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**In Control Engineering  
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Title:

**Design and Implementation of an Automated  
Spray Pyrolysis Technique**

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# ABSTRACT

In this work, we present the design and implementation of a Spray Pyrolysis automated equipment using different hardware and software components. The apparatus was designed using Solidworks software and then built with steel iron with dimensions of 400x450x600 mm. Several pieces were added in order to assemble the whole system. With the aim of realizing the control part of the automated system, a program was written on the MPLAB X IDE and transferred via Pickit2 to the microcontroller PIC18F4550. Multiple tests were performed to check the application's performance. In the end, a low-cost prototype that performs the Spray Pyrolysis technique automatically was realized.

**Key words:** Spray Pyrolysis, automated system, control, microcontroller.

# DEDICATION

First, i thank Allah for giving me the health, motivation and strength to be able to reach this point , then i would like to dedicate this work to my supportive parents who helped and encouraged me constantly, to my three older brothers who were there for me, to the friends i made along this journey, and those who became family, and to my cousin Djomana who has always been a big help.

HAMIDECHE Chahinaz.

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To all those who have played a part, big or small, in this remarkable journey, I offer you my sincerest appreciation.

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Nabila and Chahinaz.

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# GENERAL INTRODUCTION

Spray Pyrolysis (SP) is a highly used technique for thin film deposition of different materials such as semiconductors and oxides. It was established in the 1950s, and its use for depositing a wider range of materials became common in the 1990s and 2000s. Spray Pyrolysis has continued to be developed and improved over the years, and it is still active in research today and used in a wide range of applications[1].

The SP technique used to be performed manually, but thanks to the automation field, equipment was developed specifically for it. Automation is a field that goes back to ancient times, when it started with basic mechanical devices such as the wheel. It has been developed through the years until the automated systems reached their basic structure known today by the early 1800s. This structure consists of three basic elements: power, a program of instructions, and control systems. This field is still developing in the present [2].

Today, there are multiple types of Spray Pyrolysis equipment, where different models have been designed and developed to meet each technology's requirements. Among the existing products are: a flame-assisted model, a multi-nozzle model, and a vacuum Spray Pyrolysis model.

In Algeria, the Spray Pyrolysis technique is still performed manually due to the absence of the equipment because of its expensive cost. Where existing products costs range between 10.000 \$ and 20.000 \$. The aim of this project is to design and build a basic, cost-effective prototype of an apparatus that performs this technique automatically.

In order to present and explain this work, it was divided into four different chapters arranged as follows:

- **Chapter 01:** It includes the theoretical part, which consists of two sections: the first one provides an explanation of the SP technique and a description of different existing products. Whereas the second one is about the automation field and SP control system.
- **Chapter 02:** It contains a description of the apparatus to be built and the components needed to realize the automated SP technique.
- **Chapter 03:** This chapter includes the apparatus conception details, as it covers all programs, simulations, and circuit implementation undertaken to perform different tests.
- **Chapter 04:** It is the last chapter, and it is dedicated to presenting

the final tests of the apparatus's performance. It also provides results and their discussion.

This work is completed with a general conclusion.

GENERALITIES OF THE SPRAY  
PYROLYSIS TECHNIQUE AND  
AUTOMATION

**1**



# GENERALITIES OF THE SPRAY PYROLYSIS TECHNIQUE AND AUTOMATION

1

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## 1.1 INTRODUCTION

Spray Pyrolysis is a chemical technique used for thin film deposition. It requires heating and spraying a chemical solution [1]. It can be done manually, however its automation saves time, human effort and raises the accuracy. This chapter is divided into two sections. The first one provides an explanation of the technique of Spray Pyrolysis. While the second is centered around the field of automation.

## 1.2 SECTION ONE: SPRAY PYROLYSIS TECHNIQUE

### 1.2.1 Definition of Spray Pyrolysis

Spray means blowing small droplets of a liquid. And the chemical process of Pyrolysis is the thermal decomposition of organic materials [3]. The combination of these two processes is the basic principle of the Spray Pyrolysis technique.

The Spray Pyrolysis technique is a simple, low-cost technique applied for the deposition of thin films, which are used in various devices such as sensors and solar cells [4]. The process is as follows: a substrate is put on a heated surface, then a precursor solution is sprayed on it through a nozzle from an atomizer. A chemical reaction occurs between the constituents, and a compound is formed. The heat is important so that the unwanted products are volatile at the selected temperature, which is why the reactants are chosen accordingly [5]. The process is illustrated in Figure 1.1.

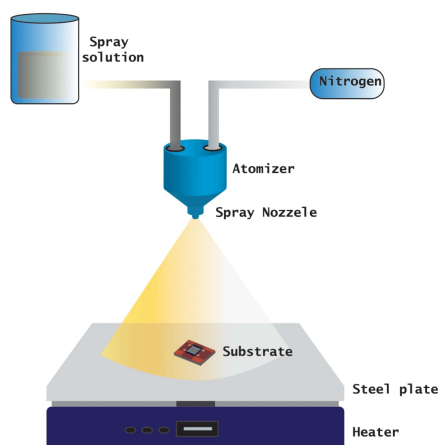


Figure 1.1 – General schematic of a spray pyrolysis deposition process [6].

### 1.2.2 Spray Pyrolysis methods

In this process, the solution can be atomized into droplets and sprayed using two different methods:

### a. Ultrasonic Spray Pyrolysis method

In the ultrasonic atomization technique, high frequency sounds give birth to vibrations that will cause the solution to be atomized into fine droplets. This method has many advantages, as it is simple, economical, and efficient [7]. This method is shown in Figure 1.2.

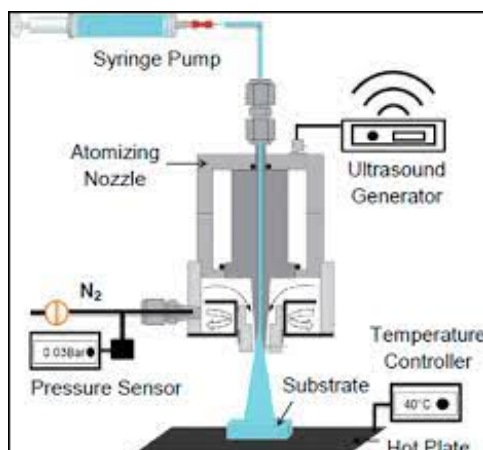


Figure 1.2 – Ultrasonic spray pyrolysis method schematic [7].

### b. Pneumatic Spray Pyrolysis method

As shown in Figure 1.3, this method uses a pneumatic nozzle where a liquid is mixed with air, and a compressor is used to supply air with a certain pressure. The compressed air causes the flow of the solution through the nozzle tip. As a result of the flow velocity, the solution will collapse into fine droplets. This process is called pneumatic atomization [8].

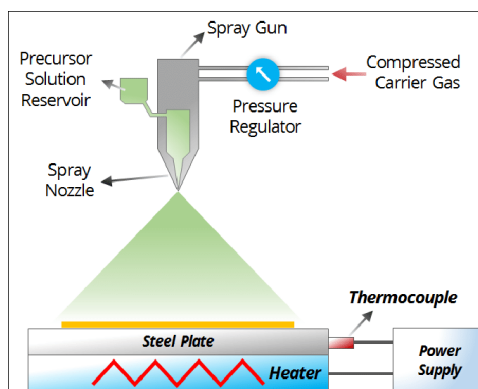


Figure 1.3 – Pneumatic spray pyrolysis method schematic [8].

#### 1.2.3 Spray Pyrolysis equipment composition

A Spray Pyrolysis equipment consists mainly of a gun nozzle to perfuse the solution; it uses either a pneumatic or an ultrasonic method to atomize the solution. The gun nozzle is equipped with a moving mechanism that allows its displacement along two stages (in X and Y directions), controlled with a stepper motor. It also includes a hot plate controlled independently,

which serves as an operating surface for the process. In the pneumatic case, a compressor is used to supply compressed air to the gun nozzle in order to atomize the solution.

#### 1.2.4 Different existing models

The spray pyrolysis technique is widely used in scientific laboratories and industry in general as mentioned before, for that different models have been designed and developed in order to meet each technology's requirements. We provide some of those models:

##### a. MTI corporation MSK-USP-02 model

It is a tabletop spray pyrolysis equipment; it includes a sprayer traverse with a maximum displacement of 200 mm along X and Y axes, a substrate base plate with a dimension of 150x150 mm, and a max temperature of 500 °C. Solution concentration and sprayer movement are controlled using a software interface [9]. The model is presented in the following Figure 1.4:



Figure 1.4 – MTI corporation MSK-USP-02 model [9].

##### b. HOLMARC HO-TH-04C<sub>3</sub> model

It is a programmable Multi-Nozzle model designed for multi-layer spraying; the apparatus operates the same process using multiple spray nozzles. It has three nozzles and a compressor with an 8–12 PSI pressure interval; its gun nozzle traverse has a maximum displacement of 150 mm along the X and Y axis; it has two containers with a capacity of 50 ml and 250 ml, respectively; and its dispensing rate ranges from 1 to 10 ml/min. The nozzle height can be adjusted manually in a range of 5–15 cm. In order to control both XY traverse and piston movement to fill the dispenser, a stepper motor is used as an actuator [10]. The model is presented in Figure 1.5:



Figure 1.5 – Multi-nozzle spray pyrolysis Equipment Model [10].

### 1.3 SECTION TWO: AUTOMATION

#### 1.3.1 Definition of automation

Automation is the use of technologies to perform tasks and produce goods with little to no human intervention. The aim of automation is to improve the efficiency in performing operations that are usually carried out by humans. It is being proven useful in several areas, such as manufacturing [2].

#### 1.3.2 Definition of Automated systems

Automated systems consist of sensors, actuators, and controllers combined together and programmed to perform a function without human interference. They are important because of their large impact in replacing humans, especially in the industrial field due to the performance they provide since they are faster, more precise, and less costly than humans [2].

#### 1.3.3 Basic components of an automated system

An automated system essentially consists of three basic elements: power to drive the process and the other components, a program to direct the process, and a control system to execute the program [2]. These three elements are connected in the configuration shown in Figure 1.6 to make the process perform its specified function.

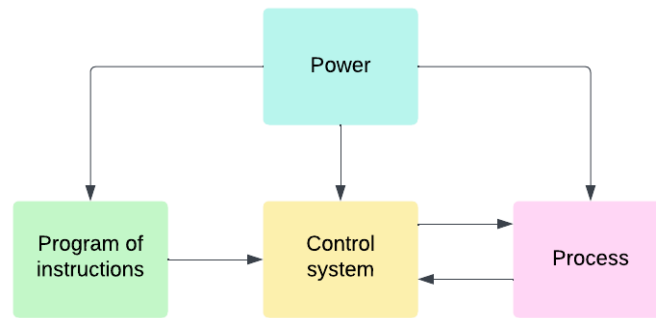


Figure 1.6 – Basic configuration of an automated system.

### a. Power

Power is essential in automated systems as it drives the process and the controls. The main source of power is electricity due to its availability, moderate cost, and facility of conversion to alternative energy forms. The type of power can differ in the same automated system since the energy required by the process depends on it (it can be electrical but also mechanical, thermal, and other energy forms). Control systems are based on digital computers, so they require electrical power for the controller to read the instructions, perform calculations, and execute the control; the actuators are electromechanical devices that require a bigger amount of electrical power so the signals sent from the controller get amplified [2].

### b. Program of instructions

The program of instructions is what determines the actions performed by an automated process. Each part requires process steps that are unique to it; these steps belong to a work cycle program, and each time a work cycle ends, a part is performed. A work cycle program consists of one or more steps (some of them may be manual, performed during the work cycle) that control one or usually more process parameters, which are inputs [2].

### c. Control system

A control system is a set of mechanical and/or electric devices interconnected to control the process of a technique. It is used in various domains, such as manufacturing. There are two types of control systems: open loop and closed loop.

An open-loop control system is composed of a controller and a plant. The controller bases its commands on the input set point only, without consideration of the value of the output [2]. A block diagram of this system is shown in Figure 1.7.

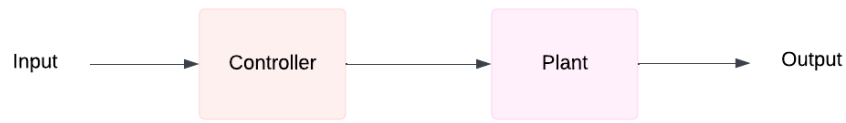


Figure 1.7 – *Open loop control system.*

A closed loop or feedback control system has a sensor in addition to the components of the open loop system. This sensor measures the real value of the output that may have been affected by the noise and provides this feedback to the controller, which will take it into account along with the input to command the plant in an optimal way to reach the set point. It can be concluded that this type of system is more accurate than the open loop [2]. The closed loop control system diagram is in Figure 1.8.

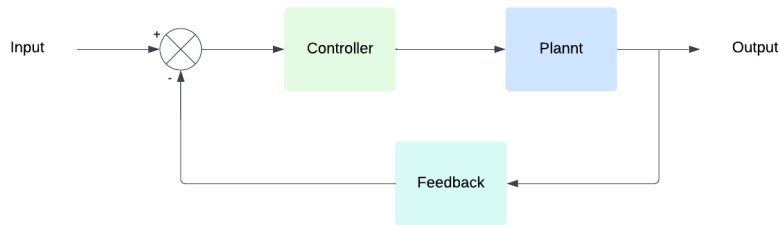


Figure 1.8 – *Closed loop control system.*

### 1.3.4 Spray Pyrolysis automated system

The global system or apparatus that realizes the Spray Pyrolysis technique is composed of several subsystems [11], depending on the complexity and sophistication of the device. In this section, we will review some basic systems that are used in order to delve deeper into control systems that serve the purpose of our project. Figure 1.9 represents a global system's diagram.

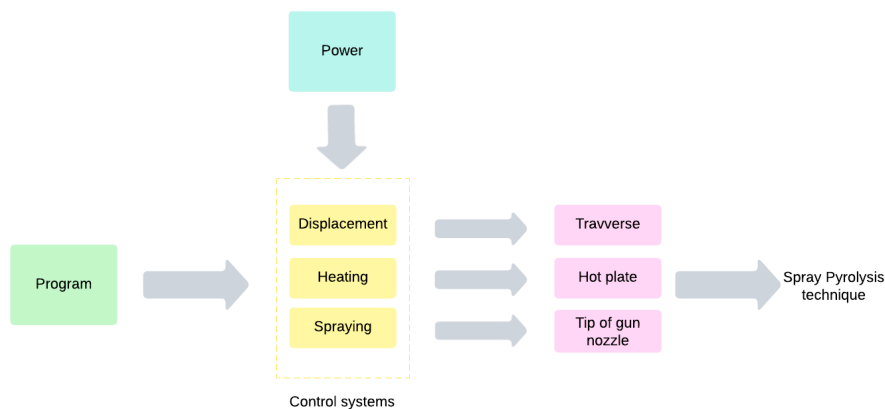


Figure 1.9 – *Spray Pyrolysis automated system.*

**a. The heating control system**

This system is used to control the temperature of the heater. It is a closed loop system with a set value as input that will be compared to the actual value measured by the temperature sensor (a thermocouple, for example). The result is fed to the temperature controller, which will command the heater to produce heat. The diagram of this control system is shown in Figure 1.10.

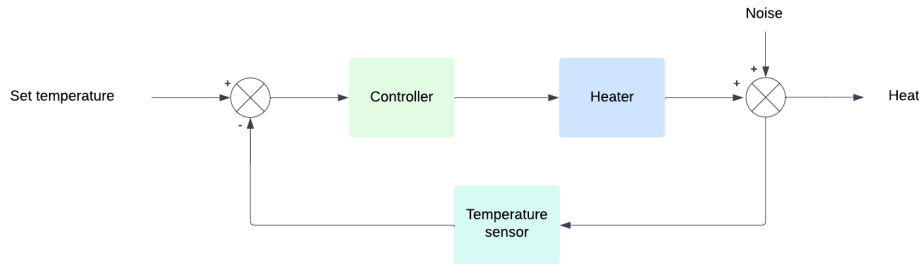


Figure 1.10 – Heating control system.

**b. The displacement Control system**

The displacement control system (illustrated in Figure 1.11) is an open loop system that consists of a controller, a driver, and a stepper motor. The controller is programmed to generate a sequence of electrical pulses with a precise order for the driver used to amplify the voltage to the amount required by the stepper motor. After receiving the pulses, the stepper motor transforms them into steps and starts rotating, causing the gun nozzle to move.

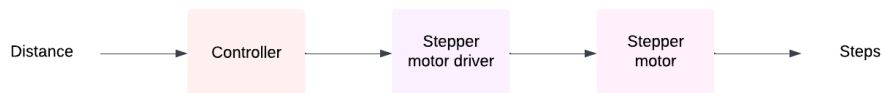


Figure 1.11 – Displacement control system diagram.

**c. The Spraying Control system**

The spraying control system is an open loop system that includes a controller, a valve, and a gun nozzle. The process of spraying starts when a signal is sent by the controller to open the valve connected to the compressor with pressure set at a precise value, then the generated compressed air will pump the solution through the gun nozzle to be sprayed. Figure 1.12 shows a diagram of this system.





Figure 1.12 – *Spraying control system diagram.*

## 1.4 CONCLUSION

This chapter was an introductory chapter where an overview of the project and a brief general explanation of its title were provided. In the first part, we gave a definition of the Spray Pyrolysis technique as well as an explanation of elements related to it, and we presented some of the existing models of the Spray Pyrolysis equipment. In the second part, we discussed automation, automated systems, and control systems. As a conclusion, a good understanding of the SP technique and the way automated systems work are both necessary for this project.

HARDWARE AND SOFTWARE  
DESCRIPTION

**2**

# HARDWARE AND SOFTWARE DESCRIPTION

# 2

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## 2.1 INTRODUCTION

This chapter is devoted to the description of the Spray Pyrolysis equipment implemented in this work. It also includes a presentation of the several hardware components and software tools that were used to design, implement, and program this apparatus.

## 2.2 DESCRIPTION OF THE EQUIPMENT

The apparatus to be built in this project in order to perform the pneumatic Spray Pyrolysis technique is equipped with a gun nozzle, a traverse that allows the displacement of the sprayer along the x-axis, an air compressor with pressure regulator, and a substrate heater plate (hotplate).

### a. The gun nozzle

A gun nozzle is an appliance used to spray the solution on the surface of the substrate, designed to make it collapse into fine droplets. In this project, we have used a gun nozzle shown in Figure 2.1, which has a length of 182 cm, a nozzle diameter of 0.3 mm–0.5 mm–0.8 mm, and a fluid cup capacity of 22 cc (View data sheet in Appendix).



Figure 2.1 – Gun nozzle.

### b. The Sprayer traverse

The gun nozzle is provided with displacement along the X axis, and its movement is controlled using a stepper motor as an actuator. To realize the displacement mechanism, two slides were recovered from old printers and linked using Plexiglas in order to hold the gun nozzle and ensure smooth movement. The traverse is presented in Figure 2.2.

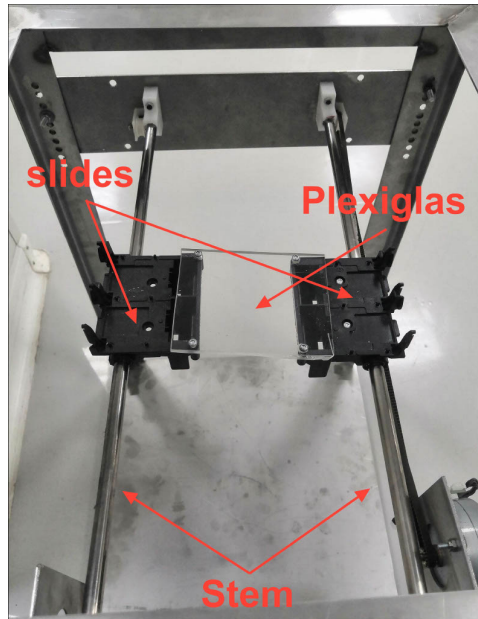


Figure 2.2 – Gun nozzle traverse.

**c. The hot plate:**

The hot plate used in this project is a DLAB HP550-S LED Hot plate with work plate dimensions of 184x184 mm made of glass ceramic; its maximum temperature is 550 °C [12]. The device is shown in Figure 2.3.



Figure 2.3 – DLAB HP550-S plate [12].

**d. The air compressor:**

It is a device used in pneumatic spraying cases, where it supplies compressed air with the required pressure to the gun nozzle in order to atomize the solution. Our apparatus is equipped with a 1/5 HP Airbrush Air Compressor Kit, which is an air compressor with a size of 310x135x310 mm, a pressure range that goes from 0 up to 10 bar, a flow of 23 L/min, and an air tank with a capacity of 3 L [13]. The compressor is shown in Figure 2.4.



Figure 2.4 – 1/5 HP Airbrush Air Compressor Kit [13].

The application to be performed is illustrated in the flowchart presented in Figure 2.5:

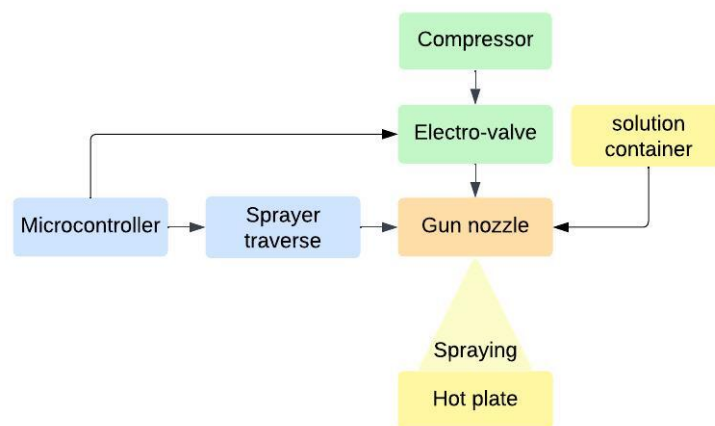


Figure 2.5 – Spray pyrolysis schematic.

The whole process is then divided into the following parts:

1. **The displacement of the gun nozzle along the X-axis:** This part is implemented using a PIC18F4550 microcontroller, a stepper motor, and a ULN2803.
2. **The gun nozzle spraying:** For this, an electro-valve and a PIC18F4550 microcontroller are used.
3. **Display and input data:** This section consists of a PIC18F4550 microcontroller, an LCD module, and push buttons. Where the user can: start the process; enter a number of scans; the delay between them; and the dimension of the sprayed area.
4. **The microcontroller:** It is programmed using the software MPLab and PICKIT2, simulations are done with Proteus software.
5. **The apparatus design:** The external structure is designed with Solid-works software.

## 2.3 HARDWARE

The hardware part consists of the following components:

### 2.3.1 Microcontroller

A microcontroller is a small, simple integrated circuit that has a processor, memory, and input/output peripherals as basic parts that help it interact with other components. This single chip is designed and programmed to control the functions of an electronic device [14].

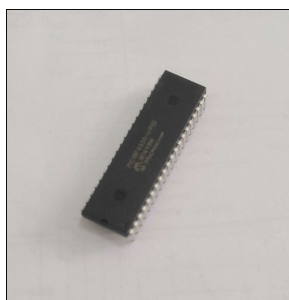
#### a. PIC18F4550 microcontroller

PIC18F4550 is a microcontroller that belongs to the PIC18 family manufactured by Microchip Technology. The microcontrollers of this family are widely used in electronic applications due to their high performance and low power consumption nano-watt technology [15].

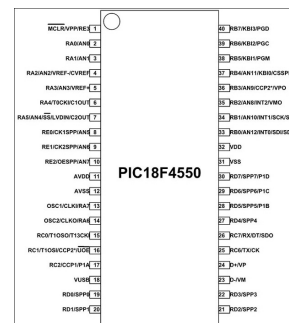
PIC stands for Peripheral Interface Controller, and F refers to the flash program memory present in this MCU, which makes it belong to the PIC18F subfamily. Some of the several characteristics that PIC184550 has are [15]:

- Forty pins, and each pin can perform more than one task, as shown in the diagram in Figure 2.6.
- Five ports labeled from A to E.
- A Program Memory of 32KB and a RAM of 2048 bytes.
- An EEPROM Memory of 256Bytes.
- A CPU Speed of 12MIPS.

Figure 2.6 shows the microcontroller PIC18F4550 and its pin configuration.



(a) Real image.



(b) Pin diagram.

Figure 2.6 – PIC18F4550 MCU .

### 2.3.2 PICkit2

Microchip has designed PICkit programmers in order to program its microcontrollers. PICkit2 is one of them.

PICkit2 is an in-circuit serial programmer composed of two main parts: an ICSP interface used to program the target microcontroller and a USB port used to communicate with the PC in order to upload the program from

the PICkit2-specific software. This programmer itself is equipped with a PIC18F2550 as its microprocessor [16]. In this project, we used the PICkit2 shown in Figure 2.7, designed and implemented at the CDTA center.

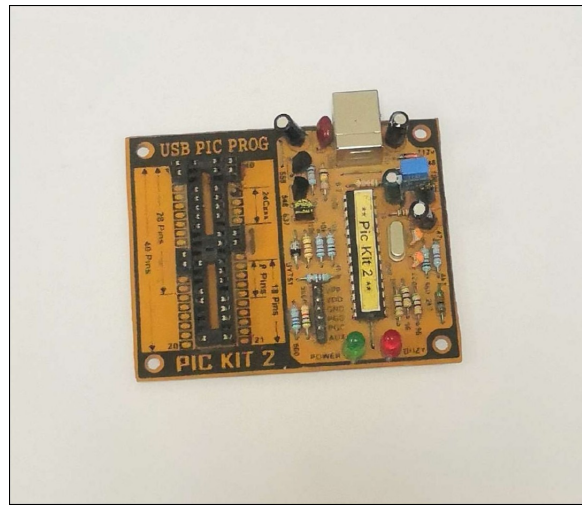


Figure 2.7 – PICkit2.

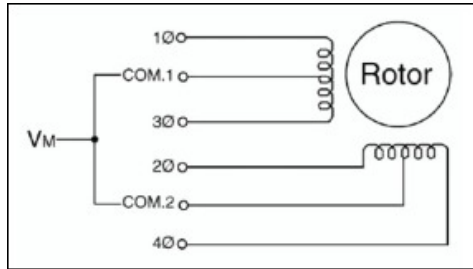
### 2.3.3 Stepper motor

It is an electric device provided with a mechanical design that allows the transformation of electrical energy into motion produced by executing steps. Its structure includes a static part called a stator that consists of teeth around which coils are wound and a moving part called a rotor made of either a permanent magnet or an iron core. After being supplied with a pulse signal, the coil generates an electromagnetic field that makes the rotor turn with a certain degree, performing one step. The coils are assembled in groups called phases, which are powered alternately and continuously in a precise sequence to keep the motor rotating [17]. Stepper motors can be classified as unipolar (5 or 6 wires) or bipolar (4 wires). As the names indicate, in bipolar configurations, polarities can be switched using an H-bridge, while in unipolar configurations, polarities are fixed [17]. The PM55L-048 shown in Figure 2.8 is the stepper motor we used in this work. It is a unipolar stepper motor with two phases; each phase has a center tap that divides the principal coil into two minor coils, resulting in three wires per winding, and as both center taps are linked, the motor ends up having five leads (view the datasheet in the appendix).





(a) Stepper motor PM55L-048

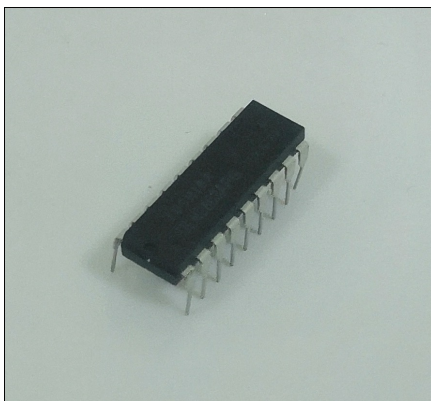


(b) unipolar stepper motor schematic [18].

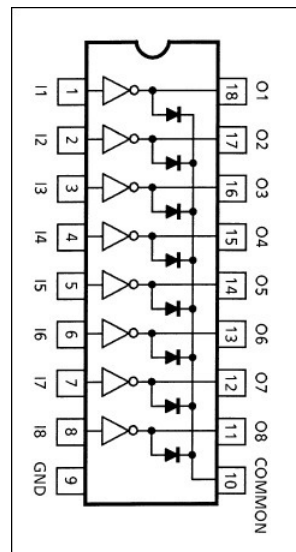
Figure 2.8 – Unipolar stepper motor.

### 2.3.4 Motor driver ULN2803

The motor driver is an electronic device used as an intermediate between the microcontroller and the stepper motor. It is a high-voltage, high-current Darlington driver. The ULN2803 is one of the most popular motor drivers. It is an 18 bits integrated circuit that contains 8 Darlington pairs with an output current of 500 mA and an output voltage of 50V. Figure 2.9 shows the ULN2803 and its pin configuration (view the data sheet in the appendix).



(a) ULN2803.



(b) Pin configuration of ULN2803.

Figure 2.9 – Motor driver ULN2803.

### 2.3.5 Electro-valve

The electro-valve is an electro-mechanical device used to control the flow of gas and liquid, where it converts electric energy into mechanical energy. There exist two types: the digital electro-valve, which has two statuses, either fully opened or closed, and the analog electro-valve, which can be

opened partially or closed. In this project, the digital electro-valve shown in Figure 2.10 is used, and its command is generated by the microcontroller. When the voltage is supplied, the electro-valve lets the compressed air flow, and then the gun nozzle starts spraying [19].



Figure 2.10 – *Electrovalve*.

### 2.3.6 End stop sensor

It is a sensor able to detect the position of a moving object, usually used to check the displacement limit. This sensor is used in various machines, and typically two of them are placed at both ends of the travel of the moving object. Several sensors can be used as end-stop sensors, for example, mechanical switches, magnetic sensors, and optical sensors. In this project, we used mechanical limit switches. They are popular for being used in 3D printers and are commonly used in other industrial applications as they offer high precision. A limit switch has a moving part on the outside connected to two or more electrical contacts from the inside; when the target comes into contact with the switch, the outside part moves and triggers the electrical contacts, which either allow the current to flow or stop it, depending on whether they are normally open or normally closed contacts.

### 2.3.7 LCD display

LCD stands for Liquid Crystal Display. As its name suggests, it uses a layer of liquid crystal to change its optical properties. By applying a small voltage to a specific area, the electric field around it results in the alignment of the tiny liquid crystal molecules in a certain direction, allowing or blocking the light and thus displaying a pattern. Modern LCDs control the display at the pixel level using transistors [20].

LCDs are low-power-consuming and vary from simple, easily programmable character displays to TV screens and other sophisticated devices. The one we are concerned with is the character display, precisely the 2004 one that displays up to 20 characters (letters, numbers, punctuation) on 4 lines.

### 2.3.8 Push button

It is a device that either opens or closes the circuit to which it is connected when pressed. This process is performed to generate or stop a signal as a way to operate or interrupt a specific function. It can be programmed to be used in momentary mode, where the button works only when pushed, or in permanent mode, where it works continuously after one push. The push button has two statuses: normally open (NO), which is used to close the circuit, and normally closed (NC), which opens the circuit when activated [21].

## 2.4 SOFTWARE

Throughout the realization of this project's different parts ( design, programming, and simulation); several software tools were used.

### 2.4.1 MPLAB X IDE

MPLAB X Integrated Development Environment is a software program developed by Microchip to allow users to easily configure, debug, and qualify embedded designs of their PIC microcontrollers, digital signal controllers, and microprocessors. MPLAB X IDE is equipped with several tools (compilers, emulators, debuggers and starter kits...) that guarantee the smooth process of debugging for both software simulations and hardware. It is user-friendly, which makes it easy to discover and use. In addition to that, this IDE is open source, based on the NetBeans Platform, and can be used on different operating systems such as Windows, Linux, or Mac OS X [22]. The start page of the MPLAB X IDE software is presented in Figure 2.11.



Figure 2.11 – MPLAB X IDE start page .

### 2.4.2 C18 Compiler

A compiler is a program that translates source code into machine language. C18 is a compiler developed by Microchip for their PIC18 MCUs.

It uses the C programming language, is compatible with the MPLAB IDE, and can be integrated into it [23].

### 2.4.3 PICkit 2 Programmer application

The PICkit2 Programmer application is a programming interface developed by Microchip that is used with the PICkit2 Programmer to program and debug the PIC MCUs it is compatible with. This software allows the visualization and performance of several functions of the programmer, including reading, writing, and erasing, since it provides a GUI. It acts as a medium between PICkit2 and the MPLAB IDE [16]. The start page of the PICKIT2 software is shown in Figure 2.12.

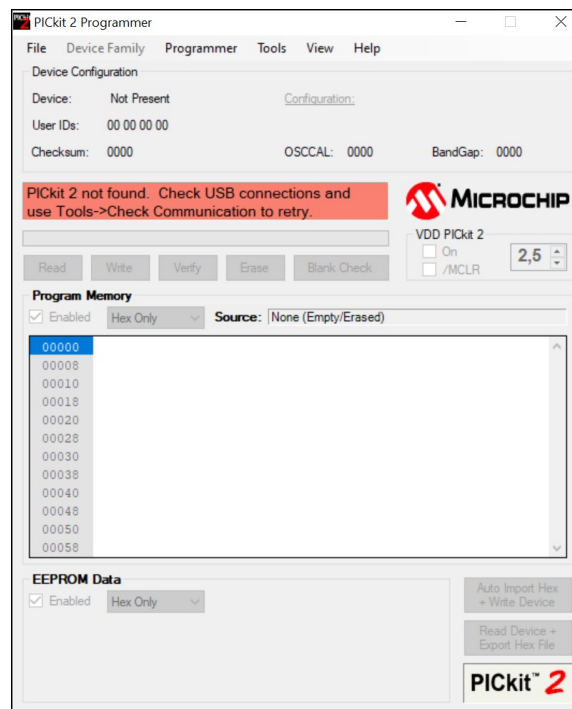


Figure 2.12 – PICkit2 Programmer application.

### 2.4.4 C programming language

It is a general-purpose, high-level programming language. It is basic and has a similar syntax to many popular programming languages that it has influenced, which makes it ideal as a first step into the programming world. Not only that, but this language provides a wide range of uses in different domains, such as operating systems and application programming. C Programming was created by Dennis Ritchie in the 1970s and is associated with the UNIX operating system [24].

### 2.4.5 Proteus

It is a software developed by Labcenter Electronics Ltd to be the first simulation program that includes microcontroller schemes and the most advanced embedded peripheral packages. Those tools ensure the simulation

of multiple tasks in the electronics and embedded systems fields, giving birth to a new perspective in their development and debugging. It is used in PCB design layouts, schematic modeling, and circuit simulation [25]. The start page of the Proteus software is shown in Figure 2.13.

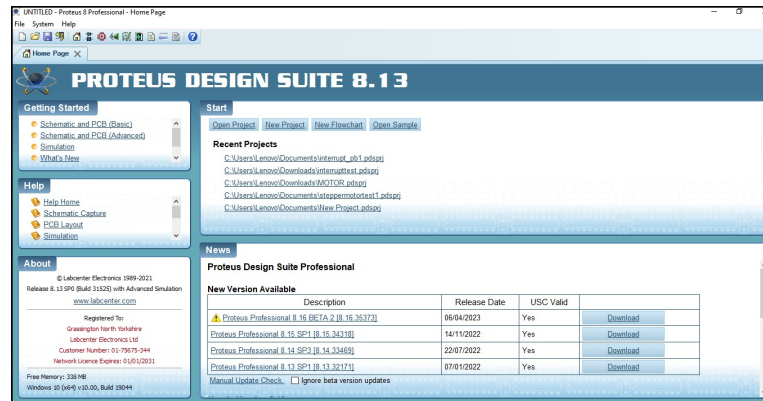


Figure 2.13 – Proteus start page.

#### 2.4.6 SolidWorks

It is a computer-aided design (CAD) software developed by Dassault Systemes. A user-friendly program used to create and design highly precise, detailed models for all sorts of solids. It contains three associated modes: parts, assembly, and drawings. It is provided with sophisticated packages and tools used to adjust and modify model features automatically and to execute different functions [26]. Its start page is shown in Figure 2.14.

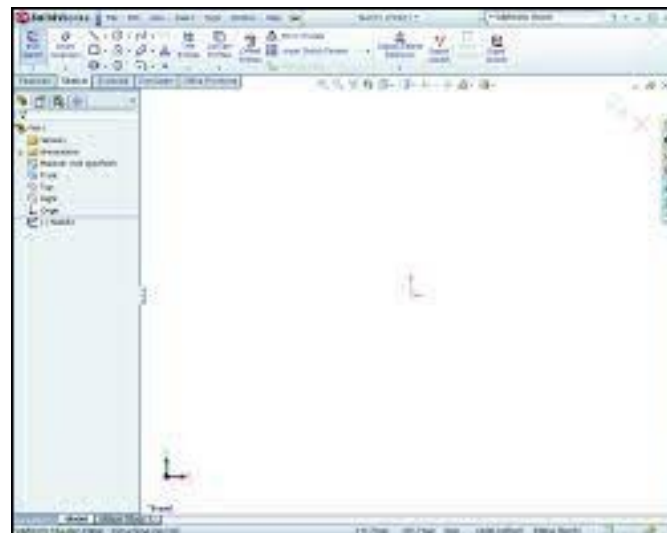


Figure 2.14 – Solidworks start page.

## 2.5 CONCLUSION

In this chapter, we described our Spray Pyrolysis equipment and gave definitions that were gathered through research of the several hardware components, like the stepper motor and PIC18F455 microcontroller, and software tools like MPLAB X IDE used to implement it.

# EXPERIMENTAL DETAILS

# 3

# EXPERIMENTAL DETAILS

# 3

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### 3.1 INTRODUCTION

This chapter is devoted to the experimental part of the project. It consists of all the steps we undertook to automate the spray pyrolysis technique and design the device. Where it includes simulation tests, circuits implementation, and apparatus assembling.

### 3.2 APPARATUS CONCEPTION

The architectural design of the equipment created using Solid-Works consists of an outer box with specific dimensions, a rectangular sheet steel base, and additional parts to support the motor, stems, and pulley. Here's an overview of the design:

1. **The skeleton:** It is composed of :
  - The base is a rectangular 400x450mm iron steel sheet with a thickness of 2mm.
  - 400mm and 450mm long sheet metal angle irons for the width and length of the box.
  - 600mm long sheet metal angle irons for the height.
  - The corners are 2mm thick and folded so as to have two sides of 20mm and 40mm respectively.
2. **The slider and motor support:** It is a rectangular 400x84mm iron steel sheet with a thickness of 2mm. Attached to it are two pierced iron steel sheet pieces for the motors designed according to the PM55L-048 stepper motor dimensions (only one of them was used in our apparatus) and two polymer pieces designed to support the slider's stems.
3. **The slider and pulley support:** This is a rectangular steel sheet measuring 400x84 mm and 2 mm thick. Attached to it are two small polymer pieces for the pulleys (only one was used in our apparatus) and two other pieces to support the slider's rods.

The slider and motor support and the slider and pulley support are facing each other fixed on the 400mm sides of the structure using bolts. The base has small pieces of iron steel sheets folded and welded to it to form the feet of the whole structure. The SolidWorks design is shown in Figure 3.1.

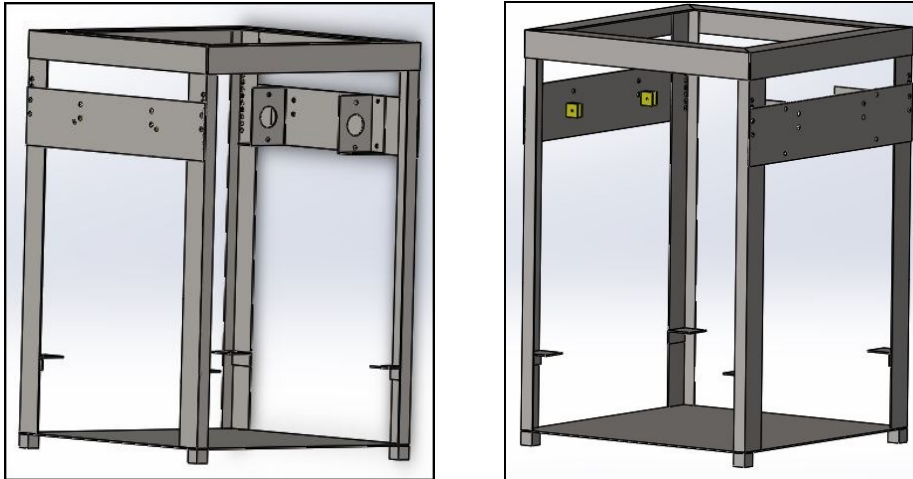


Figure 3.1 – Apparatus design on SolidWorks.

Figure 3.2 shows the structure's parts before assembling them.



Figure 3.2 – Apparatus parts before being assembled.

### 3.3 TESTS

#### 3.3.1 Stepper motor working principle

As stated before, the stepper motor PM55-Lo48 used in this project is a unipolar motor with a permanent magnet core, so it operates by attracting the north and south poles of the rotor after powering the coils. It consists of two windings, each divided by a center tap into two secondary coils. The center taps of both windings are then linked together, resulting in five wires. The motor should be connected following two steps: supplying the center tap with voltage (24 volts for PM55-Lo48) and grounding the left four wires alternately. When connected, the direction of the produced magnetic field determines which tooth pair of the rotor will be aligned with which pole pair of the stator. Poles are identified according to which secondary coil is energized. Since they are wound in parallel to each other, one represents the north pole and the other the south [17]. The distribution of the sequence of pulses for motor rotation is illustrated in

Table 3.1 and the figures (Figure 3.3 and Figure 3.4) presented below:

	Step 1	Step 2	Step 3	Step 4
phase A	1	0	0	0
phase B	0	1	0	0
phase $\bar{A}$	0	0	1	0
phase $\bar{B}$	0	0	0	1

Table 3.1 – Distribution of Sequence of pulses.

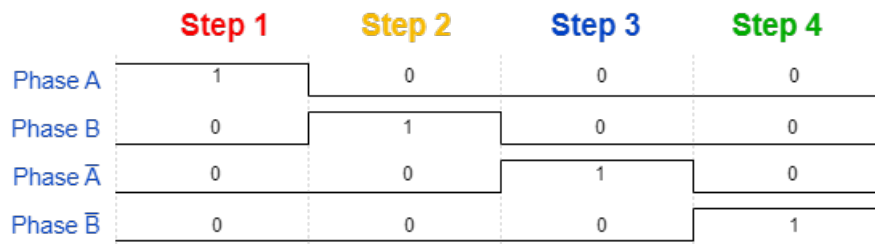


Figure 3.3 – Sequence timing diagram .

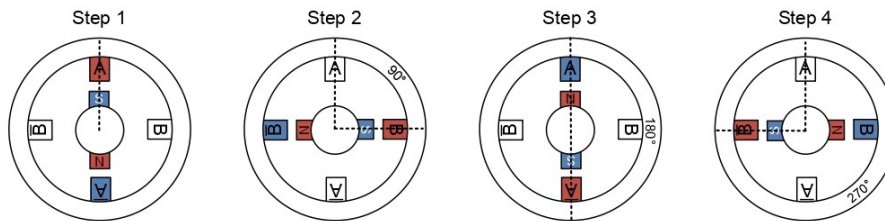


Figure 3.4 – sequence for full step [17].

### 3.3.2 Programming

#### a. Stepper motor control

After understanding the stepper motor working principle, we wrote several simple codes using the C programming language on MPLAB software in order to program it.

First These codes were basic tests that send the corresponding 0 or 1 bit to the motor pins according to the sequences mentioned in the previous section in order to make the motor rotate clockwise or counterclockwise continuously, as there is no condition to stop it. Figure 3.5 shows both codes.

```

void main(void)
{
    OSCCON=0b01110011;
    TRISD=0;

    while(1)
    {
        PORTD=1;Delay100TCYx(100);
        PORTD=2;Delay100TCYx(100);
        PORTD=4;Delay100TCYx(100);
        PORTD=8;Delay100TCYx(100);
    }
}
    
```

(a) Clockwise.

```

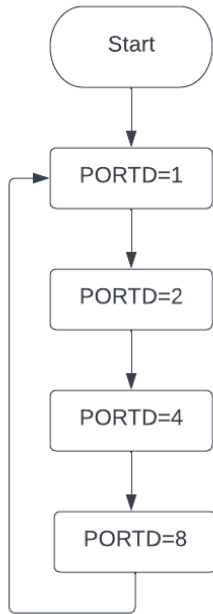
void main(void)
{
    OSCCON=0b01110011;
    TRISD=0;

    while(1)
    {
        PORTD=8;Delay100TCYx(100);
        PORTD=4;Delay100TCYx(100);
        PORTD=2;Delay100TCYx(100);
        PORTD=1;Delay100TCYx(100);
    }
}
    
```

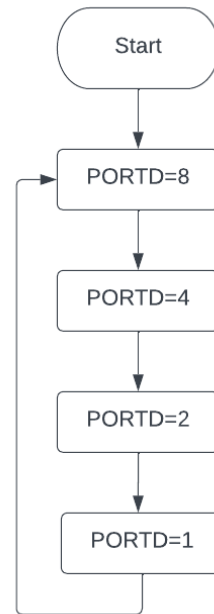
(b) Counterclockwise.

Figure 3.5 – Motor rotation C programs.

Figure 3.6 shows the flowcharts that describe both codes respectively.



(a) Clockwise.



(b) Counterclockwise.

Figure 3.6 – Motor rotation flowcharts.

The two directions were combined, and more parameters were added, such as direction parameter that makes the motor rotate in both directions according to its value (direction =1 corresponds to clockwise and 0 to counterclockwise) and endstops in each direction to stop the motor from rotating. The flowchart that describes the program is shown in Figure 3.7.

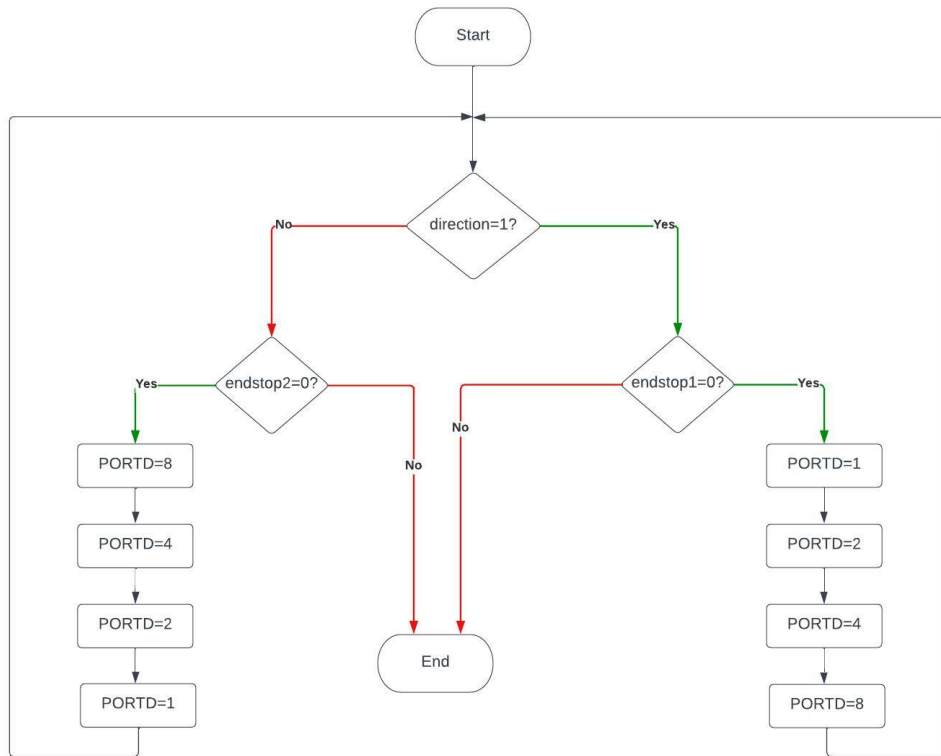


Figure 3.7 – Motor both directions rotation flowchart.

The three codes were tested and adjusted using the simulation circuits shown in the figures Figure 3.8 and Figure 3.9 in Proteus software before testing them in reality.

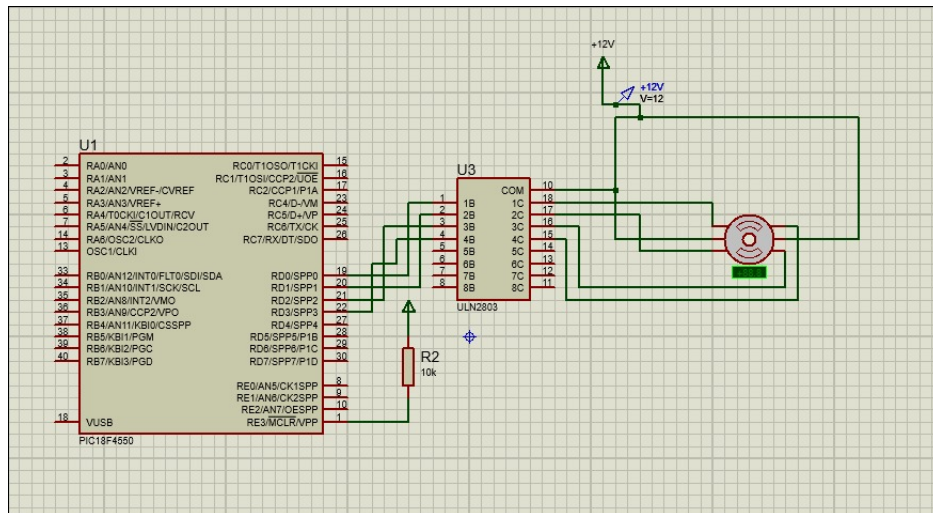


Figure 3.8 – Motor rotation simulation circuit.

We added components and made the variables direction, endstop1, and endstop2 into inputs. The direction was controlled with a switch connected to RC1, whereas for endstop1 and 2, they were controlled using two switches connected to RB1 and RB2 pins.

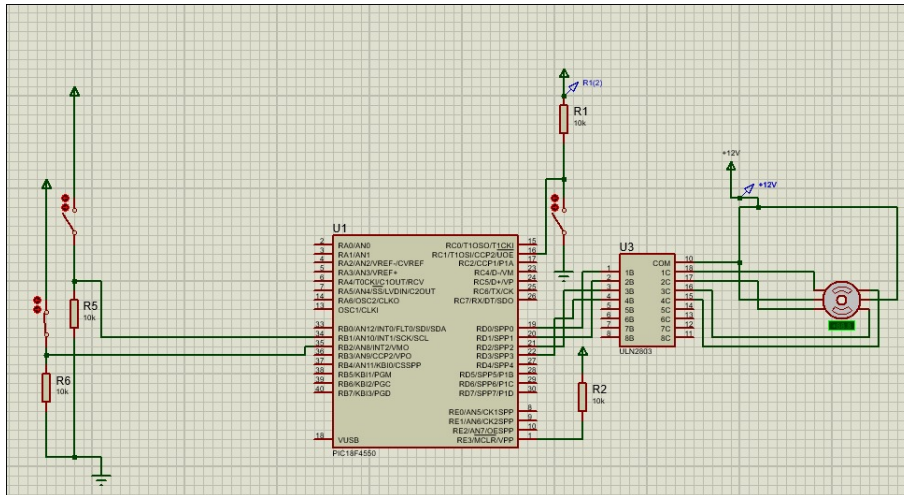


Figure 3.9 – Stepper motor rotation in both direction simulation circuit.

### b. LCD module

The LCD module can be connected and programmed in two different modes: 8-bit mode, where its outputs from D<sub>0</sub> to D<sub>7</sub> should be connected To the microcontroller, and 4-bit mode, where only outputs from D<sub>4</sub> to D<sub>7</sub> should be connected, and the instruction is sent in two stages. To test the LCD, we wrote a program that commands the LCD module in 4-bit mode and displays only characters that make the words: Distance, Scans, and Delay. The control signals RS and E were connected in pins RC<sub>0</sub> and RC<sub>1</sub>, respectively. The RS signal is used to send either command (RS = 0) or data (RS = 1), the control signal E enables the LCD module (E = 1), the potentiometer is used to adjust the intensity of the light of the LCD module, and the control signal RW sets the LCD on either Read mode (RW = 0) or Write mode (RW = 1). As it is used to enter data, only reading mode is needed, so it is connected directly to the ground. The strings displayed and codes written to send commands and data are presented in Figure 3.10 and Figure 3.11, respectively.

```

unsigned char string1[]={ 'D','i','m','e','n','s','i','o','n',' ':'};
unsigned char string2[]={ 'S','c','a','n','s',' ':'};
unsigned char string3[]={ 'D','e','l','a','y',' ':'};
    
```

Figure 3.10 – The strings displayed on LCD module.

```

void sendcommand(unsigned char command){
    PORTD =(command & 0xF0);
    LCD_RS=0;
    delay();
    LCD_EN=1;
    delay();
    LCD_EN=0;
    delay();
    PORTD =((command << 4) & 0xF0);
    LCD_RS=0;
    delay();
    LCD_EN=1;
    delay();
    LCD_EN=0;
    delay();
}

void senddata(unsigned char LCD_data){
    PORTD =(LCD_data & 0xF0);
    LCD_RS=1;
    delay();
    LCD_EN=1;
    delay();
    LCD_EN=0;
    delay();
    PORTD =((LCD_data << 4) & 0xF0);
    LCD_RS=1;
    delay();
    LCD_EN=1;
    delay();
    LCD_EN=0;
    delay();
}
    
```

Figure 3.11 – Codes to send commands and data to LCD module.

The circuit implemented to simulate the program is illustrated in Figure 3.12.

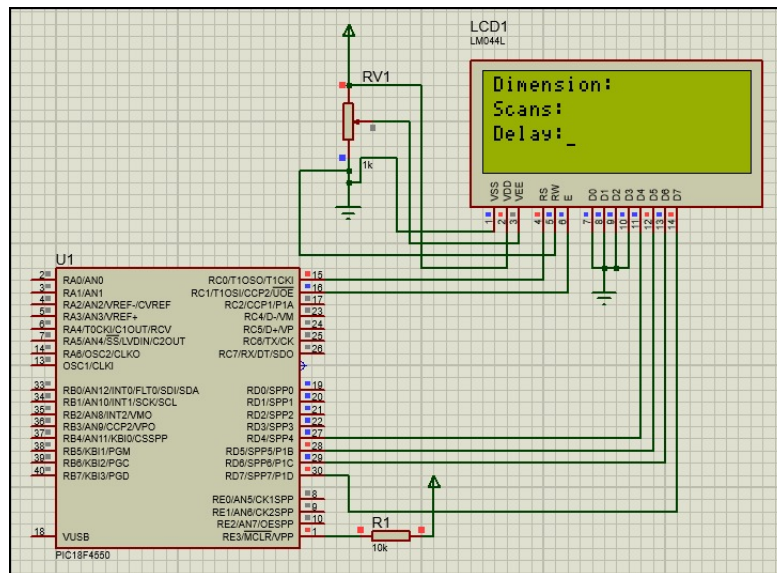


Figure 3.12 – Simulation of LCD module circuit in 4 bits.

In order to control the LCD module to display entered variables of three digits using a counter and interrupts, we used push buttons. The first push button was connected in pin RB<sub>4</sub>, and it was used to increment the counter; the second in pin RB<sub>5</sub> used to shift the cursor to the right; and the third in pin RB<sub>6</sub> used to go to the next element. The flowchart that describes the code that displays the menu on the LCD and enters variables using push buttons is presented in Figure 3.13.



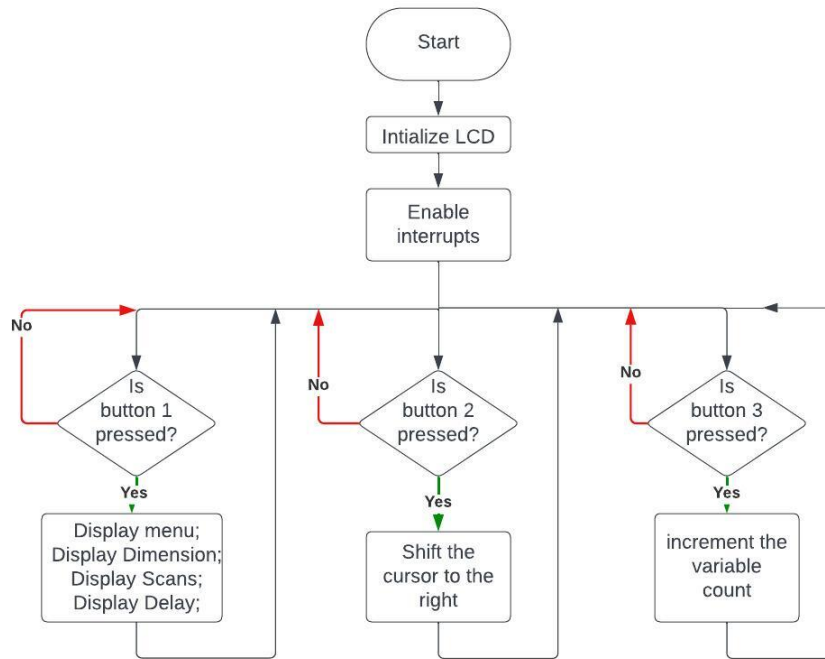


Figure 3.13 – Flowchart of LCD module code.

The simulation circuit is shown in Figure 3.14.

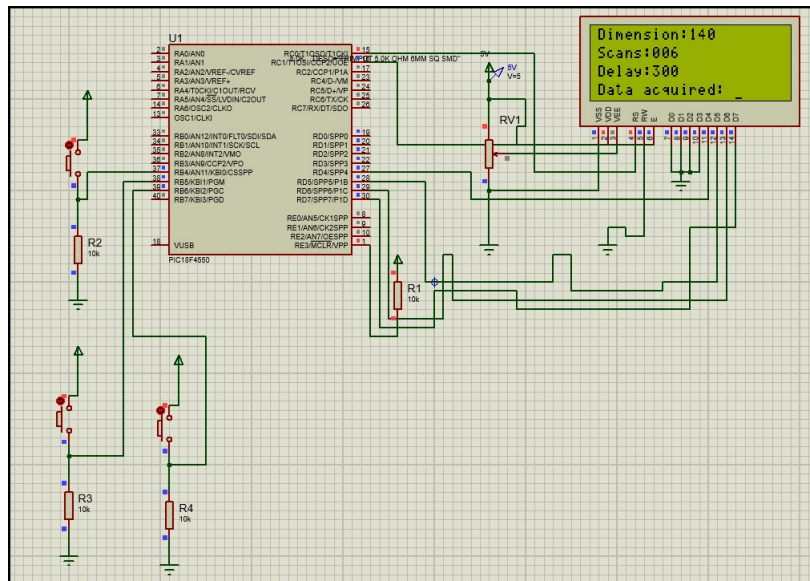


Figure 3.14 – Simulation of LCD module to display parameters.

### c. Electric valve

To test the electro-valve, the microcontroller was programmed to send either a 0 or 1 in order to open and close it. The flowchart of the program shown above is presented in Figure 3.15.



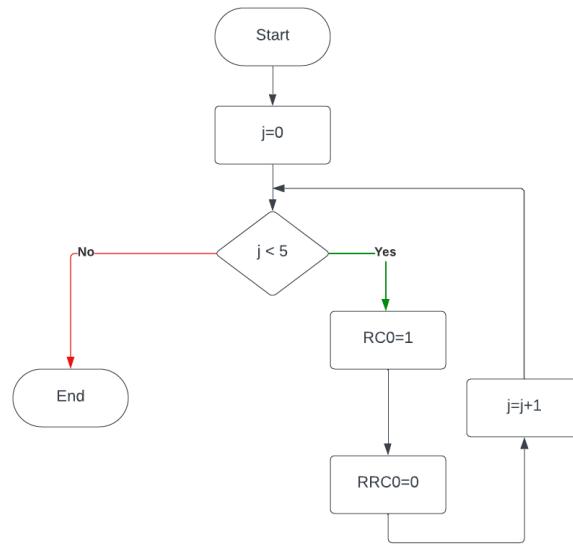


Figure 3.15 – The flowchart of electro-valve testing.

The operation was simulated in Proteus software, where the electro-valve was replaced by an LED that blinks five times, as shown in Figure 3.16.

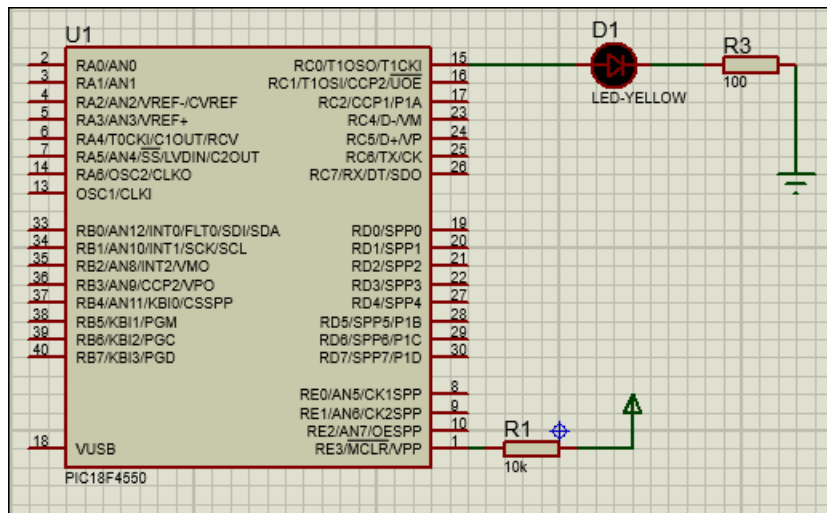


Figure 3.16 – Simulation of electro-valve.

### 3.3.3 Transfer of the program to the circuit

In order to test all codes generated in reality, we had to use the PICKit2 programmer and PICKit2 software for the transfer of the program from the PC to the PIC18F4550. Figure 3.17 shows connections between the PC, the PICKit2, and the PIC18F4550.

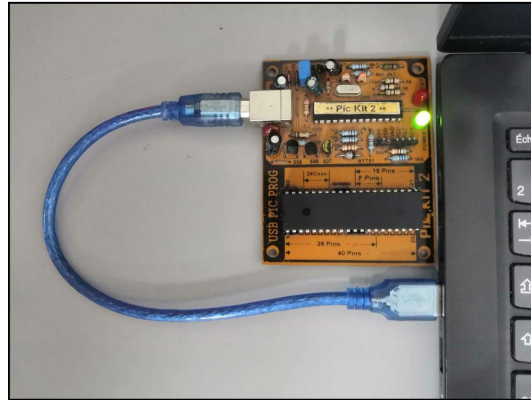


Figure 3.17 – PICkit2 with PIC18F4550.

### 3.3.4 Circuit implementation:

As mentioned previously, the actuator used for the gun nozzle traverse is a unipolar stepper motor. As it has been recovered from an old printer, its endings were not determined, and in order to recognize its phases, tests were performed after reading its datasheet (see appendix). Where we checked the connections and the resistance between each two wires. The resistance between the ends of each primary coil is 26 Ohm, while between the center tap and the left wires it is 13 Ohm. On the other hand, the endings of one primary coil are not connected with the endings of the other primary coil, while the left pairs are all connected. After performing these two steps, we could recognize the stepper motor's phases and mark them; the results are presented in Figure 3.18.

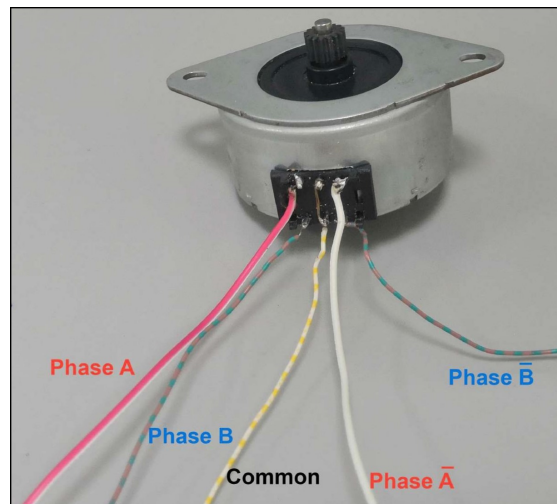


Figure 3.18 – Stepper motor phases.

#### a. Stepper motor circuit

In the part of implementation, the code was uploaded to the microcontroller, and then a circuit was built where the pins 19, 20, 21, and 22 were connected to the ULN2803 input pins. As ULN2803 contains 8 input pins with a maximum output current of 500 mA (from the datasheet), each two

of its inputs and outputs were connected to raise the maximum current output to 1A as the stepper motor needs 800mA to rotate. The stepper motor wires were then connected to the ULN2803 output pins. The endstop sensors were replaced by two push buttons placed on pins 34 and 35. The circuit is shown in Figure 3.19.

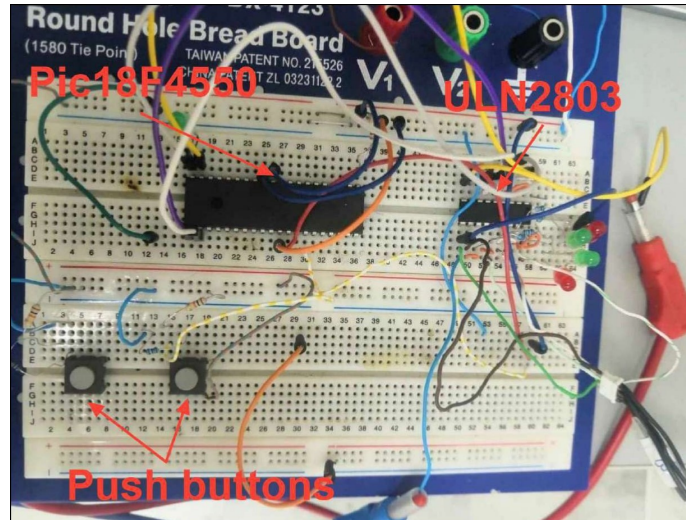


Figure 3.19 – circuit for motor rotating in both directions.

#### b. LCD module circuit

First, the LCD module was tested to display the strings: Dimension, Scans, and Delay. as shown in Figure 3.20.

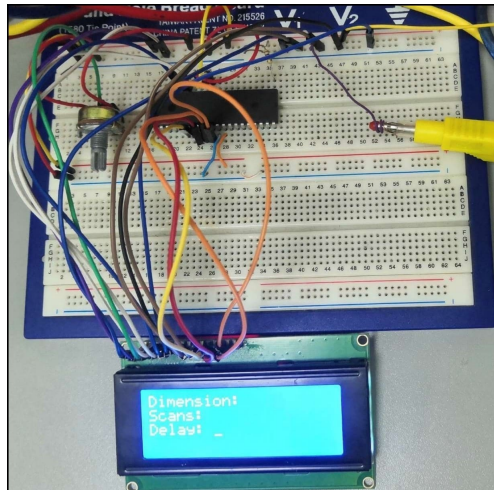


Figure 3.20 – LCD module circuit to display strings.

Then, we tested the LCD module to display entered parameters; for this, push buttons were added in interrupt pins 37, 38, and 39. The circuit is shown in Figure 3.21.

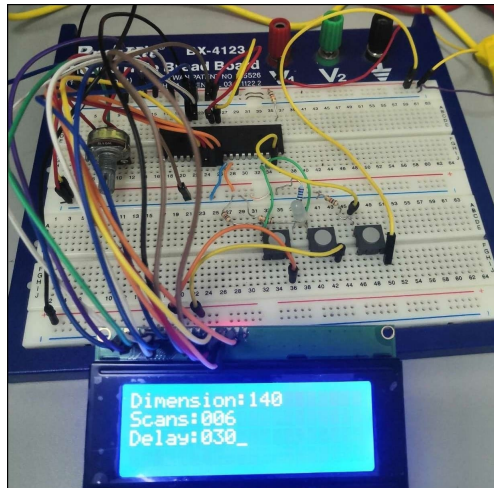


Figure 3.21 – LCD module circuit to display entered parameters.

### c. Circuit of stepper motor with electro-valve

After testing the stepper motor, an instruction was added to open and close the electro-valve according to the application specifications. In the built circuit, two ULN2803 were used. The first one's input pins were connected to pins 19, 20, 21, and 22 of the microcontroller, and its output pins were connected to the stepper motor, while for the second ULN2803, one of its input pins was connected to pin 15 of the PIC18F4550, and one of its output pins was connected to the electro-valve. The stepper motor, the electro-valve, and both ULN2803 were supplied with 24 Volts. The microcontroller was fed 5 volts through pins 11 and 32 and grounded in pins 12 and 31. The circuit is shown in Figure 3.22.

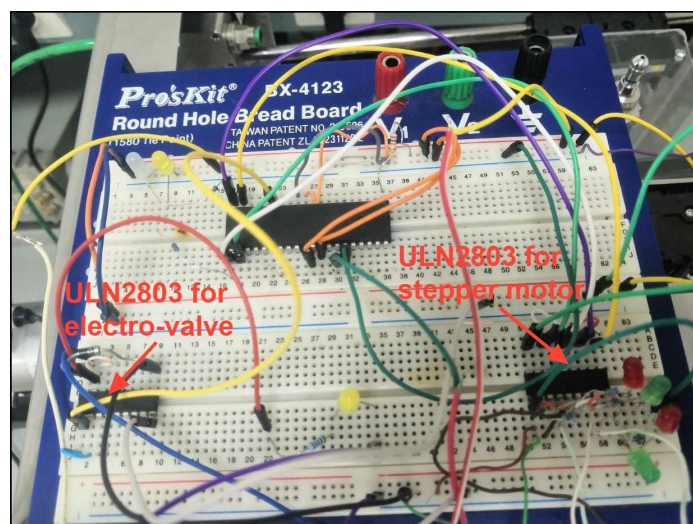


Figure 3.22 – Circuit of stepper motor with electro-valve.

### 3.4 CONCLUSION:

In this chapter, the experimental tests performed to control different parts of the realized apparatus were presented and explained. Generated codes for stepper motor, electro-valve, and LCD control were all tested individually both in simulation and implementation. All experiments were successful.

# RESULTS AND DISCUSSION

**4**

# RESULTS AND DISCUSSION

# 4

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## 4.1 INTRODUCTION:

After presenting the different experiments that lead to building the final apparatus, this chapter is dedicated to exposing and discussing the acquired results and the equipment's performance. At the end of this chapter, a comparison between manual and automated SP applications is provided.

## 4.2 REALIZATION

In the Spray Pyrolysis process, the gun nozzle position is first checked by the end stop sensor; if it is not at the start point, the gun nozzle should move backward. Once at the start point, the gun nozzle moves forward until it reaches the position where the substrate is placed. Then the spraying starts, the electro-valve valve opens, allowing the compressed air to pass to pump the solution, and the gun nozzle continues to move back and forth depending on the number of scans. The spraying and gun nozzle movement stop between scans before reversing direction according to the delay time entered.

The realization of the SP process explained above is divided into three parts:

1. The conception design was assembled.
2. A program that was written and uploaded to the microcontroller PIC18F4550.
3. Then a circuit that was built and connected to the apparatus to perform the process.

### 4.2.1 Conception

Figure 4.1 shows the structure of the apparatus explained in chapter 3 after being assembled.



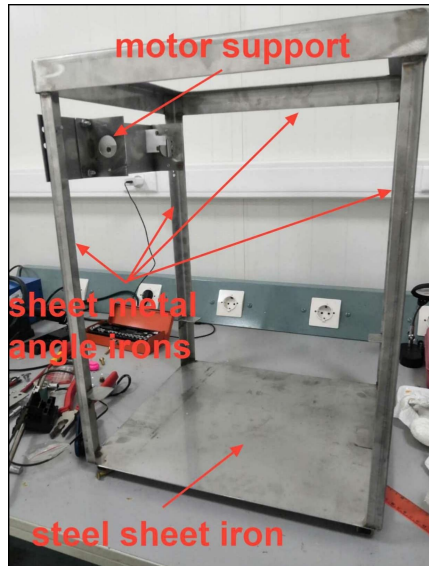


Figure 4.1 – Apparatus structure assembled.

#### 4.2.2 Programming:

The written code shown in Figure 4.2 includes the functions each corresponding to a precise part of the application:

```

void main() {

    initialization();
    while(konoff==0){
    display( &dims, &scan, &delayt);
    }
    while(konoff==1){
    startpoint();
    go_to_x0(dims);
    scanning(dims, scan, delayt);
    while(1);
    }
}

void theStartstopint(){
    if(INTCONbits.INTOIF==1){
        if (konoff==0){
            konoff=1;
        } else (konoff=0);
        INTCONbits.INTOIF = 0;}
}

```

Figure 4.2 – Main code.

- **display()**: This function includes the insertion of the needed parameters and their display on the LCD module.
- **start point()**: This function includes instructions to bring the gun nozzle to the start point after checking its position.
- **go to x0()**: This function counts the number of steps needed to bring the gun nozzle to the position where spraying should start and takes it there.

- **scanning ()**: This function counts the number of steps needed according to the spraying area, opens the electro-valve while the gun nozzle is moving, reverses direction after each spray, and stops gun nozzle movement between sprays depending on the delay time entered.

The flowchart in Figure 4.3 describes the flow of actions performed during a single application.

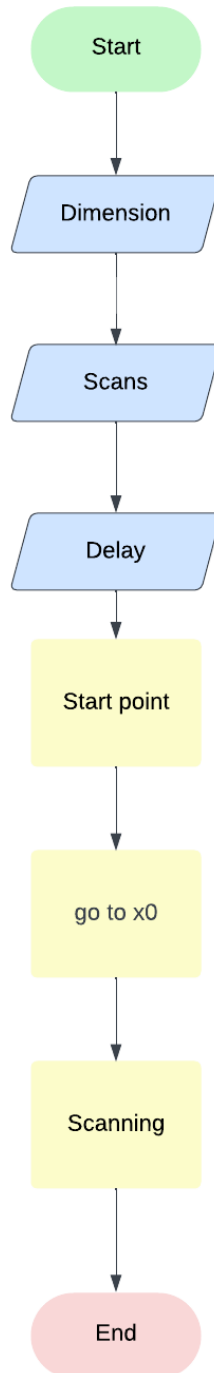


Figure 4.3 – Flowchart of the technique.

1. First, the user enters the data needed:
  - The dimension (mm) of the surface to be sprayed.
  - The number of scans.
  - The delay (seconds) that represents the rest time between scans.

This action is done using push buttons as external interrupts.

2. Second, the user presses the start button, and then the functions start point(), go to xo(), and scanning() explained before are executed sequentially.
3. Last, The user presses the start push button again to go back to the display() function in order to start a new application with other values of the parameters.

### 4.2.3 Circuit implementation

As shown in Figure 4.4, the circuit of the motor was connected to the apparatus to test the performance of the stepper motor. In the tests, one endstop was used to check that the gun nozzle was in the start position, and the second one was grounded.

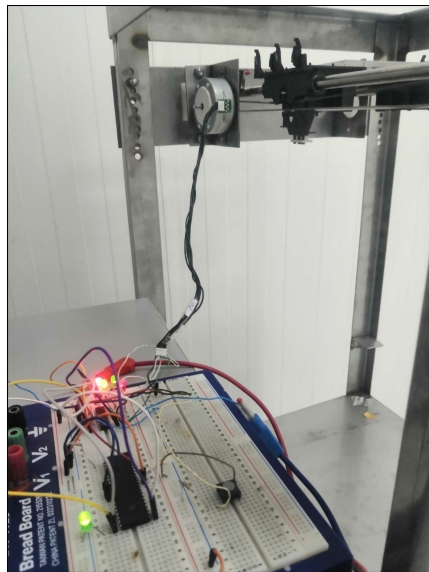


Figure 4.4 – circuit connected to apparatus.

With the aim of performing the full application, the circuit shown in Figure 4.5 was implemented. Where the previously mentioned parts were gathered, the ULN2803 used for the stepper motor was connected to pins 2, 3, 4, and 5. The one used for the electro-valve was connected to pin 15, and endstop sensors were connected to pins 16 and 17. The LCD was connected to pins 27, 28, 29, and 30, and its control signals RS and Enable were linked to pins 35 and 36, respectively. The push buttons were connected to pins 37, 38, 39, and 33 of the microcontroller.

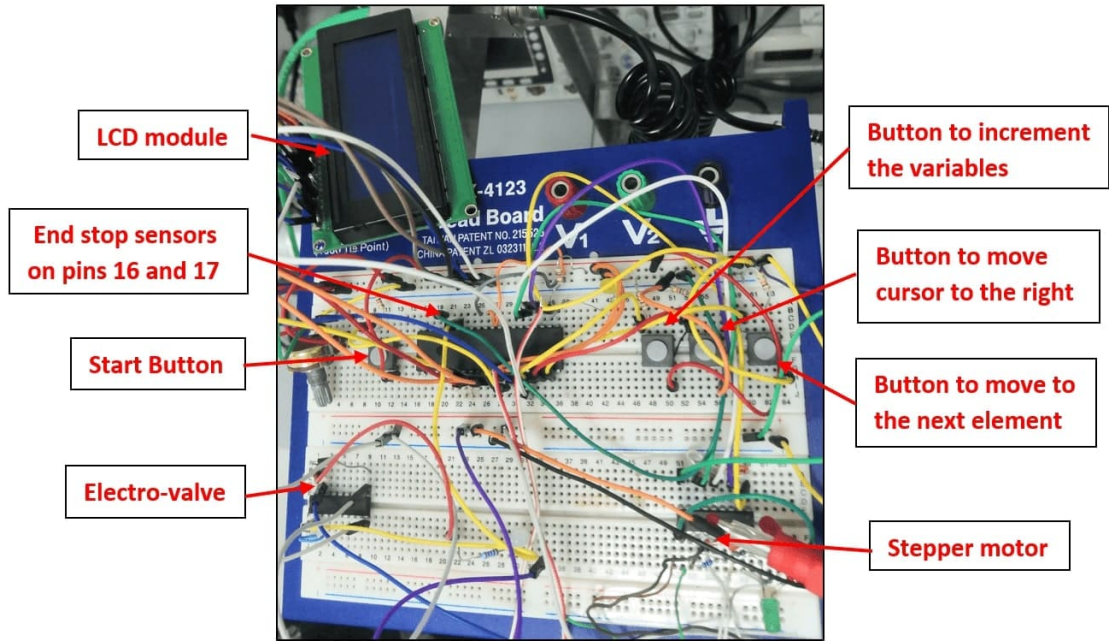


Figure 4.5 – Global circuit.

### 4.3 COMPARISON BETWEEN MANUAL AND AUTOMATED SP

Figure 4.6 shows the SP technique before and after automation:

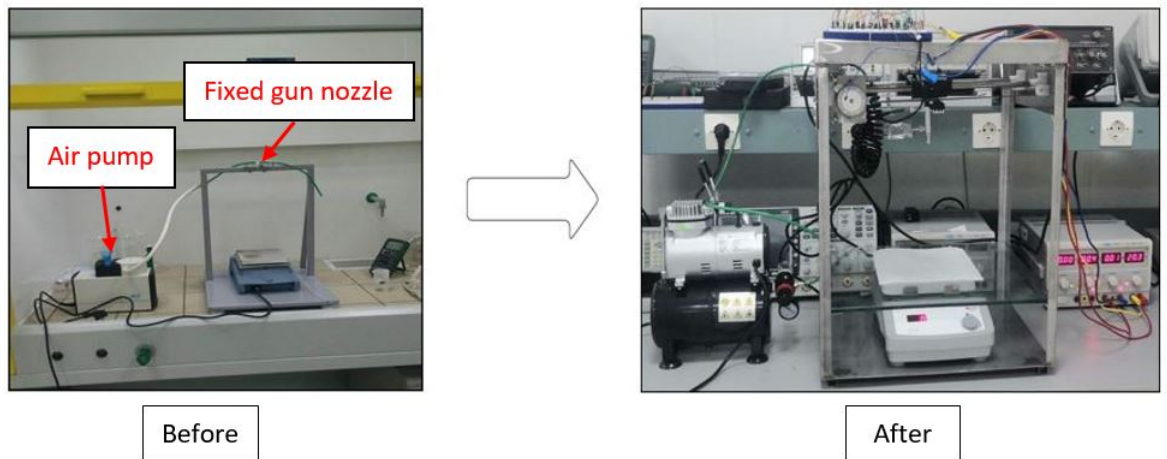


Figure 4.6 – Manual and automated SP technique.

The realization of this automated apparatus has facilitated the application of the SP technique. Where it has brought the following changes compared to the manual application:

1. In the manual application, the gun nozzle was stationary; after automation, it became dynamic because it was equipped with a displacement mechanism (composed of a stepper motor, a traverse, and endstop sensors), allowing it to move along one axis. The displacement system is shown in Figure 4.7.



Figure 4.7 – The gun nozzle in automated apparatus.

2. The spraying used to be performed with an air pump, while in the realized apparatus it is controlled using an electro-valve connected to an air compressor from one side and to the gun nozzle from the other side. The electro-valve connections are shown in Figure 4.8.

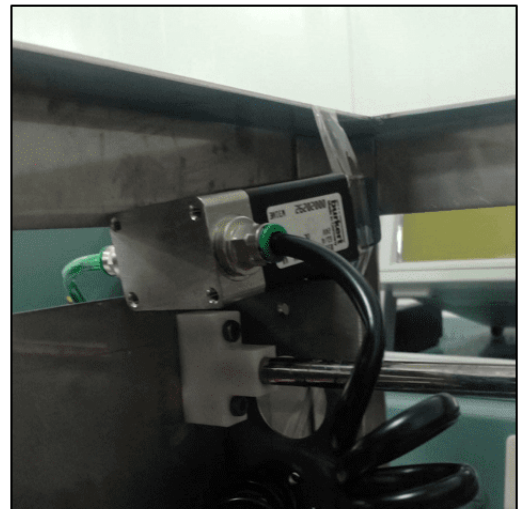
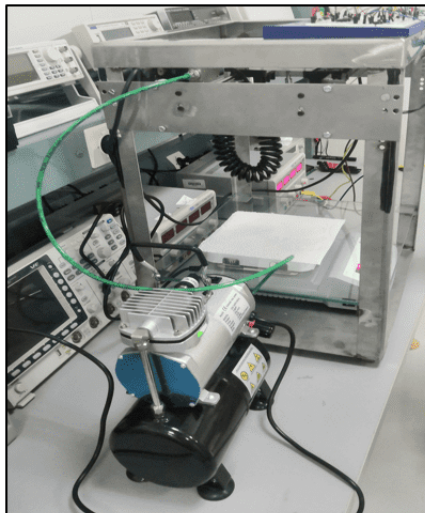


Figure 4.8 – The electro-valve connected to air compressor and to the gun nozzle.

After uploading the main code, the global circuit has been implemented and connected to the appliance. The SP technique was tested using water as a solution, and the full application was performed successfully.

LEDs were added to the circuit in order to follow the application's different steps. Figure 4.9 shows the results of code execution.



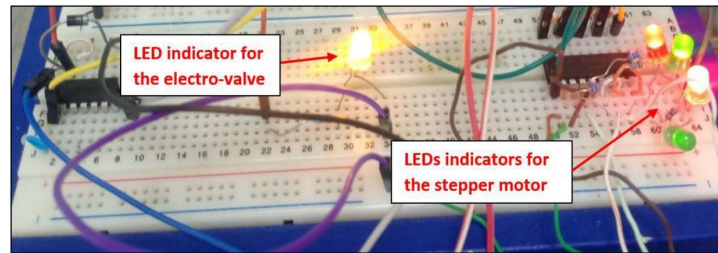


Figure 4.9 – LEDs indicators for stepper motor and electro-valve.

The objective of this project's achievement is illustrated in Figure 4.10 which shows the apparatus while spraying.

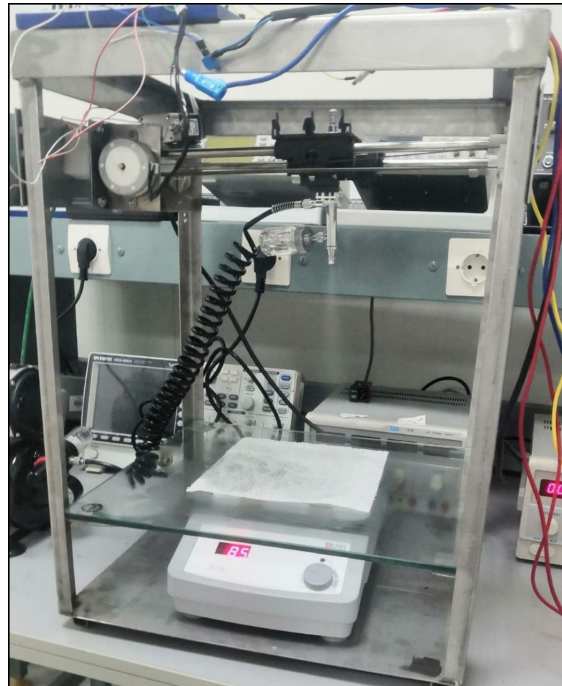


Figure 4.10 – The apparatus while performing the spray.

#### 4.3.1 Advantages of this SP apparatus

This automated apparatus has the advantages mentioned below over the manual application of the SP technique:

- The movement of the gun nozzle widens the area that can be sprayed compared to the one with the gun nozzle fixed, where a larger number of substrates can be placed at once.
- The movement of the gun nozzle also results in more homogeneous solutions depositions.
- The control of the valve allows for a rest time which also contributes to the SP technique's good results.
- This device saves the user time as it performs the whole application automatically after the needed data is provided.

#### 4.4 CONCLUSION

In this chapter, we have described the main code's different parts, which include the application functions. We also presented the global circuit that gathers the parts tested individually in the previous chapter. The circuit was implemented and connected to the apparatus. According to the results shown and discussed, we can conclude that the objective has been reached.

# GENERAL CONCLUSION

The realization of this work within the Platform of Micro Electro Mechanical Systems (P-MEMS) of the CDTA center permitted us to gain first-hand experience in the process of building projects.

The objective of this work, titled "Design and Implementation of an Automated Spray Pyrolysis System", was to build an apparatus that performs the SP technique. To fulfill this objective, we went through several steps. From them, we mention the main stops:

- First, we started with the theoretical part, where we researched and understood the working principle of the SP technique;
- Second, we studied the important electronic components used;
- Then, familiarization with the software tools was required;
- After that, the acquired knowledge was put into simulation;
- Last, the actions performed in simulation were transferred into realization through experiments and tests.

At the end of this process, the aim of this work has been achieved, as we could build a low-cost prototype.



# PERSPECTIVES

As the device is a prototype, it can be improved to be more sophisticated in the future by making a number of modifications, some of which are mentioned below:

- Additional axes can be added to the displacement mechanism, where the gun nozzle will be able to move along the z-axis and y-axis.
- An outer box can be designed and added to complete the structure.
- The human-machine interface can be enhanced using a more sophisticated HMI panel, or variables can be entered from the computer using an application.
- The spraying surface can be widened by changing the hot plate.
- By changing the gun nozzle type, the spraying method can be changed, hence the application the apparatus is used for.
- A PCB card can be designed and integrated into the apparatus.
- As the apparatus is not available on the Algerian market, after some modifications, it can be commercialized.

# APPENDIX

# A



# PM55L-048



PM Motor  
PM Type

### Reference Characteristics

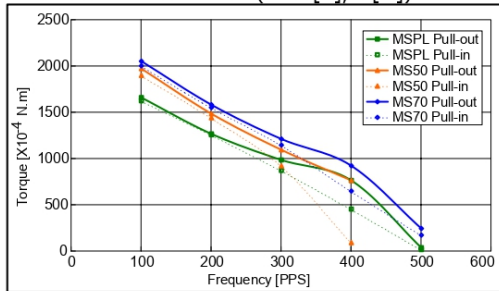
Motor Size	PM55L-048	
Number of Steps per Rotation	48(7.5°/Step)	
Drive Method	2-2 PHASE	
Drive Circuit	UNIPOLAR CONST. VOLT.	BIPOLAR CHOPPER
Drive Voltage	24[V]	24[V]
Current/Phase		800[mA]
Coil Resistance/Phase	30[Ω]	5.5[Ω]
Drive IC	2SC3346	UDN2916B-V
Magnet Material	Ferrite plastic magnet (MSPL) Polar anisotropy ferrite sintered magnet (MS50) Nd-Fe-B bonded magnet (MS70)	
Insulation Resistance	100M[Ω] MIN	
Dielectric Strength	AC 500[V] 1[min]	
Class of Insulation	CLASS E	
Operating Temp.	-10[°C] ~ 50[°C]	
Storage Temp.	-30[°C] ~ 80[°C]	
Operating Hum.	20[%] RH ~ 90[%] RH	

### Applications

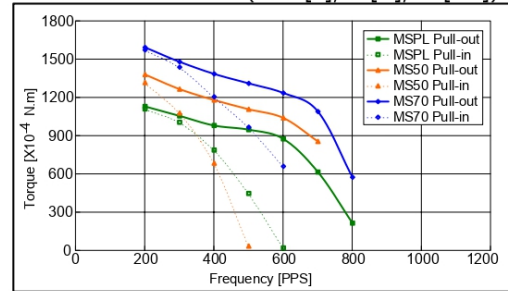
- OA Equipment : Printers / Scanners
- Industrial equipment : Flow control valves
- Toys : Slot machines
- Home automation appliances : Sewing machines

### Torque Characteristics

PM55L-048 UNI-CONST. V (at 24[V],30[Ω])

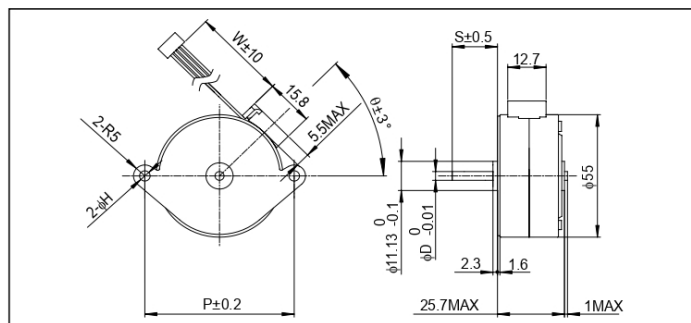


PM55L-048 BI-CHOPPER (at 24[V],5.5[Ω],800[mA])



These torque values are reference only. Heat radiation conditions and temperature rise effect by duty are different on each equipment, therefore please select motors after considering the heat conditions in the actual equipment.

### Dimensions



If you would like to know this Dimensions(D,S,W,θ), Please see Stander Dimensions in our Home Page.

Figure A.1 – Stepper motor datasheet.

## Aerograph instruction booklet

<b>■ SPECIFICATIONS</b>	182
Nozzle diameter:	0.3mm-0.5mm-0.8mm
Fluid Cup capacity:	22cc

**■ APPLICATIONS**  
Commercial arts, illustrations, photo retouching, hobby and crafts.

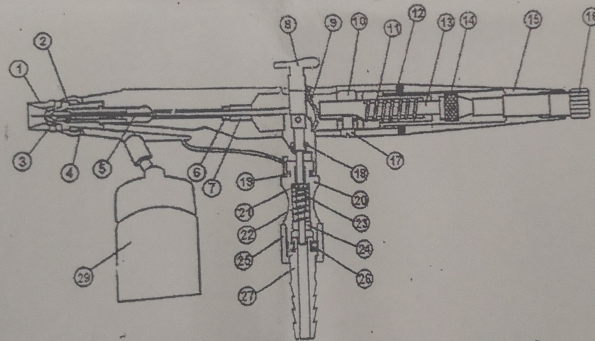
**■ HOW TO SPRAY**

1. Fill fluid in the cup after thinning appropriately.
2. Hold the airbrush lightly in your hand.
3. By pressing the main lever, a stream of air emerges. Then draw it backward gradually for Color atomization.
4. The spray pattern is in accordance with the distance between a work surface and a air brush.
5. For fine line spray, remove the needle cover and hold the air brush near a work surface.

**■ MAINTENANCE**

1. Empty the fluid cup and wash with water or solvent by a brush.
2. Refill cup with water or solvent, then block the needle cover with a finger and spray. The air flows backward into nozzle to clean the paints remained the air brush.

### AIRBRUSH MECHANISM



#### Parts Name

1. Needle Cap
2. Needle Cap
3. Needle
4. O-Ring for Needle Cap
5. Needle
6. O-Ring for Needle Guide
7. Needle Guide
8. Operation Lever
9. Lever Guide
10. Stopper
11. Spring
12. Spring Case
13. Needle Chucking Guide
14. Needle Chucking Nut
15. Standard-Handle Adjusting
16. Adjusting Screw
17. Guide Screw
18. Lever Guide O-Ring
19. Valve O-Ring
20. Valve Body
21. Valve Rod O-Ring
22. Valve Rod
23. Valve Spring
24. Valve Screw
25. Hose Connector Nut
26. O-Ring for hose Connector
27. Hose Connector
28. Nozzle Spanner
29. Color jar

### PARTS DETAILS

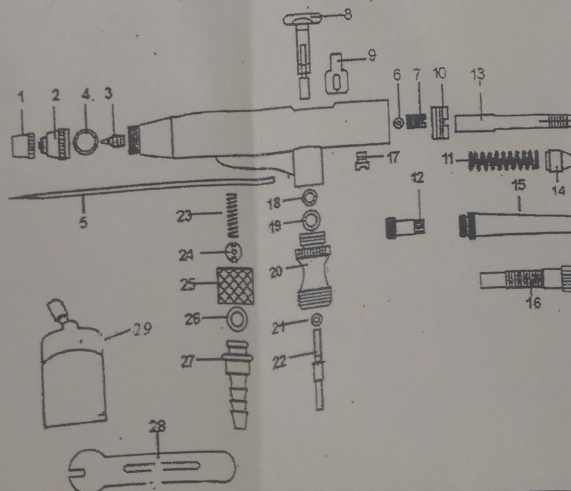


Figure A.2 – The gun nozzle datasheet.

**TOSHIBA**

ULN2803,04APG/AFWG

TOSHIBA Bipolar Digital Integrated Circuit Silicon Monolithic

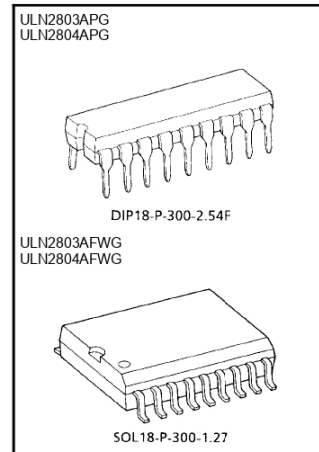
**ULN2803APG, ULN2803AFWG, ULN2804APG, ULN2804AFWG**  
(Manufactured by Toshiba Malaysia)

8ch Darlington Sink Driver

The ULN2803APG / AFWG Series are high-voltage, high-current darlington drivers comprised of eight NPN darlington pairs. All units feature integral clamp diodes for switching inductive loads. Applications include relay, hammer, lamp and display (LED) drivers. The suffix (G) appended to the part number represents a Lead (Pb) Free product.

**Features**

- Output current (single output) 500 mA (Max.)
- High sustaining voltage output 50 V (Min.)
- Output clamp diodes
- Inputs compatible with various types of logic.
- Package Type-APG : DIP-18pin
- Package Type-AFWG : SOL-18pin



Weight  
DIP18-P-300-2.54F: 1.478 g (Typ.)  
SOL18-P-300-1.27 : 0.48 g (Typ.)

**Pin Connection (top view)**

Type	Input Base Resistor	Designation
ULN2803APG / AFWG	2.7 kΩ	TTL, 5 V CMOS
ULN2804APG / AFWG	10.5 kΩ	6-15 V PMOS, CMOS

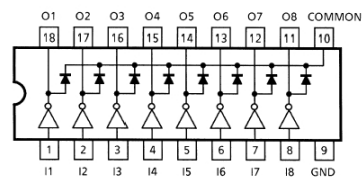


Figure A.3 – ULN2803a datasheet.

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# NOTATIONS

SP	Spray Pyrolysis
MCU	Microcontroller
PIC	Peripheral Interface Controller
LCD	Liquid Crystal Display.
ICSP	In-Circuit Serial Programmer