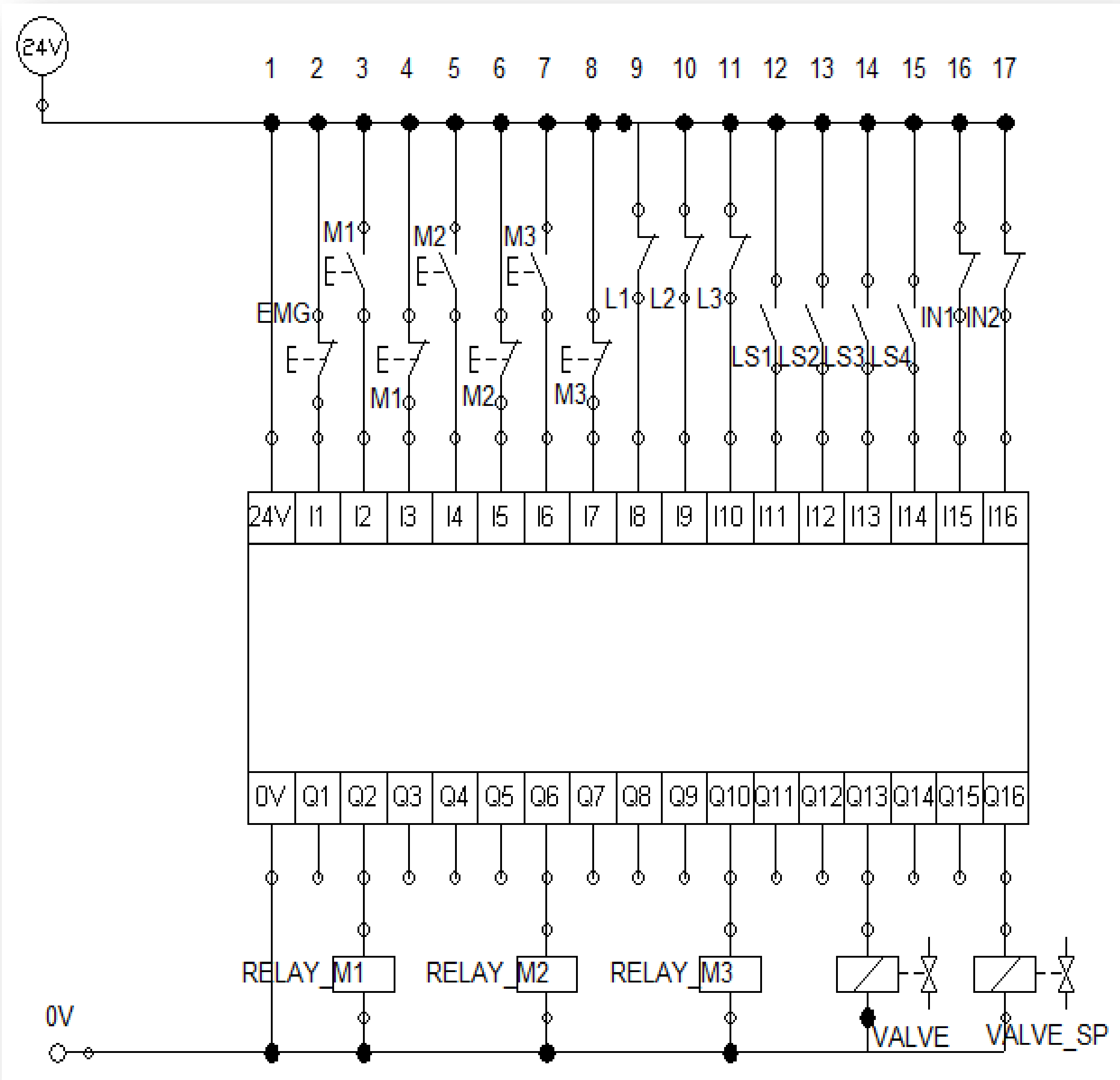

Figure 35: PLC Configuration.

5.5. Input- output table

the following table shows PLC I/O's table.

Symbol	Function	Address

M1(N.O)	Motor 1 start	%i 0.1.1
M1(N.C)	Motor 1 stop	%i 0.1.2
M2(N.O)	Motor 2 start	%i 0.1.3
M2(N.C)	Motor 2 stop	%i 0.1.4
M3(N.O)	Motor 3 start	%i 0.1.5
M3(N.C)	Motor 3 stop	%i 0.1.6
L1	Optical sensor	%iw 0.5.0
L2	Optical sensor	%iw 0.5.1
L3	Level sensor	%iw 0.5.2
LS1	Limit switch	%i 0.2.0
LS2	Limit switch	%i 0.2.1
LS3	Limit switch	%i 0.2.2
LS4	Limit switch	%i0.2.3
IN1	Encoder for M2	%iw 0.5.3
IN2	Encoder for M3	%iw 0.5.4
Frequency converter_M1	On/off signal	%q 0.3.0
Frequency converter _M1	Direction signal	%q 0.3.1
Driver_M2	Pulse train signal	%q 0.3.2
Driver_M2	Direction signal	%q 0.3.3
Driver_M3	Pulse train signal	%q 0.3.4
Driver_M3	Direction signal	%q 0.3.5

Table 3: PLC I/O Table.

5.6. Power circuit:

The following figure show motors power circuit. Figure 36.

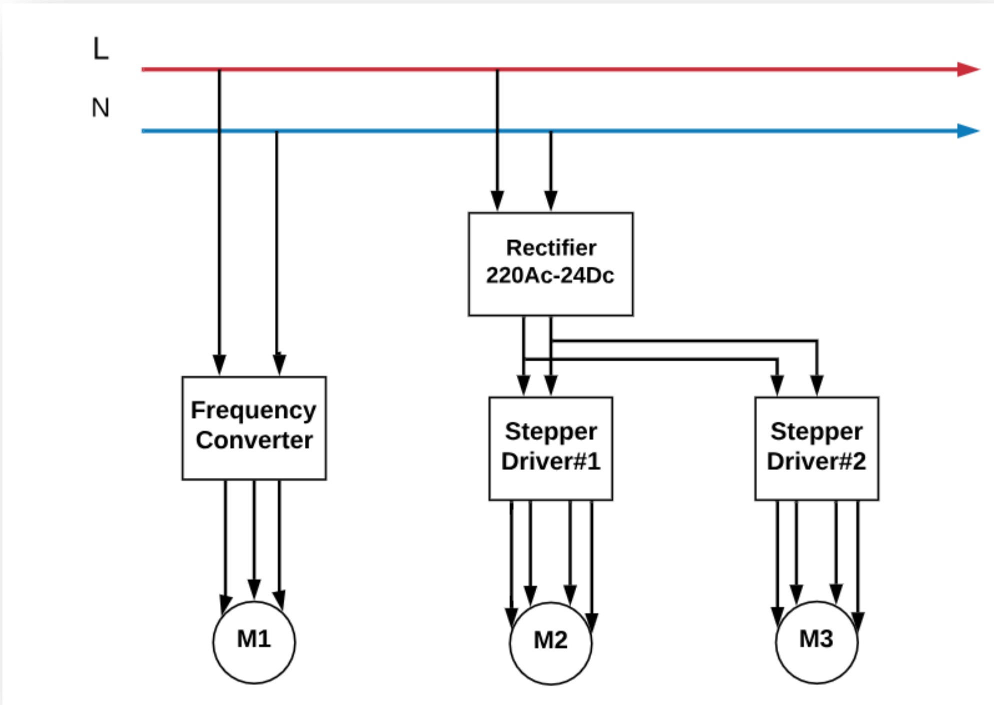

Figure 36: Power circuit.

5.7. Discretion for Electrical and Pneumatic design:

Here we have the 3Φ ac motor diagram:

1-source which is 220 v AC.

2- push button that used to run and stop the motor.

3- Frequency converter ALTVAR 312that used to drive the AC motor via PLC Schneider DVP SA12A2 signal and HMI order.

4- m1: 3Φ ac motor.

5-piece slider move that the action which the motor do.

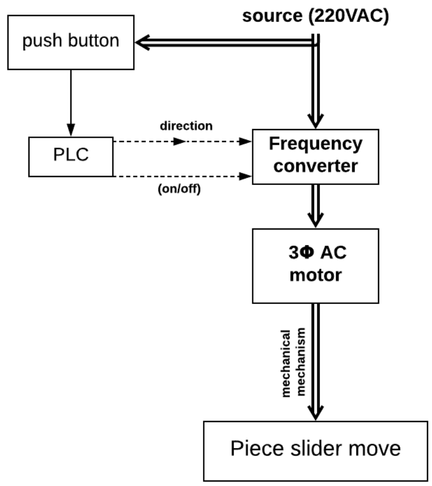

Figure 37: AC motor “M1” Block diagram.

Here we have the 1st stepper dc motor “M2” diagram:

1-source which is 24 V DC.

2- Push button that used to run and stop the motor.

3- Stepper motor driver that used to control the speed and position of the motor via PLC Schneider DVP SA12A2 signal and HMI order.

4- M2: stepper DC motor 40watt “Next standard”.

5-spray process that the action which the motor does.

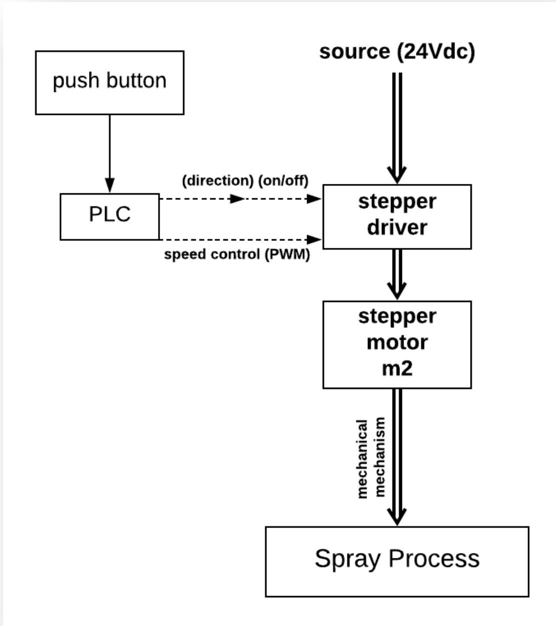

Figure 38: M2 stepper motor Block diagram.

Motor Model	17BL40202030
Number of Phase	3
Number of Poles	8
Rated Voltage(VDC)	24
Rated Speed(Rpm)	3000
Rated Torque(N.m)	0.2
Rated Power(W)	40
Rated Current(A)	4.0
Peak Current(A)	12.0
Peak Torque(N.M)	0.6
Rotor Inertia(kg.cm2)	4.2
Torque Constant(N.m/A)	0.05
Torque Constant(V/krpm)	5.235
Line-Line Resistance(Ω)	0.9
Line-Line Inductance(mH)	0.6
Length(mm)	78
Weight(kg)	0.9

Table 4: M2 stepper motor Name plate.

Here we have the 2nd stepper motor “M3” diagram:

1-source which is 24 v Dc.

2- push button that used to run and stop the motor.

3- Stepper motor driver that used to control the speed and position of the motor via PLC Schneider DVP SA12A2 signal and HMI order.

4- M3: stepper DC motor

5-flip the piece that the action which the motor does.

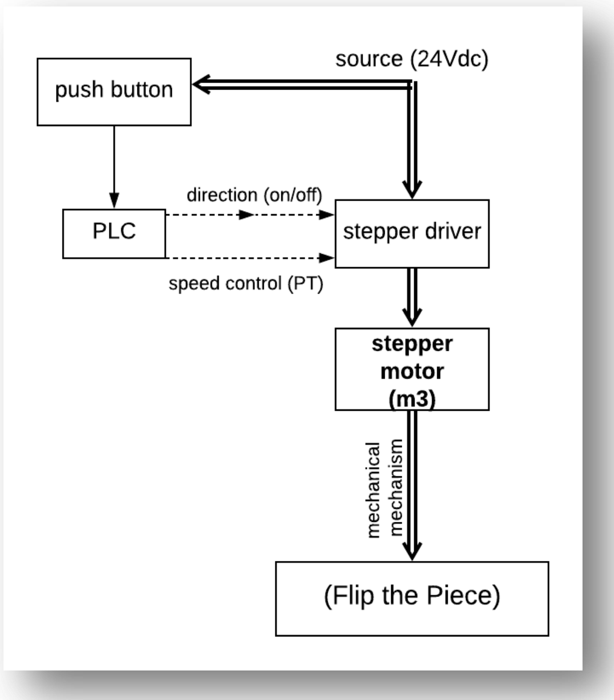

Figure 39: M3 DC motor Block diagram

Motor Model	17BL60203030
Number of Phase	3
Number of Poles	8
Rated Voltage(VDC)	24
Rated Speed(Rpm)	3000
Rated Torque(N.m)	0.3
Rated Power(W)	94
Rated Current(A)	6.0
Peak Current(A)	18.0
Peak Torque(N.M)	0.9
Rotor Inertia(kg.cm2)	4.9
Torque Constant(N.m/A)	0.05
Torque Constant(V/krpm)	5.235
Line-Line Resistance(Ω)	0.5
Line-Line Inductance(mH)	0.3
Length(mm)	98
Weight(kg)	1.3

Table 5: 2nd DC motor name plate.

Here we have the air cylinder diagram:

1-source which compressor.

2- Air service unit that used to run and stop the cylinder.

3- Signal via PLC Schneider DVP SA12A2.

4- C1: double acting cylinder.

5- Cylinder stroke, to spray the side of the door.

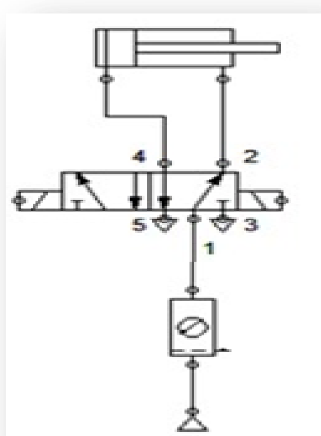

Figure 40: Pneumatic cylinder Power circuit.

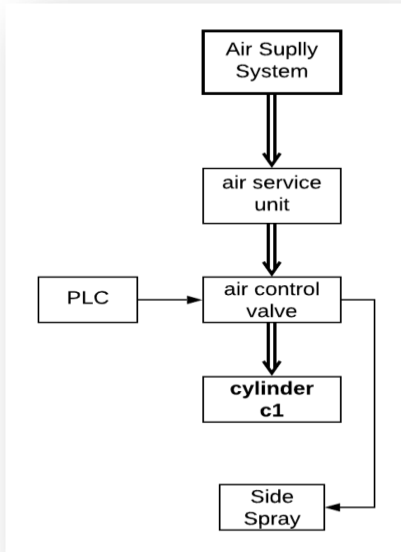

Figure 41: Pneumatic cylinder block diagram.

Here we have the spraying process:

When the on/off valve receive the signal from PLC, it will allow the paint material flow into spray gun, relief valve function is to return the excessive paint material to the tank.

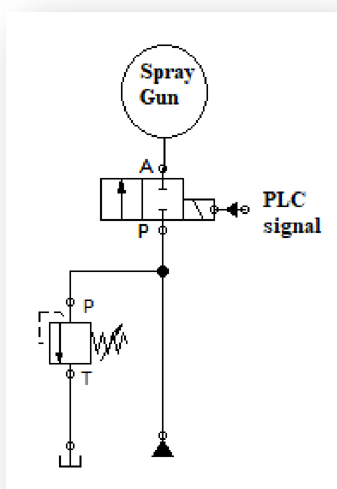

Figure 42: Spraying Process.

Chapter 6

Control

In this chapter we will describe the design and control of the machine.

6.1. For conveyor motor:

steady state error and transient response that represented in the figure below:

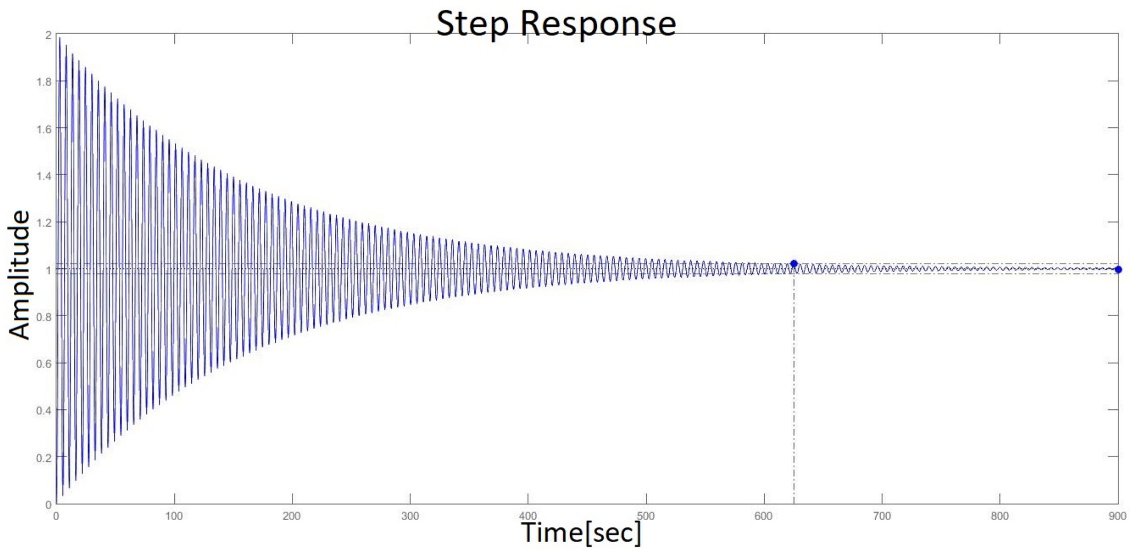

Figure 43: Original response before adding any controller

We use SISO tool in MATLAB to design a PID controller to eliminate the steady state error and transient response as shown in Figure 45.

We control the motor that carry one mass, so the system is 2^{nd} order system as shown in Figure 19.

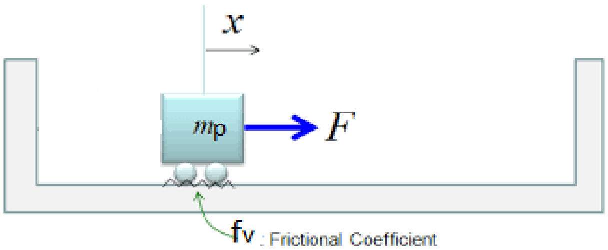

Figure 44: physical representaion

Differential equations:

$$m_p\ddot{x} + f_v\dot{x} = F$$

$$F(s) = s^2 mx(s) + f_v sx(s)$$

with initial condition =0

$$F(s) = [s^2 m + f_v s]x(s)$$

$$G(s) = \frac{1}{s^2 + \frac{f_v}{m}s} = \frac{1.325}{s(s + \frac{f_v}{m})}$$

(4.2.9)

Let $\zeta = 0.7$, $wn = 12red/s$

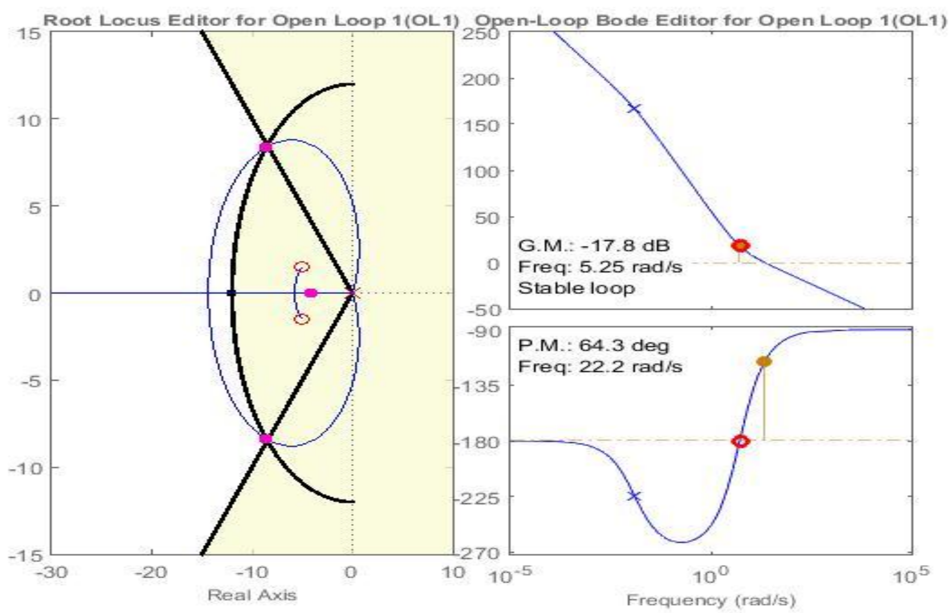

Figure 45: SISOTOOL configuration.

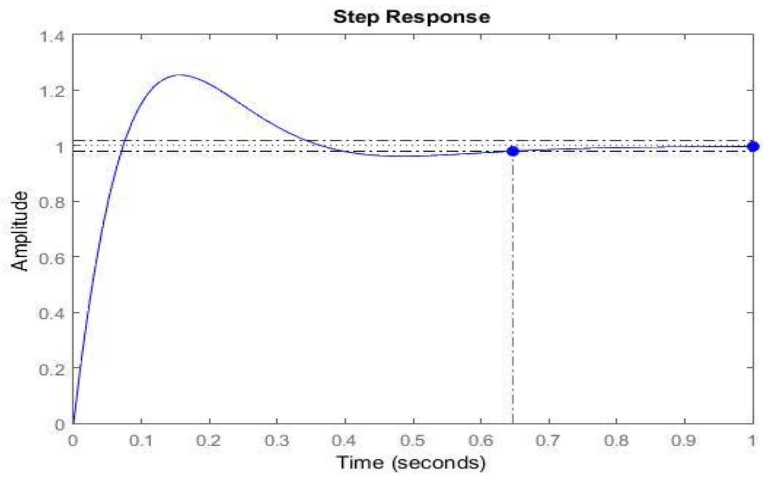

Figure 46: PID response.

As in transfer function mentioned in equation(4.2.9), the system is type one, so the steady state error is zero, so we used lead controller to enhance the transient response.

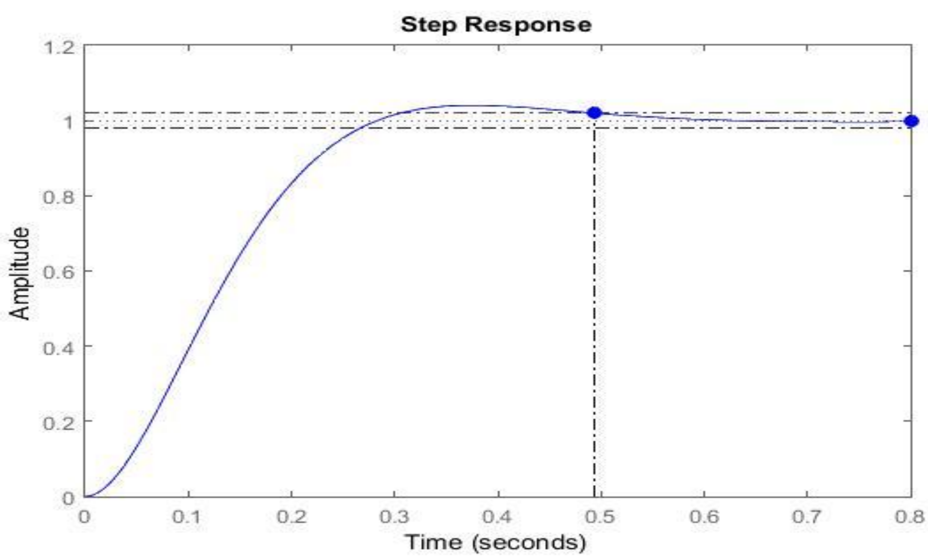

Figure 47: Lead response.

From previous step responses we chose the Lead controller because it gives better steady state error, transient response and less overshoot than PID.

$$G_s(c) = \frac{106.81(s+0.000864)}{(s+16.9)}$$

6.2. For spry gun motor:

We need to control the speed and position of stepper motor shown in Figure 48, this can be done using the driver shown in Figure 49.

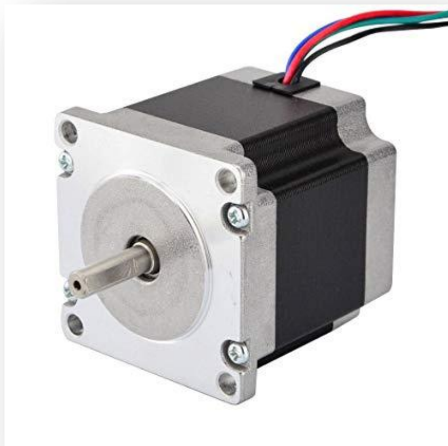

Figure 48: Stepper motor.

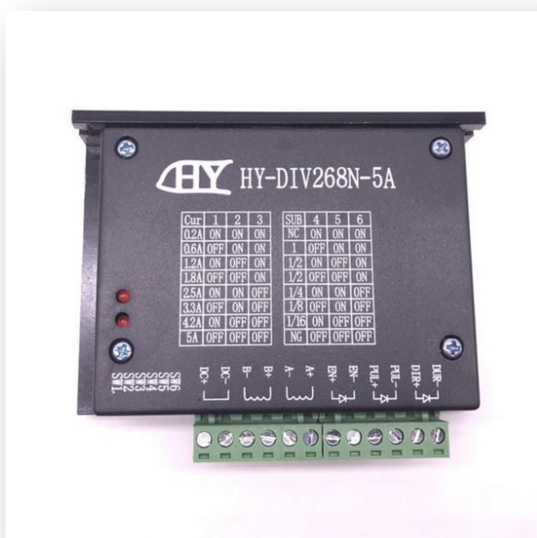

Figure 49: Stepper motor driver.

Controlling the speed and position of stepper motor:

We can control the speed by the frequency of pulse train, that come from PLC, the relationship between speed and frequency is proportional.

The position can be controlled by determination the number of pulses that come from PLC, each pulse rotates the rod of motor 1.8 degree “the resolution of the motor”.

Chapter 7

Prototyping

7.1. Introduction

In this part of the project, we have built a prototype painting machine, that can paint a wood plate which its dimensions in the range of (15*25) cm up to (30*40) cm.

So, the new dimensions of whole machine are approximately (100*100*100) cm. Figure 50 shows the new design of the machine.

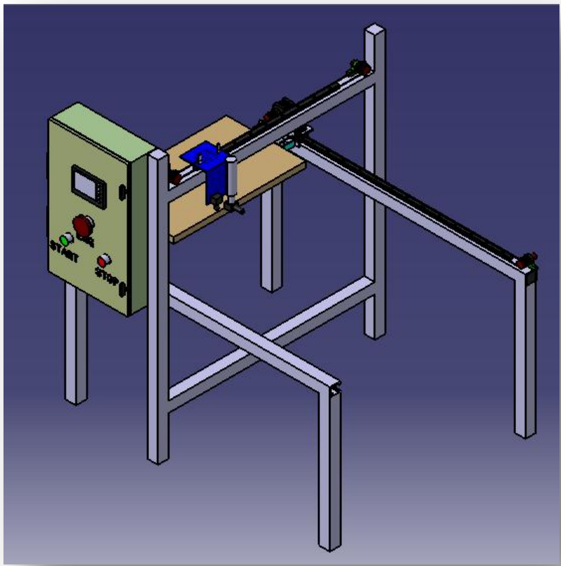

Figure 50: Prototype Design.

7.2. Machine Description

The technique which used to move the spray gun and piece of work in full-scale design **as mentioned in section 2.2.3 and 2.2.4** , is power screw with two support rods, here, in prototype, we have used another technique, because the power screw and smooth support rods cost a lot of money, and in prototype we have to look after controlling the speed and position of the motors and set there speeds compatible with each other, to cover all the surface homogeneously as possible as we can. So, we have used special linear guide and bearing slides on it with very low friction coefficient, Figure 51 shows the linear guide and the bearing.

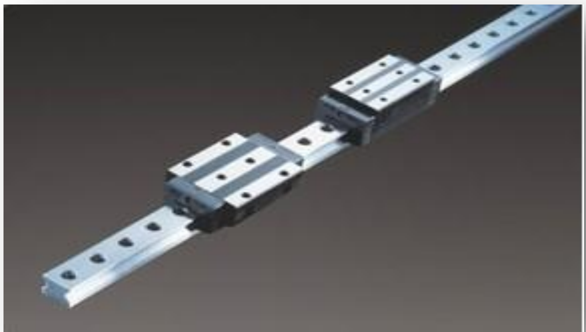

Figure 51: Linear guide with bearing.

Figure 52 shows the technique we have used, the motor shaft tied with first roller using shaft coupler and bearing, the rope turns around the rollers and tied with the sliding bearing as shown in Figure **52**.

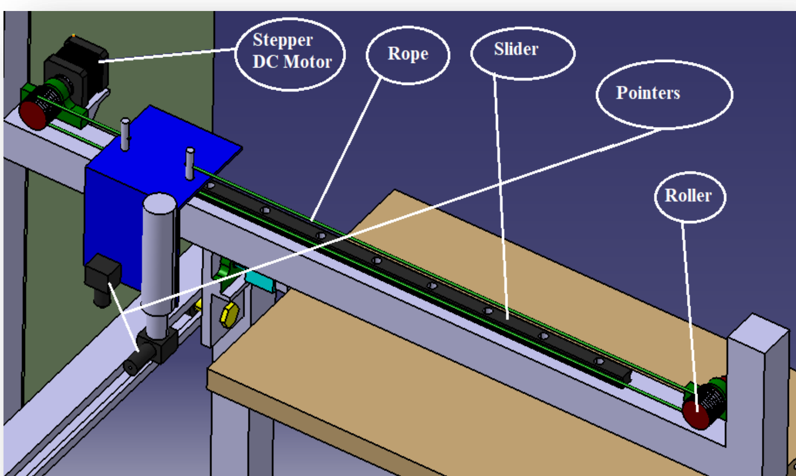

Figure 52: Motion technique.

7.3. Mechanical Design

As mentioned in section 7.3, we have used the mechanism shown in Figure 52. Now, we have to calculate the maximum deflection in the sliders to be ensure that the deflection is very small to achieve good quality products. We have to loads, one from the piece of work "concentrated load", and the other load from the weight of slider "distributed load".

Deflection due to concentrated load:

The following figure shows the free body diagram for concentrated load "Figure 53"

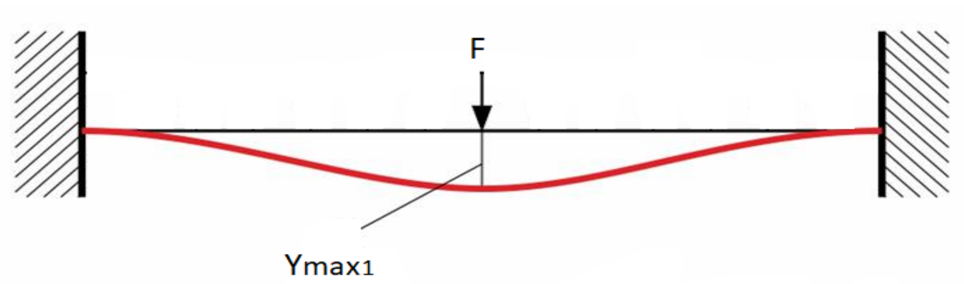

Figure 53: concentrated load.

F: the weight of the load, where maximum mass of piece of work is 6 kg.

Ymax1: the maximum deflection occurred in the beam, and it's in the midpoint of the beam.

$$Y_1 = -\frac{FL^3}{192EI}$$

Where:

L: slider length.

E: modulus of elasticity.

I: Area moment of inertia.

$$Y_{\max 1} = \frac{3*9.81*(0.85)^3}{192*207*(10)^9*I}$$

$$Y_{\max 1} = \frac{4.547 * 10^{-13}}{I}$$

Deflection due to distributed load:

The following figure shows the free body diagram for distributed load “Figure 54”.

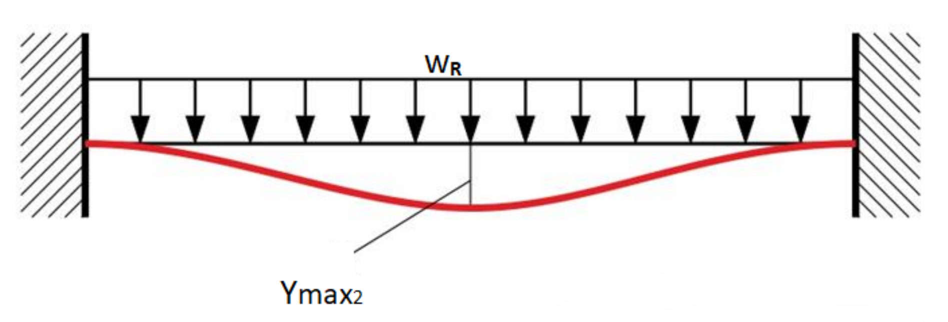

Figure 54: distributed load.

WR: Weight of slider per unit length.

Ymax2: the maximum deflection occurred in the beam, and it’s in the midpoint of the beam.

$$Y_2 = \frac{5 w_R L^4}{384 EI}$$

$$Y_{\max 2} = \frac{5 * 1.51 * 9.81 * (0.85)^4}{384 * 207 * (10)^9 * I}$$

$$Y_{\max 2} = \frac{21.877 * 10^{-13}}{I}$$

Now, the maximum deflection due to two loads is:

$$Y_{\max} = Y_{\max 1} + Y_{\max 2}$$

$$Y_{\max} = \frac{4.547 * 10^{-13}}{I} + \frac{21.877 * 10^{-13}}{I}$$

The area moment of inertia is for the shape shown in Figure 55 "$I = 1.329*10^{-6}$".

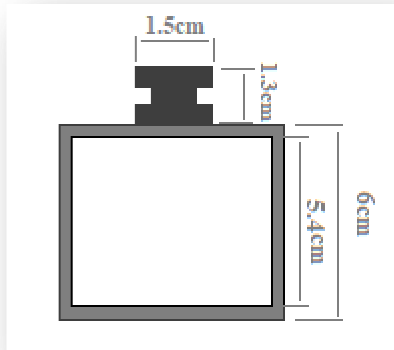

Figure 55: side cross section.

Now, the maximum deflection become:

$$Y_{max} = \frac{4.547*10^{-13}}{1.329*10^{-6}} + \frac{21.877*10^{-13}}{1.329*10^{-6}}$$

$$Y_{max} = 1.98*10^{-6}m$$

So, the deflection is very small, then the dimensions are accepted.

Torque calculation for motors:

For the first motor that moves the piece of work, the max velocity is $8m/\min$, the time assumed to reach to this velocity is 1s. So, the acceleration is $0.133m/s^2$.

Figure 56 shows the free body diagram for the mechanism that move the spray gun and piece of work.

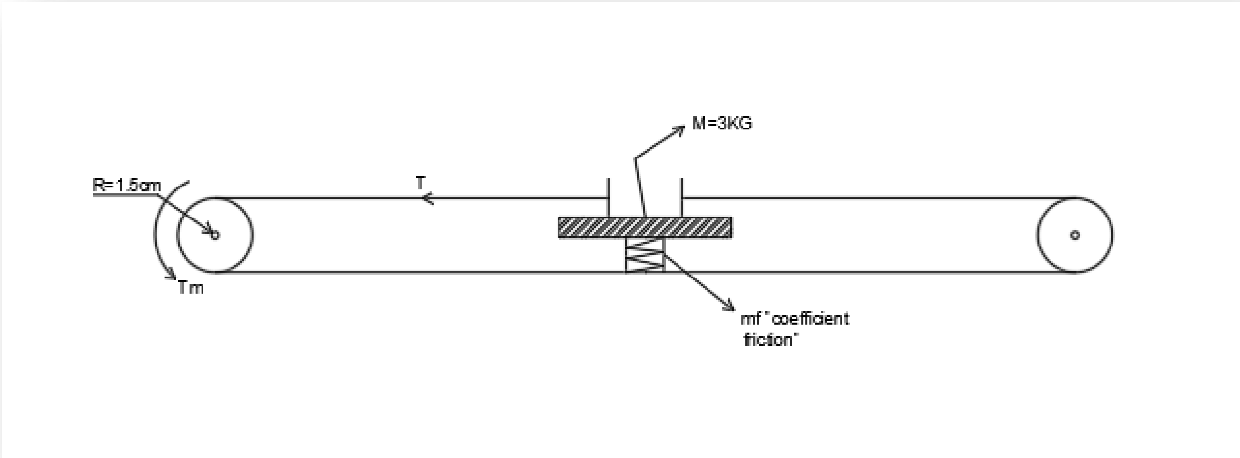

Figure 56: Free body diagram.

So,

$$\sum F_x = m * \mathrm{a}$$

$$T - F_f = m * a$$

Where:

T: Tension.

F_f : Friction force.

m: mass of piece of work.

a: Acceleration.

$$T - 3*9.81*0.1 = 6*0.133$$

Now, the torque needed can be calculated by the following equation:

$$T_m = T * \mathrm{R}$$

Where:

Tm: torque that the supplies.

R: Radius of roller.

$$T_m = 0.0561 N.\mathrm{m}$$

As the first motor calculated, the second motor supplies torque:

$$T_m = 0.039 N.m$$

7.4. Electrical Design and Control:

in this section we will show the electrical design which we designed in the prototype machine. The electrical design here is similar to full scale electrical design, but instead of 3phase motor, we have used stepper motor. And instead of spraying system we have used pointers to simulate the principle of work operation. The side spray gun will be extended and retract manually to reduce the cost of project.

Motors sizing:

According to the mechanical design, we have used motors with the following next standard specifications:

#of motor	Type of motor	Volt “V”	Current “mA”	Power “watt”	Torque “N.m”
M1	Stepper	24 DC	1700	40	0.4
M2	Stepper	24 DC	1700	40	0.4
M3	DC with gear	12 DC	200	2.4	0.8

Table 6: motors specifications.

Note, for more details, appendix A explains the datasheet for motors.

Protection of electrical equipment method:

- For stepper motors, the motors will be protected via determining the rated current for motors from drivers.
- For DC motor the protection circuit is just a fuse with a nominal current 0.5A.
- For pointers “Laser” the protection circuit is just a fuse with a nominal current 0.1A.
- For PLC and HMI touch screen, the protection circuit is fuses built in.

Power circuit:

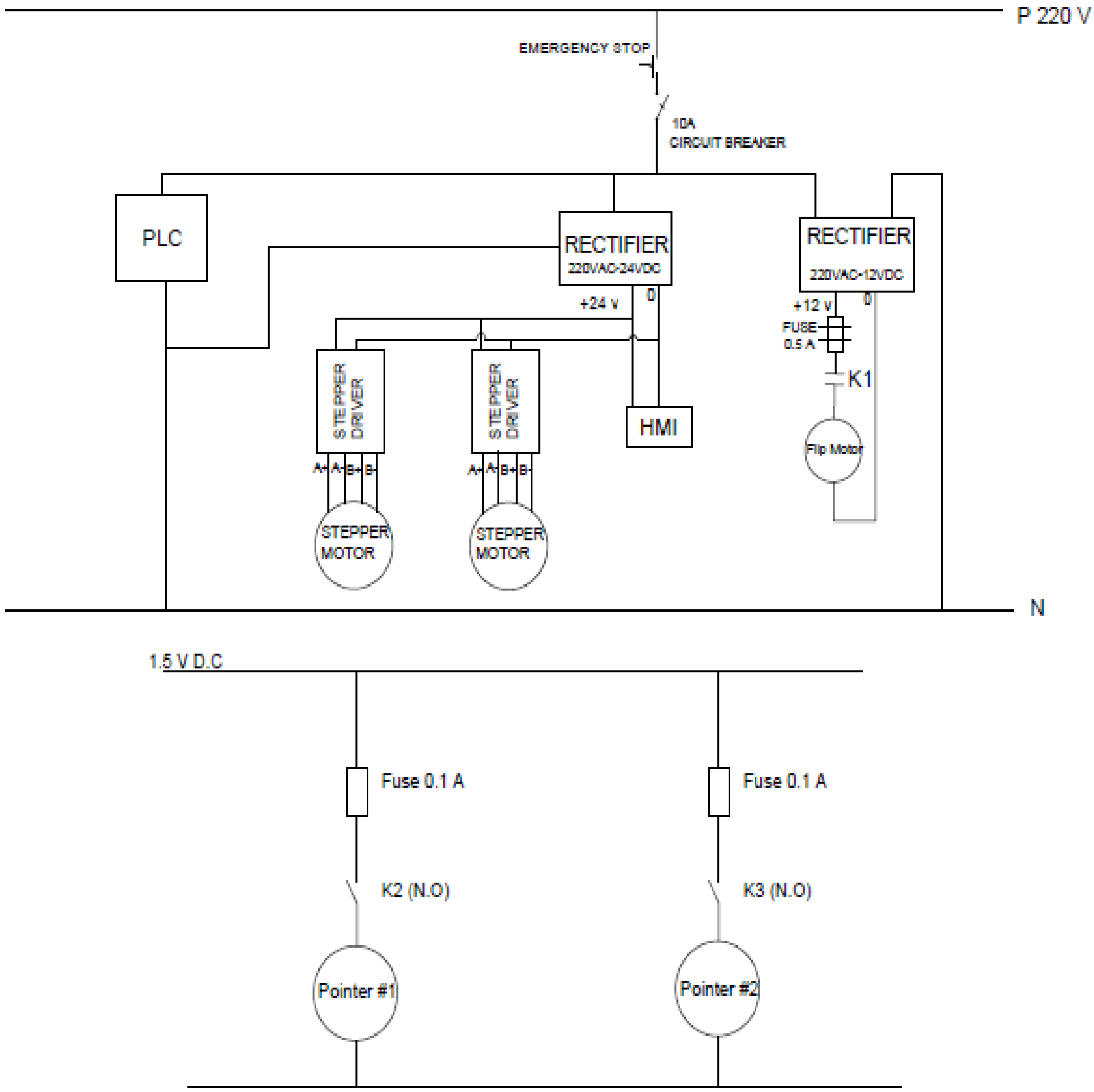

Figure 57: Power circuit.

PLC Connection:

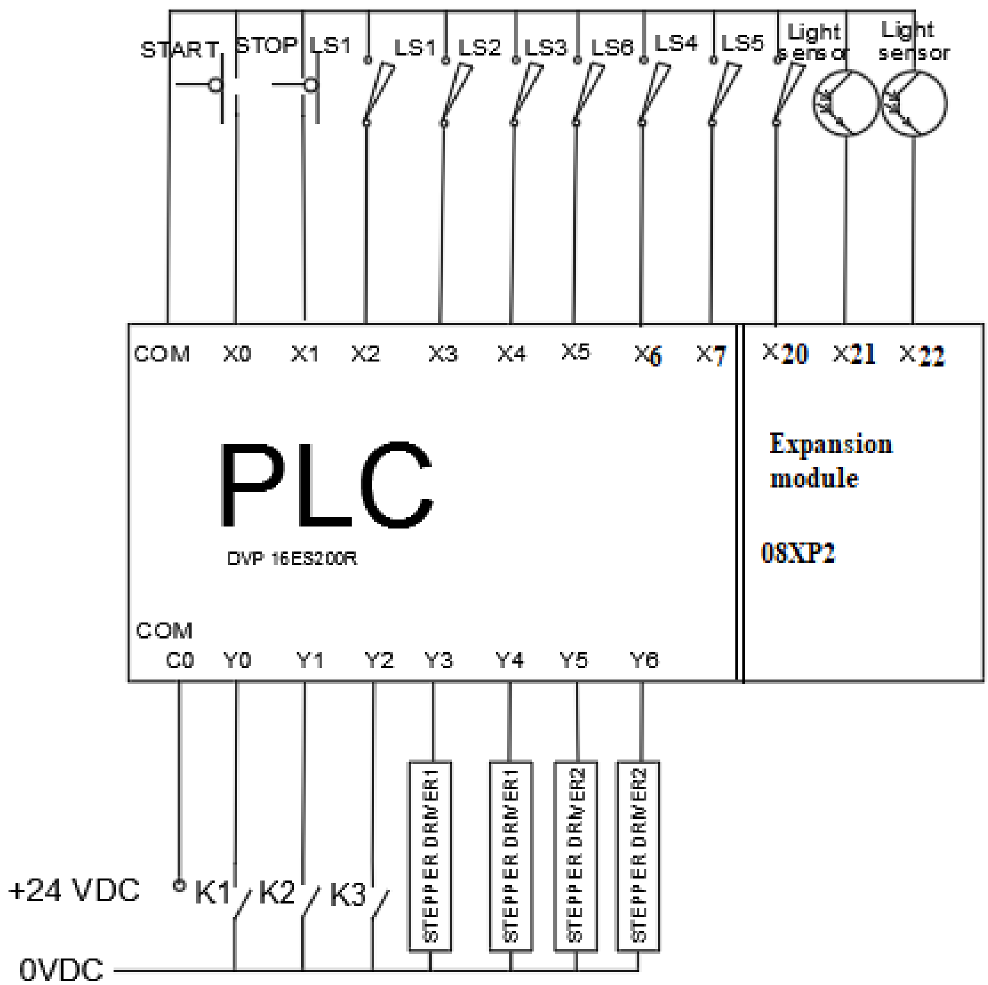

Figure 58: PLC Connection.

Input/output table:

Symbol	Function	Address
start	start up the machine	**X0**
Stop	stop the machine	**X1**
LS1	Limit switch #1	**X2**
LS2	Limit switch #2	**X3**
LS3	Limit switch #3	**X4**
LS4	Limit switch #4	**X7**
LS5	Limit switch #5	**X6**
LS6	Limit switch #6	**X5**
Light sensor 1	Start moving spray gun	**X20**
Light sensor 2	Reverse the direction of pointer	**X21**
K1	Flip motor relay	**Y0**
K2	Pointer #1 relay	**Y1**
K3	Pointer #2 relay	**Y2**
Pulse 1	Pulses to driver#1	**Y3**
Direction 1	Direction to driver#1	**Y4**
Pulse 2	Pulses to driver#2	**Y5**
Direction 2	Direction to driver#1	**Y6**

Table 7: Input/output table

SFC diagram:

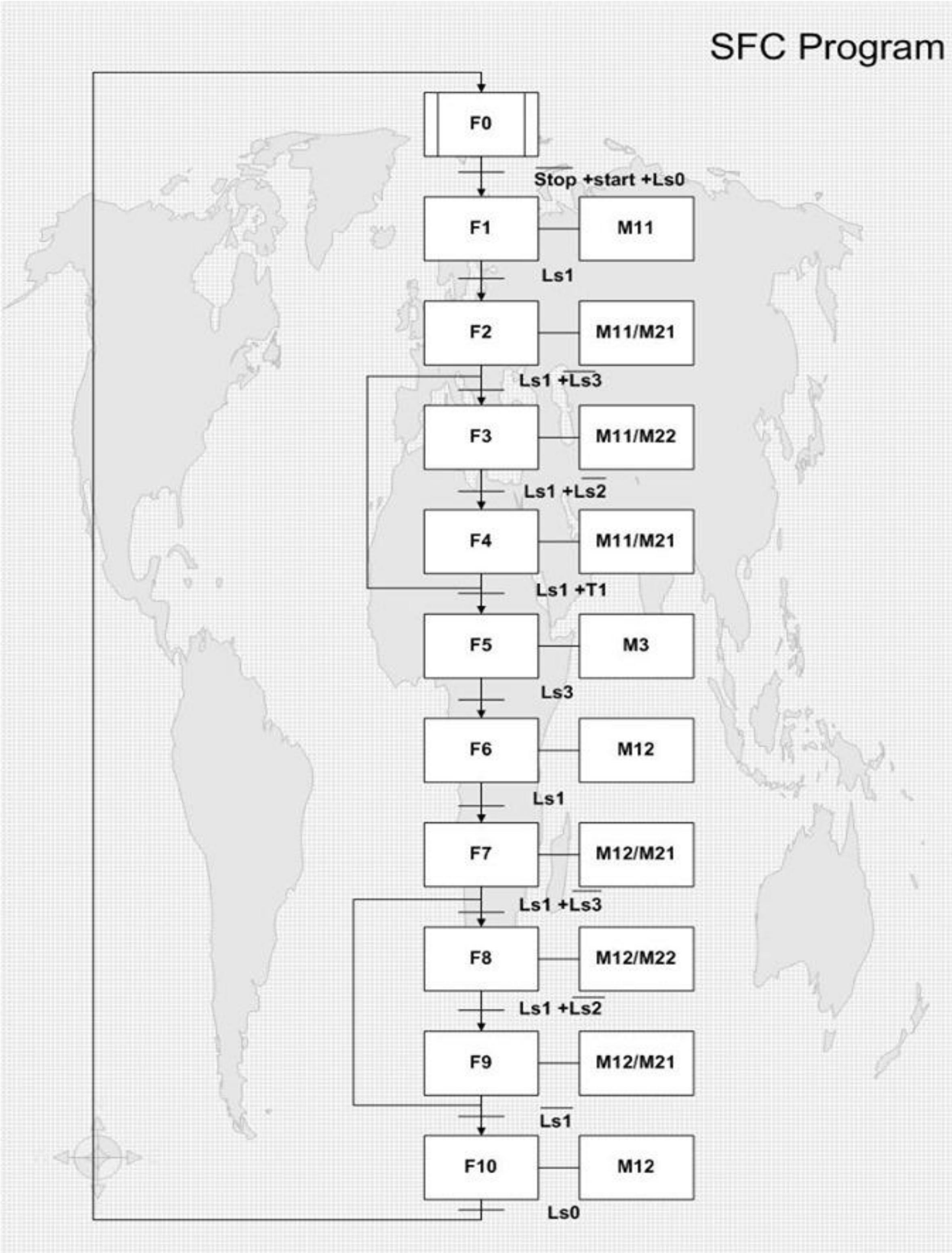

Figure 59: SFC diagram.

Chapter 8

Results and Conclusions

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