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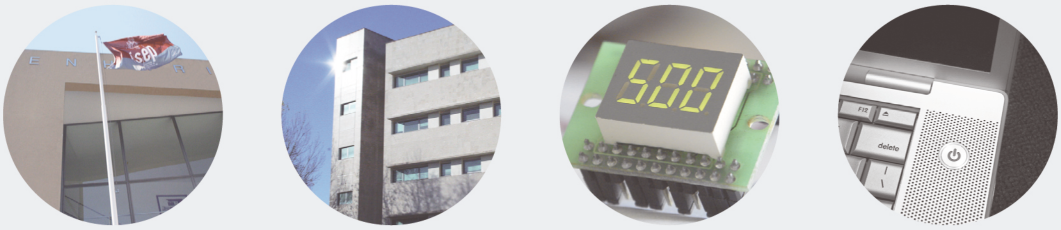

Design of a machine for the production of composite prepregs

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DESIGN OF A MACHINE FOR THE PRODUCTION OF COMPOSITE PREPREGS

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Relatório elaborado para satisfação parcial dos requisitos da Unidade Curricular de Tese/Dissertação do Mestrado em Engenharia Electrotécnica e de Computadores

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Abstract

The mechanical properties of materials are crucial in the creation of new technologies. The search for new, lighter, and more versatile materials, such as polymeric matrices, has led to the creation of new technologies to produce these materials. This study reflects in the development of a machine for producing composite materials of thermoplastic matrix. This material imposes challenges in its production, such as temperature control and processing speed.

The aim of the work is to design a machine for producing pre-impregnated composites. To this end, the main objectives are the selection of the necessary components, control and monitoring of process parameters and the acquisition and transmission of information to a computer.

After briefly analysing the process and its main parameters, various technologies are selected for temperature and speed control. Regarding temperature, thermocouple sensors are needed to read the temperature values in the thermoplastic processing range. Resistive heating elements are also used to provide heat to the system to reach the processing temperatures. To produce the material, a motor is needed to pull the fibres through the molten thermoplastic matrix. This material, in its plastic state, has high viscosity and therefore requires the use of a geared motor in order to obtain a high pulling torque.

Production is controlled by a microcontroller that interacts with the different components of the system. A computer application is also implemented which allows the process setpoint values to be entered and allow remote control via Bluetooth communication between the computer and the microcontroller. The machine developed fulfils the requirements proposed for the solution.

Keywords

Composite materials, composite prepregs, thermoplastics, temperature, thermocouple, control, bluetooth

Resumo

As propriedades mecânicas dos materiais são cruciais na criação de novas tecnologias. A procura por novos materiais mais leves e versáteis, tais como as matrizes poliméricas, promovem a criação de novas tecnologias para a produção destes materiais. Este estudo reflete-se no desenvolvimento de uma máquina para produção de materiais compósitos de matriz termoplástica. Este material impõe desafios na sua produção como é o caso do controlo de temperatura e velocidade de processamento.

Como objetivo do trabalho pretende-se realizar o projeto da máquina de produção de compósitos pré-impregnados. Para tal, são definidos como principais objetivos à sua concretização a seleção dos componentes necessários, o controlo e monitorização dos parâmetros do processo e a aquisição e transmissão de informação para um computador.

Após uma breve análise do processo e dos seus principais fatores, são selecionadas diversas tecnologias para o controlo de temperatura e velocidade. Relativamente à temperatura, são necessários sensores termopares para efetuar a leitura dos valores de temperatura na gama de processamento dos termoplásticos. Também são utilizados elementos resistivos de aquecimento que proporcionam calor ao sistema de forma a atingir as temperaturas de processamento. Para produção do material é necessário um motor capaz de puxar as fibras pela matriz termoplástica derretida. Este material no estado plástico apresenta uma elevada viscosidade e como tal é necessária a utilização de um motor redutor de forma a obter um elevado binário.

O controlo da produção é feito através de um microcontrolador que interage com os diferentes componentes do sistema. Também é implementada uma aplicação de computador que permite a introdução dos valores de setpoint do processo e um controlo remoto disponível através de uma comunicação bluetooth entre o computador e o microcontrolador. A solução desenvolvida cumpre com os requisitos propostos para a solução.

Palavras-Chave

Materiais compósitos, pre-impregnados, termoplásticos, temperatura, termopar, controlo, bluetooth

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Acronyms

AC – Alternating Current

ADC – Analog-to-Digital Converter

DC – Direct Current

emf – Electromotive force

GPIO – General Purpose Input Output

I^{2}C – Inter-Integrated Circuit

LED – Light Emitting Diode

NTC – Negative Temperature Coefficient

PTC – Positive Temperature Coefficient

PID – Proportional Integral Derivative

PD – Proportional & Derivative

PI – Proportional & Integral

RPM – Revolutions per Minute

RTD – Resistance Temperature Detector

SPI – Serial Peripheral Interface

SRAM – Static Random Access Memory

SSR – Solid-State Relay

UART – Universal Asynchronous Receiver/Transmitter

VFD – Variable Frequency Driver

1. INTRODUCTION

This document describes the research work carried out to the realization of the project proposed - Design of a machine to produce composite prepregs. In order to carry out this project an introduction to the manufacture process is necessary to introduce concepts and objectives to comply.

1.1. CONTEXTUALISATION

The mechanical properties of material are preponderant in the performance of structures when submitted to mechanical stresses. The need to create lightweight structures with good mechanical properties has led to the creation of innovative materials such as polymer matrix composites. More recently, thermoplastic matrix composites have greater interest due to the possibility of being recycled.

The manufacture of thermoplastic composites requires process control, using efficient monitoring and control systems to guarantee the desired material properties. This new generation of composite materials further reinforces the need for process control in order to provide versatile and user-friendly solutions.

1.2. OBJECTIVES

The aim is to design and develop a machine for the manufacture of continuous fibre prepregs with thermoplastic matrix. In this context, the following objectives can be established:

1. Selection of components.

2. Control and monitoring of production process parameters.

3. Data acquisition and transmission

Firstly, is necessary to study and understand the manufacturing process in order to figure out which are the main parameters to monitor and control. Then, it is necessary to select the sensors, controllers and other components which will be part of the production machine developed.

The second objective aims to create and develop a system capable of monitoring and controlling the process parameters.

Finally, as a third goal, it is intended that the process parameters can also be changed by the user of the equipment. This also allows versatility and adjustability of the process according to the specifications desired for the composite material produced. It is also interesting to make the data acquired during the production process available for later analysis.

1.3. SCHEDULING

In order to achieve the proposed objectives, a division of work was carried out, resulting in the timetable shown in Table 1. Initially is studied the manufacturing process and control strategies, then project and develop of the proposed solution. Finally, tests were carried out to validate the solution.

Table 1 – Project Schedule.

Task	SEP		OCT		NOV		DEC		JAN		FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP	
Documentation & process study	🟥	🟥	🟥	🟥	🟥																					
Solution project					🟥	🟥	🟥		🟥	🟥																
Solution development									🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥	🟥	🟥	🟥	🟥				
Validation Tests															🟥	🟥	🟥	🟥	🟥	🟥		🟥				
Report			🟥	🟥	🟥	🟥		🟥	🟥	🟥	🟥	🟥	🟥				🟥	🟥	🟥	🟥	🟥	🟥		🟥	🟥	🟥

1.4. REPORT ORGANIZATION

The work resulting from this project is described throughout several chapters, each of them dedicated to the explanation of different stages of the project developed. The first chapter provides a brief contextualisation of the scope of the project as well as the structure and organisation of the report concerning the work carried out.

The next chapter, State of Art, consists in the description and analysis of the process to produce prepreg composite materials. From this chapter comes an understanding of the process and its requirements. It also describes the most important parameters to monitoring and control the system. This allows to outline a strategy for the development of the desired solution.

The third chapter, System Architecture, presents the different modules that make up this project. Four modules are listed and the function of each explained.

Then, in chapter four, Prototype, the technologies used in each of the modules described in the system's architecture are defined. The technologies used for monitoring the system and actuator are presented and explained.

The fifth chapter, Results, provides the results obtained from the various system configuration tests. First, the results of the system temperature characterisation tests are presented. Them, the results from the motor speed control and finally the application developed for data visualisation.

The final chapter, Discussion & Conclusion, describes the conclusions drawn from the project and future improvements.

2. STATE OF ART

Understanding the production process of prepreg composite materials allows to define the key parameters to monitor and control so that the final product is of good quality. This chapter provides a brief description of such process and lists some parameters that influence the product outcome.

2.1. COMPOSITE MATERIALS

A composite material can be defined as a combination of two or more materials with different properties which together produce a single material. This results in better mechanical properties of the material compared to the individual characteristics of each of its component [1]–[3]. An example of a composite material are the carbon fibre components often found in the automotive and aeronautics industries.

These components are formed from a pre-impregnated material, or prepreg, which consists in a mixture of fibres and polymer. There are various types of fibres such as carbon, glass, and aramid. These reinforcement materials are responsible for supporting the applied loads to the material and establish mechanical properties such as rigidity, hardness, and mechanical resistance. Meanwhile, the polymer is responsible to fill empty spaces between the reinforcement fibres and can also be from different composition. The most common ones are thermosets and thermoplastics [1]–[3]. This project focuses on the use of thermoplastics for the production of composite materials as this polymer can be recycled whereas thermosets cannot [3-5].

2.2. MELT IMPREGNATION

From a mixture of reinforcement fibres and polymer results a pre-impregnated material, or prepreg. It is characterised as a semi-finished product since it is used as raw material for the construction of composite components and structures.

One of the biggest challenges in this manufacturing process is to achieve a good degree of polymer impregnation in the fibres. The melt impregnation is one of the simplest production techniques regarding fibre impregnation. There are different techniques regarding the melt impregnation process, however, here will only be described the one addressed in this project which is based on continuous pultrusion.

The continuous pultrusion method consists in unrolling a fibre spool which is lead to a melt polymer pool, as represented in Figure 1.

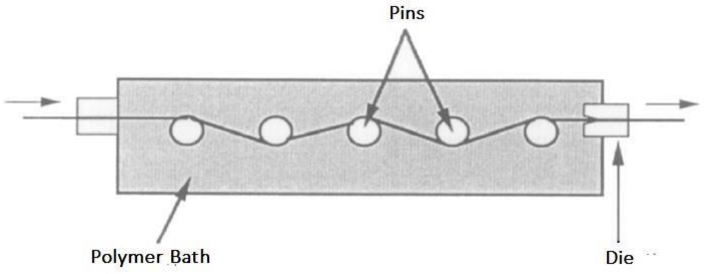


Figure 1 - Melt Impregnation process (adapted from [6])

The polymer pool consists of melted thermoplastic and has several pins which define the path taken by the fibres. These pins are used to increase the permeability of the impregnation of polymer through the fibres since there is more exposure area of fibres to the polymer. Finally, the impregnated fibres pass through a die responsible for the consolidation of the prepreg and give a desired shape. The final product consists in a unidirectional tape that can be applied in many industries [7]–[9].

2.3. PROCESS PARAMETERS

Each prepreg impregnation technique has several parameters worth considering evaluating to study and control the manufacturing process. Regarding hot melt thermoplastic impregnation there are different stages responsible for applying distinct techniques in the manufacturing process. Each stage of the processes has its particularities. Firstly, there are the fibre tow velocity and tension to consider. Then, the temperature for thermoplastic melt and the size of wedge slit die [4]. There are other parameters worth considering especially when a different method of prepreg impregnation is implemented.

2.3.1. TEMPERATURE

temperature is a relevant parameter on the processing of thermoplastic matrix. Each thermoplastic has different viscosities and processing temperatures. This way, the impregnation degree is directly associated with thermoplastic temperature [5].

The high viscosity associated with thermoplastics makes it difficult to impregnate the fibres [5]. Temperature and viscosity are two proprieties that are intimately related, higher temperatures decrease the viscosity of a material [5], [6]. That way, higher temperatures will be associated with lower viscosities hence better impregnation [5], [6]. However, this is not always the case. There is a limit for maximum heating temperature since the polymer at very high temperatures starts to degrade [5]. This thermal degradation reduces the mechanical properties of the material decreasing the overall quality of the final composite produced.

There are several techniques to monitor and control the temperature in the impregnation die. One can be through heating the chamber, controlling the overall temperature in the chamber [6]. Another reported technique consists in temperature control on the impregnation pins [5]. This technique resumes in a configuration like the one represented on Figure 2.

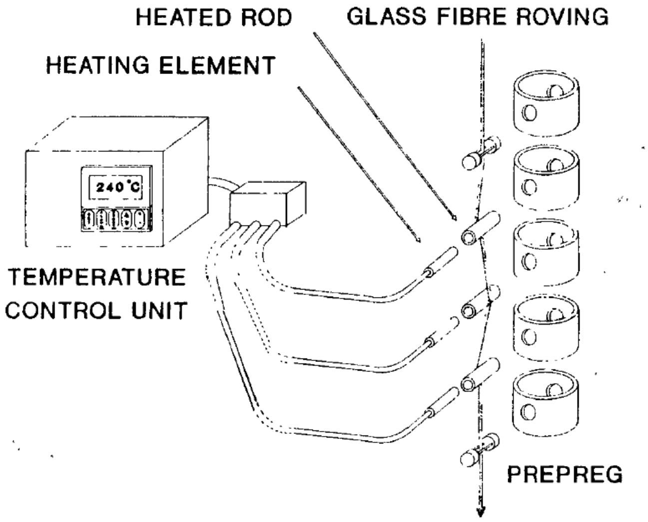


Figure 2 - Melt impregnation die with heated pins [5].

In this particular case, the temperature in the heated rods can be controlled and achieve a different temperature than the chamber where they are confined. The higher temperatures reached by these pins can improve, slightly, the degree of impregnation [5]. Moreover, in this configuration it was determined that the speed also influenced the degree of impregnation [5]. This way, the relation between the distinct process parameters is made evident.

2.3.2. SPEED

Like other industrial processes the speed is an important parameter to consider. In industry, the speed of a process is an added value. Inherently the process time has also influence in the degree of impregnation. The fibre tow speed and the processes time affect the degree impregnation since a melted polymer is a fluid with high viscosity. As a result, there has to be time for the melted polymer to penetrate the fibres. Research shows that an increase in impregnation time is beneficial to enhance the degree of impregnation [5], [6]. In the same way, a decrease in speed would achieve the same results since tow speed and impregnation time are inversely proportional. Figure 3 establishes the relation between degree of impregnation and impregnation time.

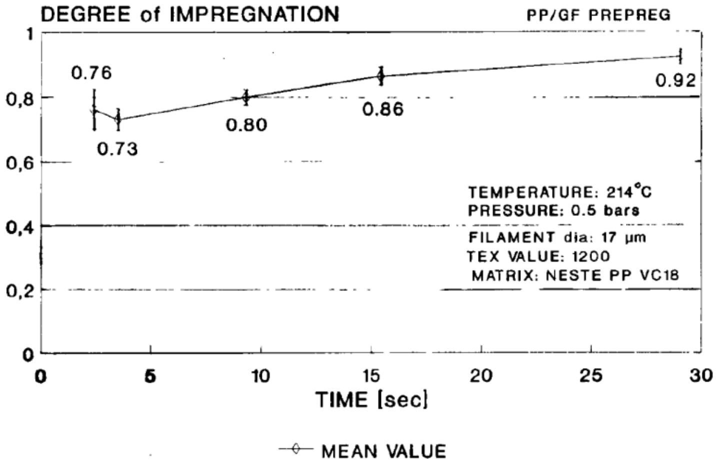


Figure 3 - Impregnation degree as a function of impregnation time [5].

Regarding the configuration previously represented in Figure 2, where it is evaluated the hypothesis of temperature control in the rods, it is established a relation between temperature and speed. In order to achieve higher impregnation degree there had to be a decrease in speed. However, when compared to the rods temperature influence on the impregnation, speed is more effective in increasing the degree of impregnation [5].

Considering temperature and process speed it can be concluded that an increase in speed must be accompanied with an increase in temperature otherwise, the impregnation degree will be compromised [5], [6].

In addition, there is a relation between the degree of impregnation and the number of rods [6].

2.3.3. PINS

The number of pins can influence the degree of impregnation of the fibre tow. The pins are responsible for imposing path changes on the fibre, which facilitate the impregnation of the polymer into the fibres. This is represented in the schematic of Figure 4.

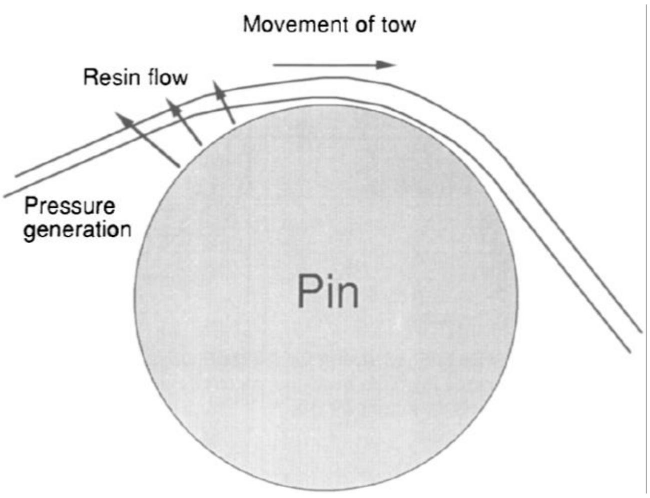


Figure 4 - Impregnation mechanism using pins [7].

The melted polymer entrained between the fibre tow and the pin generates a pressure which drives to a more efficient impregnation [7]. To that extend, the degree of impregnation is improved when using more pins [8]. This also implies a more uniform impregnation of polymer in the fibres [7]. The number of pins is directly related to the cumulative contact surface. Regarding this, an increase of the cumulative surface length reflects in an improvement degree of impregnation [5], [8]. Such relation is represented in Figure 5.

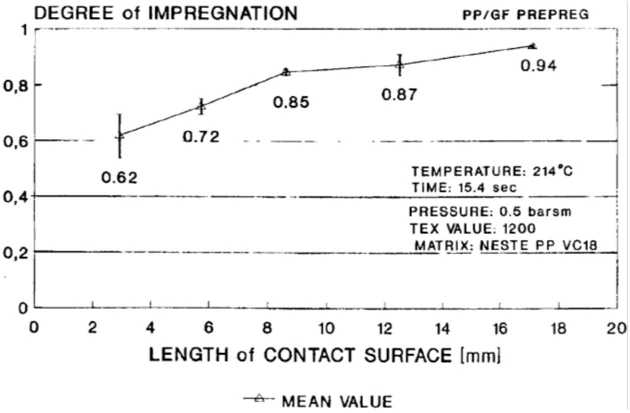


Figure 5 - Degree of impregnation as function of cumulative contact surface length [5].

The use of pins also presents another advantage, it is possible to manipulate the cross-section of the fibre tow. The addition of side guides or grooves in the rods can be beneficial to achieve better impregnation since, these shapes help redistribute the melted polymer [7], [8].

Other thing to consider is the dimension of the pins. The pins impose tension on the fibre which can cause damage if the impregnation pins dimensions are inadequate [7]. A small diameter of the impregnation pins could split off or even break some fibres [4].

Considering this, pressure also plays an important role on the impregnation degree.

2.3.4. PRESSURE

The pressure on the impregnation cavity can influence the degree of impregnation. The pressure acts on the polymer impregnation through the compression on the fibres. An increase in pressure results in a higher compression between fibres, decreasing the permeability of the fibre tow and preventing effective penetration of molten polymer through the fibres [5]. In Figure 6 is represented the degree of impregnation as a function of the pressure in the impregnation chamber.

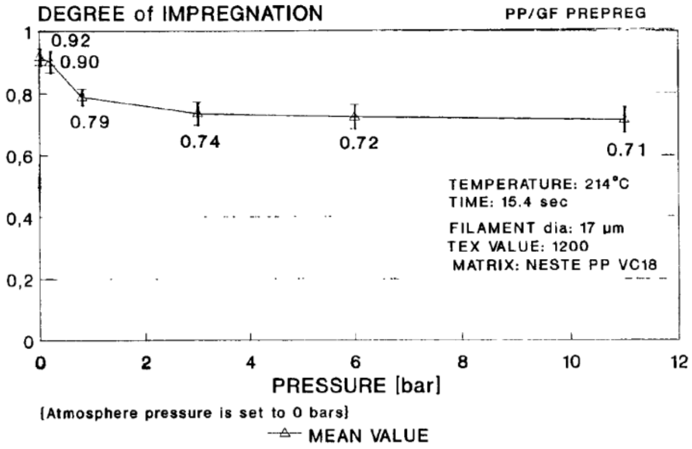


Figure 6 - Degree of impregnation as a function of pressure of molten polymer [5].

Other parameter that has some influence on the degree of impregnation is the tension on the fibre tow.

2.3.5. TENSION

The tension on the fibre tow can be imposed by breaking the spool of fibres. The presence of impregnation pins and the friction between molten polymer and the fibre tow already enforce tension on the fibres [5]. Prepreg tension can improve the degree of impregnation by 16% [5]. In Figure 7 is represented graphically the influence of the fibre tow tension on the degree of impregnation.

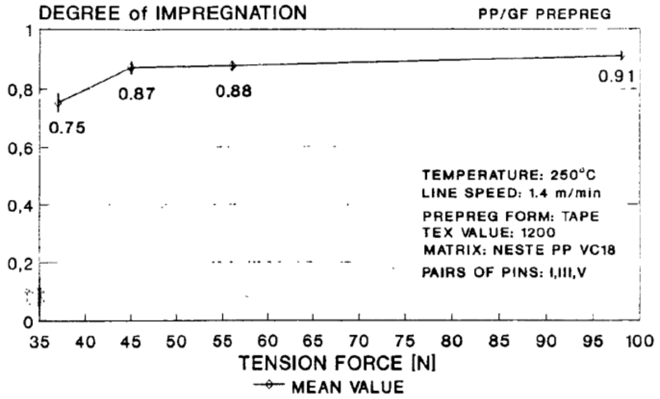


Figure 7 - Influence of prepreg tension on the degree of impregnation [5].

A higher tension reflects on a higher degree of impregnation. The elevated tension flattens out the fibre tow against the impregnation pins. This phenomenon has two advantages for impregnation. First, the flattening of the fibres allows for a better impregnation of the molten polymer. Then, the elevated tension increases the pressure gradient in the impregnation pin as previously represented in Figure 4. The molten polymer can easily impregnate the fibre tow with this increase in the gradient pressure and the decrease in fibre tow thickness [5].

Each of these parameters can be monitored to control prepreg manufacture process. The acquisition of data also benefits to understand and improve the process in order to achieve higher quality prepreg.

2.4. SENSORS

In order to monitor the process parameters, it is necessary to use sensors. These devices are responsible to acquire physical data and transform it to another physical parameter. For instance, read the ambient temperature and convert it to an electric parameter such as voltage or current. When it comes to monitoring and control of a process, the sensors enable data acquisition for the control unit extolling the importance of these devices.

There are various sensors with distinct capabilities. They differ according to the conversion of physical parameters hence care must be taken when choosing a sensor. Furthermore, sensors can be classified as active or passive [9]. Active sensors are characterized for generating voltage or current from the physical phenomenon being measured. Conversely, passive sensors require electrical energy to convert the physical parameter to a passive electrical quantity such as capacitance, resistance or inductance [9].

2.4.1. TEMPERATURE SENSORS

Regarding temperature monitoring, there is a variety of sensor options with different characteristics that are suitable for distinct circumstances [10]. Each type of sensor uses different technologies to acquire the temperature measurement. They can vary from a simple ON/OFF device to a sensitive semiconductor that detects any physical change of temperature. Regarding this, there has to be some clarification on the different types of sensors. The focus will be on the sensors that are most used at the industry level for applications as injection, pultrusion and, extrusion in composite manufacture.

2.4.1.1. THERMISTOR

To begin there are the thermistors, which are very small and generally made from ceramic semiconductor materials [10], [11]. The semiconductor is formed into small pressed discs or balls, like the one represented in Figure 8, which are hermetically sealed to give a relatively fast response to any changes in temperature.

These sensors consist in a thermal sensitive resistor that changes its electrical resistance when exposed to changes in temperature [10]–[12]. They can either be a negative temperature coefficient of resistance (NTC), their resistance values go down with an increase in the temperature, or a positive temperature coefficient of resistance (PTC) when their resistance value goes up with an increase in temperature [12].

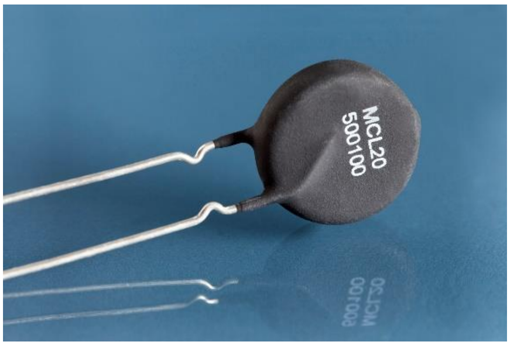


Figure 8 – Thermistor [13].

It is noteworthy that thermistors are passive devices which means they need to be in an electric circuit with current passing through to produce a measurable output. They are usually allocated to overheat protection since their main advantages are their speed of response to any changes in temperature, sensitivity and small size [10], [12].

As disadvantages it has to be pointed that thermistors are non-linear devices [10]–[12], [14]. In Figure 9 is represented a comparison between thermistor and other temperature sensors, resistance temperature detector and thermocouple.

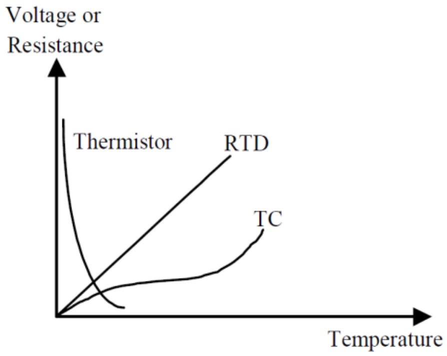


Figure 9 - Linear characteristic comparison between thermistor, resistance temperature detector and thermocouple [11].

Furthermore, thermistors are prone to overheating itself incurring in temperature measurement errors [10].

2.4.1.2. RESISTANCE TEMPERATURE DETECTOR

There is another sensor, the resistance temperature detector (RTD), that is similar to the thermistor in that it also varies electrical resistance with temperature changes [10], [12]. However, has a different composition, it is made from conducting metals such as copper, nickel, and platinum. With an increase in temperature, these metals will be less electric conductive which means that the electrical resistance increases [10], [12].

Also, an RTD is a passive sensor which means it requires current excitation to produce an output voltage [12], [14]. This will incur in an increase in overall energy consumption of the process. In Figure 10 is represented an RTD.

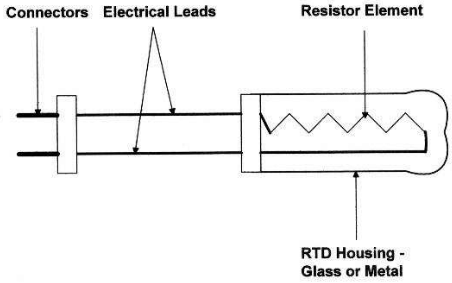


Figure 10 - Resistance Temperature Detector.

RTD sensors are characterized for its linearity, good sensibility, and repeatability [11], [12], [14]. The different metals constituent of RTD have different working ranges that truly approximate the resistance/temperature relation to a linear characteristic. The most common being Platinum with a working range between -270°C and 1000°C, Copper (-200°C to 260°C), Nickel (-200°C to 430°C) and Tungsten (-270°C to 1100°C). In Figure 11 is represented the typical resistance/temperature characteristic of the previous mentioned metals.

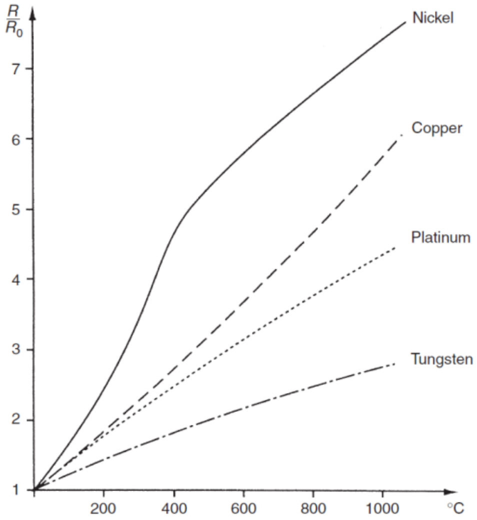


Figure 11 - Typical resistance/temperature characteristic of metals [10].

However, RTDs have some restrictions like the inability to measure temperature near fusion temperature and sensor overheating situations. It is important to take into account the electronic circuit so it doesn't overheat as this can cause erroneous sensor readings [14]. Moreover, these sensors usually are more expensive than other temperature sensors [12]. There is also greater susceptibility of the sensor due to oxidation and corrosion limiting sensor accuracy and longevity [10].

2.4.1.3. THERMOCOUPLE

There is another type of sensor, the thermocouple, widely used in the industry due to its simplicity, ease of use and speed of response. This sensor also has a wide temperature range from below -200 °C and over 2000 °C [10], [14]. Thomas Seebeck stated that when two wires composed of dissimilar metals are joined at both ends and one of the ends is heated it causes a voltage difference in the thermo-electric circuit [10], [12]. Hence these sensors are characterized as active sensors. In Figure 12 is represented a thermocouple.

Figure 12 – Thermocouple [15].

A thermocouple consists in two different metals that produce a voltage as a function of the differential temperature of the two junctions. One junction is defined as reference since it has a constant temperature while the other junction is subjected to the intended environment to measure. Each junction, composed by different metals, is in different temperatures so that creates a difference in voltage between the junction's resultant from the Seebeck effect. It is noteworthy that the measured voltage depends on the material of the junctions as well as the temperatures of both junctions [12], [16].

Since thermocouples are composed by two distinct metals there are different combinations which result in different temperature range, environment, and calibration. Each combination of metals can be denominated by letter such as type N, T, E, J and K thermocouples, which are the most common ones [10], [12], [14]. The choice of thermocouple type rests with the application requisites such as temperature range, chemical, abrasion and vibration resistance as well as installation requirements. Table 2 summarizes some characteristics of a few thermocouple types.

Table 2 - Thermocouples characteristics [10], [14].

TYPE	TEMPERATURE RANGE (°C)	SENSITIVITY (µV/°C)	CONDUCTOR ALLOYS
K	-180 to +1300	41	Chromel & Alumel
J	-180 to +800	55	Iron & Constantan
N	-270 to +1300	39	Nicrosil & Nisil
R	-50 to +1700	10	Platinum (13%) & Rhodium
S	-50 to +1750	10	Platinum (10%) & Rhodium
B	0 to +1820	10	Platinum (6%) & Rhodium (30%)
T	-250 to +400	43	Copper & Constantan
E	-40 to +900	68	Chromel & Constantan

The thermocouples have the particularity of measuring the temperature differential between the two junctions, not the absolute temperature. In order to determine the absolute temperature, the cold junction must be maintained at 0 °C. However, this method is not practical since it is difficult to maintain this temperature in some engineering applications with hot environments [10].

The alternative is to place the two junctions in equal ambient temperature. This way it is possible to determine the absolute temperature at the hot junction after measuring the temperature at the cold junction using the law of intermediate temperatures. This law states that additional thermojunctions, that are at the same temperature, will make no net contribution to the total thermoelectric electromotive force (e.m.f.) of the system, as represented by Equation (1) [10], [14].

$$E_{(T_h,T_0)} = E_{(T_h,T_r)} + E_{(T_r,T_0)} \tag{1}$$

Where $E_{(T_h,T_0)}$ is the e.m.f. with junctions at T_h (hot-junction temperature) and T_0 (0°C), $E_{(T_h,T_r)}$ is the e.m.f. with junctions at T_h and T_r (nonzero reference junction temperature) and $E_{(T_r,T_0)}$ is the e.m.f. with junctions at T_r and T_0 [10].

For temperature measurement at the reference junction an RTD or thermistor can be used since the temperature will be lower and it is important.

2.4.1.4. TEMPERATURE SENSORS COMPARISON

When choosing the right temperature sensor for the prepreg manufacture process there are some sensor characteristics to consider between thermistors, RTDs and thermocouples. In Table 3 are compared some characteristics between these temperature sensors.

Table 3 - Comparison between thermocouples, RTD and Thermistor [10], [17]

	THERMOCOUPLE	**RTD & THERMISTOR**
RANGE	-200° to 1250°C (Type K)	-200° to 500°C
RESPONSE TIME	Very fast	Fast
DURABILITY	Very long	Long
ACCURACY	1 °C	0,1 °C
LINEARITY	Over specific range	Over wide range
COST	€	€€€

Firstly, the temperature range of the sensor must be adequate for the application and the sensor itself has to withstand the ambient temperature where it will be installed. Regarding this, thermocouples are the most appropriate sensor since they have the widest range of measure. The other previously mentioned sensors can also measure in the expected range (200 °C to 300 °C). However, RTDs are the most sensitive to ambient temperature variations since they are subject to inaccuracies from self-heating. And thermistors are more accurate on a limited range of temperature.

Secondly, for better temperature control the response time from the sensor must be short. This allows a rapid response from the control unit to regulate the temperature through the actuators, responsible for varying the temperature. The thermocouple has a better response time when compared with RTDs or thermistors [17].

Finally, it is relevant to consider the cost of the sensor. This will depend on the type of final product and installation. In this regard thermocouples tend to be the most cost-efficient technology.

2.4.2. SPEED SENSOR

Speed can be monitored through the use of encoders. These devices can quantify position, angles, velocity, and other parameters. An encoder is an electro-mechanical device that can measure rotational or linear movement. Encoders can provide incremental or absolute information. The most common encoders rely on optical or electromagnetic effects [9], [18], [19]. In Figure 13 is represented an optical encoder.

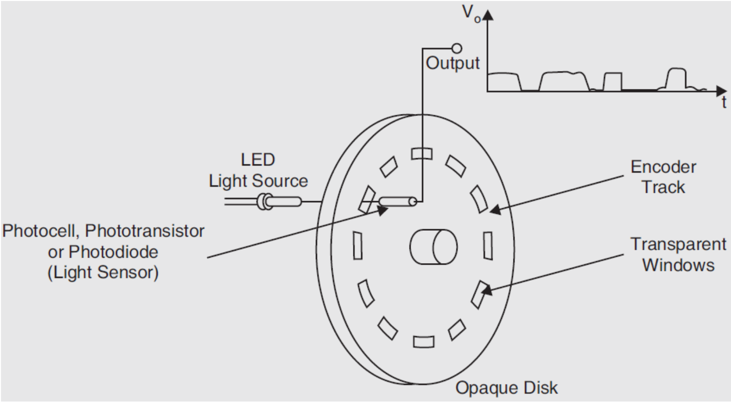


Figure 13 - Optical encoder [9].

The optical encoders consist in a light emitting diode (LED), a perforated disk and a phototransistor. The LED emits light to the phototransistor creating a constant signal in the phototransistor output. However, when the perforated disc is placed on the rotating shaft it disrupts the light beam between LED and the phototransistor. This way, the output of the phototransistor will be a pulse signal that will vary with position and velocity of the disc and consequently the rotating shaft [9]. In Figure 14 is represented the output signal from an encoder.

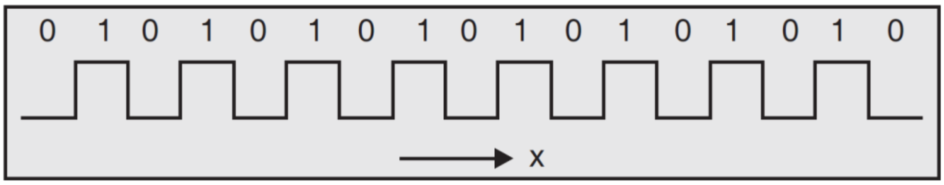


Figure 14 - Digital output from an encoder [9].

While the motion is in the same direction this method can provide a counter with the accumulated pulses to determine the displacement. However, if the motion changes direction it would produce identical pulses which result in errors [9]. In fact to consider the direction of rotation it is necessary another signal 90° offset resulting from the same perforated disc [9], [18], [19]. This allows to detect which signal rises first and consequently the direction of movement. A third output can produce a pulse to provide a zero reference [9]. These signals are represented in Figure 15.

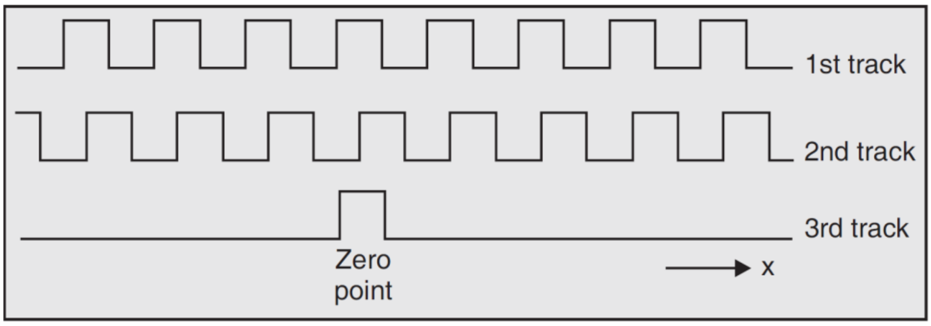


Figure 15 - Digital output form a 3-signal encoder [9].

Regarding the electromagnetic encoders there are the hall sensors. These sensors are sensitive to magnetic field variations. The output of these sensors is a potential differential whenever the magnetic field changes [9], [20]. The operating principle of these sensors is similar to the optical ones previously described.

It is noteworthy that there are two types encoding, incremental or absolute. The incremental gives the current position based on the previous one. Otherwise, the absolute encoding assigns a unique code to each displacement position. Therefore, the absolute encoders require more sensors than the incremental ones. In Figure 16 is represented a possible output from a four-track encoder.

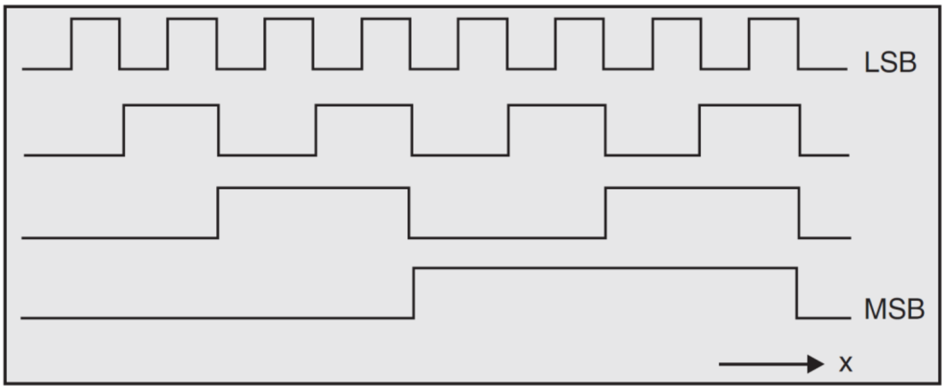


Figure 16 - Digital output from an absolute encoder [9].

These absolute encoders usually are limited to the measurement of a single revolution [9].

2.5. CONTROL

After the analysis of the process parameters and the respective sensors it is relevant to review the control strategies. A process control consists in a parameter observation, comparing it to a desired value and initiate a control action in order to match the desired value [11].

2.5.1. DEFINITION OF THE PROCESS CONTROL

One of the earliest registers of a process control is man's use of fire to maintain the temperature of the surrounding environment [11]. Temperature, position, pressure, and speed are some of several process control variables. These variables manipulate process parameters like temperature, mechanical position, motor speed and others. For each controlled variable there must be an associated manipulated variable [11].

A process control system must adjust the manipulated variables to the desired controlled variable value. This has to be accomplished independently of disturbances applied to the system [11]. Disturbance is an event that tends to drive the controlled variable away from the desired value. This can be changes in ambient temperature, electrical failure, measurement errors, and others [11].

There are four elements that form a control system, which are process, measurement, evaluation, and control. In Figure 17 is represented a block diagram of the elements of a control system.

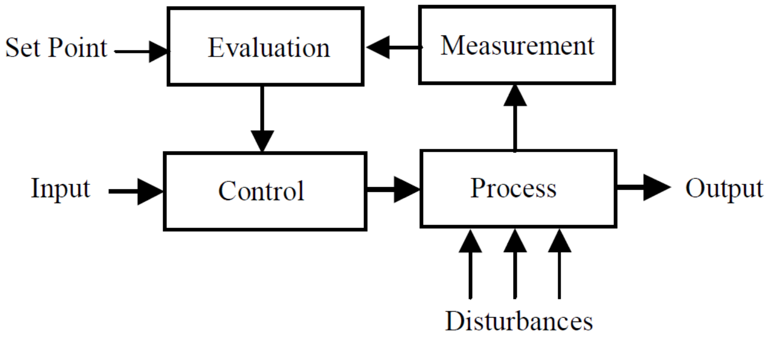


Figure 17 - Elements of a control system [11].

The process consists in the mechanical equipment and material that is related to the operation. Depending on the quantity and complexity of the operation it may involve several dynamic variables to be controlled. However, sometimes one variable can be sufficient to control the process within acceptable limits [11], [21].

The measurement element refers to the conversion of the process variables to analogue or digital signals that can be monitored by the control system. It is up to the sensors to acquire the dynamic variables and convert to valid information for the control system [11], [21].

The evaluation stage of the control process examines and compares the measurement value with the desired setpoint. It determines the corrective action needed to maintain the process control. This evaluation id performed by a controller. This device can be a pneumatic, electrical, mechanical or even a computer control system [11], [21].

Finally, there is the control element. It involves the devices that exert a direct influence on the process. These devices receive the controller command and transform it to the desired operation to be performed on the process. The devices can be electrical motors, heating elements, pumps, and other control elements [11], [21].

2.5.2. GENERAL REQUIREMENTS OF PROCESS CONTROL

The implementation of a control system meets the requirement to stabilize a system. This means that the control response must be fast and reduce the system error to zero or near zero

[11]. The system error is the difference between the value of the controlled variable setpoint and the value of the process variable [11], [21]. It can be expressed by the following equation:

$$e(t) = PV(t) - SP(t) \tag{2}$$

Where, e(t) is the system error, PV(t) is the process variable value, and SP(t) is the setpoint value all of which are functions of time (t) [11].

The system response is described as the ability of a control system to recover from a disturbance that causes a change in the controlled process variable [11]. As previously mentioned, the main purpose of a control system is to maintain the dynamic process variables at the desired setpoint [11]. This way it is essential to design a control system with a response adequate to the process.

A system response can be classified as underdamped or damped response. A underdamped system response is characterized by oscillations of the process variable between the setpoint after a disturbance in the process [11]. Such response is represented in Figure 18.

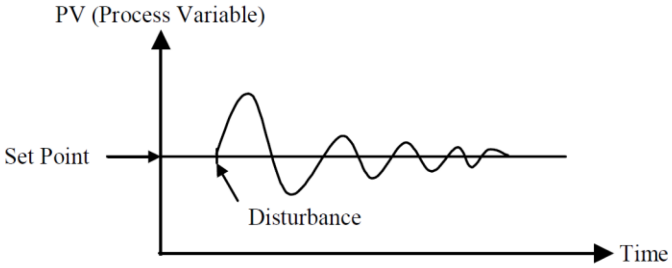


Figure 18 - Undamped system response to a disturbance [11].

On the other hand, when the system is able to return the process variable to the setpoint value without oscillations, it is a damped system response [11]. In Figure 19 it is represented a damped response to a system disturbance.

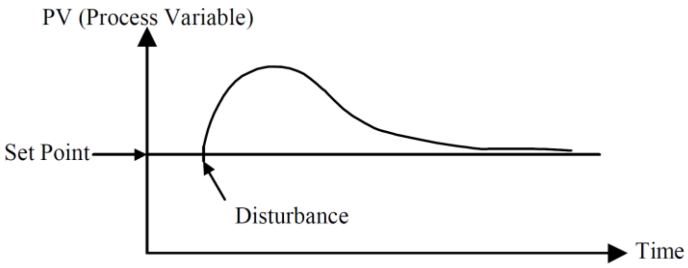


Figure 19 - Damped system response to a disturbance [11].

In order to evaluate the system response to an input change there are several criteria to analyse to achieve an effective system. The most common are settling time, maximum error, offset error and error area [11]. These criteria are represented in Figure 20.

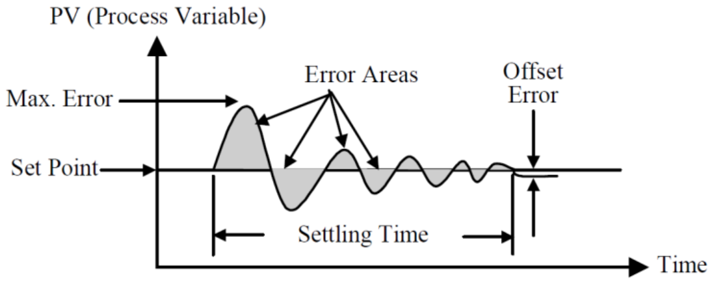


Figure 20 - Evaluation criteria of control system response [11].

Settling time is defined as the time the process control system needs to restore the process variable to the setpoint within an allowable error. Like the name says, maximum error is the maximum allowable deviation of the dynamic variable. An offset error can result from the linear or nonlinear qualities of the system preventing the process variable to return to the setpoint after the input change. Finally, the error area is the area between the response curve and the setpoint line [11].

There are several techniques to apply control in a system all of each having the same purpose, maintain the setpoint value and process variable value as close as possible.

2.5.3. ON/OFF CONTROL

The On/Off control method is a two-position control. It either is fully open (on) or fully closed (off) [11]. It can be compared to a valve which can only operate on two states, open or closed. This control is simple and easily implemented since it has only two states, however the efficiency of this control is beyond other methods of control.

Assuming that it is applied an On/Off control to a system to keep the temperature of a fluid constant at a determined setpoint. When the measured temperature is lower than the setpoint the control unit commands the system to rise the temperature. However, because of lag on temperature variation and the process itself having some dead time, the system response is delayed. This way the temperature continues to drop before responding to the command of the control unit. This phenomenon is represented in Figure 21.

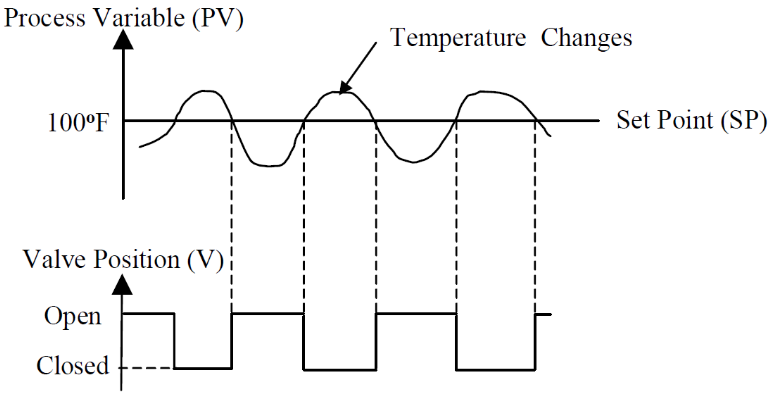


Figure 21 - On/Off temperature control [11].

When the temperature exceeds the setpoint the control unit inverts the command, disabling system heating to decrease its temperature. Again, the system response is delayed by the same reasons previously mentioned, adjusted to these conditions. This means, the temperature continues to rise before reverting by the control unit command. This cycle repeats when the temperature drops below the setpoint value.

The On/Off method is ruled by the Equation (2) , when the error (e) is positive there is an Off command, and an On command when (e) is negative, regarding the situation previously described [11]. This cyclical behaviour is characteristic to On/Off control method since the control is limited by only two options [11].

The control of the system can be smoother in a way that reduces the variance of system response like the one observed with On/Off control method.

2.5.4. PROPORTIONAL INTEGRAL DERIVATIVE (PID) CONTROL

Three mode control or Proportional Integral Derivative (PID) control combines three control functions, proportional, integral, and derivative [11]. This control method is widely present in the industry. Its success can be justified by three reasons: past success, wide availability and simplicity in use [21].

The control actions, proportional, integral, or derivative are used in the control system depending on the characteristics of the process to control. In Figure 22 is represented a symbolic representation of the three terms. Each one can achieve different control actions on the process [21].

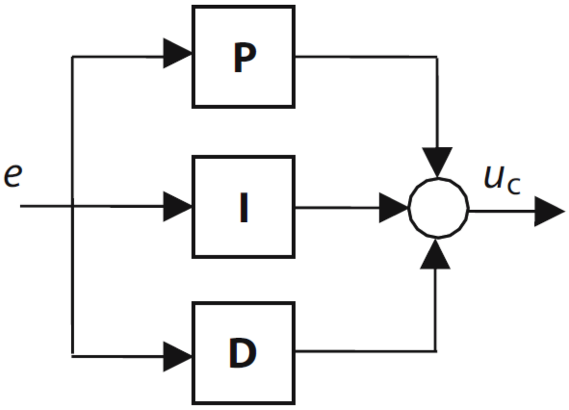


Figure 22 - PID controller representation [21].

Regarding Figure 22, e is the process error input to the controller, u_c is the controller output, P is the proportional term, I the integral one and D the derivative term.

2.5.4.1. PROPORTIONAL CONTROL

The proportional component of a PID controller is responsible to establish a proportional response to the system error. This response fallows the change in error and deviation from the setpoint proportionally. This proportional control can be described by the next equation:

$$u_c(t) = K_p e(t) \tag{3}$$

Where $u_c(t)$ is the controller output, e(t) is the process error input to the controller and, K_p is the proportional gain.

From Equation (3) it is possible to understand that when ($K_p = 1$) the controller output follows the error change in a one-to-one ratio. A low gain ($K_p < 1$) would result in a change in control when a large error change occurs. Contrarily, a high gain ($K_p > 1$) is reflected in control changes responding to small error changes. However, the gain (K_p) cannot be increased indefinitely, otherwise the control system becomes unstable [11].

The proportional control has some limitations. Proportional control is unable to keep the process variable at the setpoint if the process is frequently disturbed [11]. Other thing to consider is that it introduces an offset error to a step response as represented in Figure 23 [22].

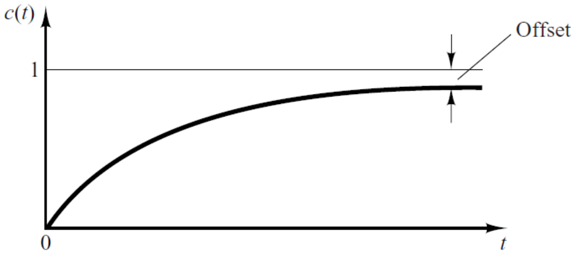


Figure 23 - Unit-step response and offset of a proportional controller [22].

The offset results form the difference at steady state between the desired setpoint and the actual controlled value. This is due to the absence of an integrator controller [11], [22].

2.5.4.2. INTEGRAL CONTROL

Integral control consists in the integration of the input error signal over a very small time period [11]. The integral control action changes the value of the controller output ($u_c(t)$) at a rate proportional to the actuating error signal (e(t)) [11], [22]. The following equations describe the integral control action.

$$\frac{du_c(t)}{dt} = K_i e(t) \tag{4}$$

Or

$$u_c(t) = K_i \int_0^t e(t)dt \tag{5}$$

Where K_i is an adjustable constant, the integral controller gain. This control action not only responds to the duration of the error but also its magnitude and direction [11]. The integration action corresponds to the area under the actuating curve up to given instant as is represented in Figure 20 by the error area. This allows the control signal to have a nonzero value when the error signal is zero. On the contrary, this cannot be reproduced by the proportional control since a nonzero control signal requires a nonzero control error signal [22]. Therefore, the integral control mode eliminates offset.

The integral control overcomes the offset problem from the proportional gain without the use of excessively large controller gain [21]. Thus, combining the proportional and integral control is advantageous in eliminating the steady-state error or offset [11], [21], [22].

However, while removing offset, the integral control action may lead to oscillatory response of slowly decreasing amplitude or even increasing amplitude which are undesirable [22].

2.5.4.3. DERIVATIVE CONTROL

The derivative control allows a system to respond to the rate of change of an error signal [11], [21], [22]. This introduces an element of prediction into the control action and enhances the control system sensitivity [21], [22]. Derivative control uses the rate of change of an error signal as an input allowing to produce a correction action before the magnitude of the error increases. This action can be described through the next equation.

$$u_c(t) = K_d \frac{de(t)}{dt} \tag{6}$$

Where $u_c(t)$ is the control action, $e(t)$ is the error signal and K_d is the derivative control gain [11], [21], [22]. Its noteworthy that the control action exists only while the error is changing. When the error is constant and stops changing there is no control action, although there may be a large error [11].

Since derivative control responds to the rate of change of the error and not the error itself it cannot be used alone. It has to be used combined with proportional or with proportional-integral control action [22]. A proportional and derivative control can be described by Equation (7). The derivative term adds damping to the system allowing larger gains which result in improvement of steady-state accuracy [22].

$$u_c(t) = K_p e(t) + K_d \frac{de(t)}{dt} \tag{7}$$

Where $u_c(t)$ is the control action, $e(t)$ is the error signal, K_p is the proportional control gain and, K_d is the derivative control gain [11], [21], [22].

The derivative control action is particularly important in temperature control since it can improve correction action and process response time. The rate of change of the error signal is an important characteristic of the temperature systems [11].

2.5.4.4. THREE MODE PID CONTROL

When combining the three modes previously described, proportional, integral and, derivative, we have a PID controller. The different control actions grant the controller distinct characteristics and are dependent of the process. Each controller mode is configured according the process requirements [21]. This way there are several configurations of PID controllers.

The simplest configurations consist in the proportional component complemented with either integral or derivative components. Combining proportional and integral control results in a two mode proportional-plus-integral (PI) controller which is expressed by the next equation [11], [21].

$$u_c(t) = K_p e(t) + K_i \int_0^t e(t)dt \tag{8}$$

This configuration allows to establish a rapid control action without the offset problem from the proportional component. This has been previously mentioned on Section 2.5.4.2.

The other two mode combination, proportional-plus-derivative (PD) controller is expressed by Equation (7). The derivative term of this controller responds to the rate of change of the error input signal, as previously described in Section 2.5.4.4.

The three mode PID controller can be described by Equation (9). It combines the action of the proportional, integral, and derivative control.

$$u_c(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{9}$$

The PID controller can also be described as function of a new time constant as represented in the next equation.

$$u_c(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt} \right) \tag{10}$$

Where,

$$T_i = \frac{K_p}{K_i} \tag{11}$$

$$T_d = \frac{K_d}{K_p} \tag{12}$$

In this time constant form, K_p is the proportional gain, T_i is the integral time constant, and T_d is the derivative time constant.

Each term of the controller is selected to accomplish a particular effect and can be tuned to meet the system requirements [21].

After choosing the structure of the PID controller, it is necessary to choose numerical values for the PID coefficients so that it meets the process requirements [21]. Regarding this there are different methods to achieve the best tunning of a PID controller parameters, being the Ziegler-Nichols method one of the most common [21].

The methods for tunning a PID controller consist in a set of rules to calculate the numerical values of the PID coefficients. The Ziegler-Nichols method requires to determine the gain and period for the closed loop control [11]. The gain is set as the maximum allowable value of gain for a proportional controller with a stable sine wave response to a disturbance [11]. The period is determined by the oscillations of said response.

To achieve the parameters for Ziegler-Nichols method is necessary to perform some steps.

1. Remove integral and derivative parameters form controller.
2. Impose an upset, like changing the setpoint, and observe the system response.
3. If the response is unstable and does not damp, then the gain is too high. It is necessary to decrease the gain and repeat step 2 until obtain a stable response.
4. Otherwise, if the response is damped then the gain is too low. It is necessary to increase the gain and repeat step 2 until obtain a stable response.
5. When a stable response is obtained, record the values of the gain and the period associated with the response. The period is the time between successive peaks on the stable response curve.

The determined gain and period are used to calculate the settings for the PID controller. The controller parameters will depend on the structure of the controller. In Table 4 are represented the different equations to obtain the control parameters for each controller structure. These parameters are defined in order to obtain a one-quarter-wave response curve [11].

Table 4 - Control Parameters by Ziegler-Nichols method [11].

	P	**PI**	**PD**	**PID**
K_P	0,5K	0,45	0,6	0,6
T_I	-	$\frac{P}{1,2}$	-	0,5P
T_D	-	-	$\frac{P}{8}$	$\frac{P}{8}$

Each system may be tuned so the process requirements are met. In some cases, there cannot be an overshoot in system response, while in others is required a slow and smooth response. Furthermore, a rapid response may be the principal requirement and the oscillations consequent of the response are not important. This way the control parameters must be determined and tuned for each control system [11].

Either way the PID control may be used for improvements in transient and steady-state performances [22].

3. SYSTEM ARCHITECTURE

This chapter focuses on planning the project solution to comply with the proposed objectives. The proposed system consists in different modules for monitoring, controlling and acting on the process.

3.1. OVERALL SYSTEM ARCHITECTURE

Through the overall system architecture, it is possible to get a general idea of how the system works. This project is divided into different modules, each one with its purpose, in order to achieve all the system requirements. In Figure 24 is represented the general architecture of the system.

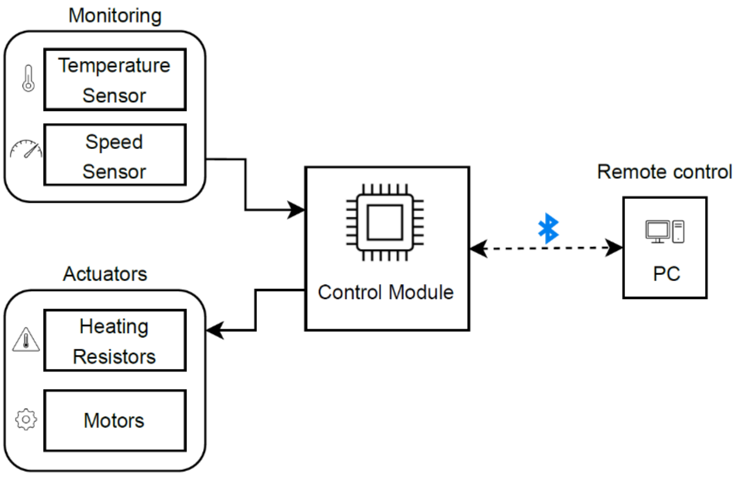


Figure 24 – System Architecture.

The monitoring module is responsible for acquiring temperature and motor speed data. This data is transferred to the control module which processes it and produces an output command to the system actuators. These actuators are responsible for changing the physical properties acting on the system. Finally, there is a PC module where data from the process can be displayed and saved for future analysis. This also makes it possible to control the process remotely. Each module is explained below.

3.1.1. MONITORING SYSTEM

This module consists of a set of sensors capable of acquiring data from the main process parameters. The temperature is a parameter of high importance in the correct functioning of the process and with high influence on the final product. Due to processing conditions to produce composite materials it is necessary to pay attention to the characteristics of the chosen sensor.

To process thermoplastics, it is necessary to reach temperatures higher than their glass temperature. Considering that, each thermoplastic has different material characteristics, it is required to take into account the choice of a sensor that allows a wide temperature measurements spectrum. Depending on the thermoplastic to be processed, temperatures between 160 °C and 250 °C must be reached. Regarding this requirement, the best option for temperature measure was a type K thermocouple due to its linearity and wide range of temperature measurements.

In addition to temperature, motor speed is also a process parameter to be controlled. Like temperature, speed has an influence on the degree of impregnation of thermoplastics in fibres. Therefore, it is important to adjust the speed of the process according to the polymer being processed. The speed control can be achieved through the use of an encoder such as an optical sensor. The sensor is responsible to count the revolutions the motor performs during a certain period. This data allows to determine the speed imposed on the system in revolutions per minute (rpm).

Both sensors transmit the data acquired from the system to the control module. The monitoring system is responsible for acquiring the data and transmit it to the control module so that it is processed.

3.1.2. ACTUATORS

The actuator module includes all the actuators implemented in the system, such as temperature actuators and motors. These are responsible for changing the values of the process parameters which are necessary to control. The command of the actuators is controlled by the control module, as explained on Section 3.1.3. Actuators work to convert the controller’s electrical signals into physical changes in the system, such as temperature and speed.

Concerning temperature, it is necessary to choose a technology that is capable of reaching the desired temperatures. As these are high temperatures, in the order of 200 °C, it is also important to consider that the actuator is resistant and reliable. There are different technologies that could be implemented however, it is important to consider the space available for installation. In sum the temperature actuator converts the electrical control signal to heat so that the temperature of the system changes.

Regarding the process execution speed, the solution is to install a motor capable of exerting the necessary force to pull the fibres. Hence the electrical control signal is converted to mechanical rotational motion.

Since the sensors and actuators complement each other, it is possible to implement a fine control of the process parameters. For instance, the temperature sensor can monitor the temperature generated by the temperature actuators, hence feedback closed loop control can be implemented. This type of control allows to coordinate the power of the actuator according to the data provided by the sensor. The same applies to the process speed parameter where the power of the motor can be manipulated through the information obtained by the speed sensor.

3.1.3. CONTROL MODULE

The control system is the central element of the system. This module is responsible for managing and process the information acquired from the process as well as act on the actuators of the system. Furthermore, the control system can establish communication with other devices both to transmit process information and to receive commands to control the system.

From the sensors data, the control module has information about the process status. Then it can control the process parameters through commands to the system actuators which change the process status. These commands result from the control logic carried out by the control module. The logic implemented is customized for the process in which it will be applied, in this case to control the temperature and the speed of the process.

As a control module, a microcontroller-based system is implemented due to its versatility in the implementation of technologies and systems as well as communication between different devices. A microcontroller consists of several elements such as a processor and several peripherals. The microcontroller peripherals establish the interface between the processor, which is responsible for the logic of the process and external physical variations.

General Purpose Input Output (GPIO) pins as well as serial communication peripherals such as Inter-Integrated Circuit (I^2C), Serial Peripheral Interface (SPI) or Universal Asynchronous Receiver/Transmitter (UART) are preponderant in the communication between the microcontroller, sensors, and actuators. It is noteworthy that a microcontroller also allows to establish communication and transmit information to other control systems.

3.1.4. REMOTE CONTROL AND DATA TRANSFER

The control module is responsible for controlling the process parameters which implies that it is close to the process due to the sensor and actuators connections. Besides this, although this module has some processing power and memory it is not suitable for storing and analysing the collected data from the process. Hence arises the need to implement a complementary system.

The integration of a computational unit makes it possible to implement an application for visualising the process parameters. Furthermore, it also allows remote control of the process via a wireless communication system. To do this, it is necessary to establish a communication protocol between the remote control unit and the control module such as Bluetooth.

The development of a python script makes it possible to achieve these objectives by creating a data visualisation application for a computer and establishing communication with the microcontroller via Bluetooth.

The computer receives from the microcontroller the process parameters data and the setpoint values. For this, it is necessary to establish a protocol by which the data is transferred correctly to the respective parameters.

4. PROTOTYPE

The developed prototype is composed of different technologies that meet the resolution of the proposed objectives. This chapter focuses on the explanation of each technology to meet the system requirements and how they were developed.

4.1. MICROCONTROLLER

The central module of the system consists of a microcontroller capable of interacting with the other components of the system. In addition, it is responsible for controlling and supervising the system. For this a Raspberry Pi Pico was chosen, represented in Figure 25.

Figure 25 - Raspberri Pi Pico microcontroller [23].

This microcontroller has a powerful processor, a dual-core arm cortex M0+ with a clock capable of running up to 133 MHz. It also has 264 kB on chip of Static Random Access Memory (SRAM) and 26 GPIO pins with a wide range of options like I^2C, SPI, Pulse Width Modulation (PWM) channels and others [24]. The large number of GPIO pins makes it possible to control various devices such as Solid-State Relay (SSR), transistors and sensors required to this solution. In addition, they can be combined with other functions like I^2C and PWM which allows for different devices to communicate and control. It is noteworthy that this microcontroller is available on a development board which helps with its implementation and integration with other devices and, due to its small size, simplifies its installation. The Raspberry Pi Pico is a powerful microcontroller and a versatile option to implement in projects of different natures, both for industrial and educational purposes.

The versatility of this microcontroller is highlighted by the fact that it can be programmed using C or Micropython language. C language is frequently used in other microcontrollers, and it can implement the control logic as well as access to low-level programming to interface with the system’s hardware. On the other hand, Micropython is a Python version suitable for microcontrollers, facilitating low-level programming [25]. Like C language, it allows accessing and change the contents of the microcontroller registers. In addition, it is possible to implement some of Python libraries and it also includes modules for easier access to low-level hardware [25]. Regarding the execution of this project, it was opted for Micropython programming in order to expand the knowledge to other technologies.

4.2. TEMPERATURE CONTROL

As previously mentioned in Section 2.3.1, temperature is one of the most relevant parameters to control on the production of prepreg composites. This way, the process temperature is a crucial to monitor and control. As such, a type K thermocouple, as seen in Figure 26, was chosen to monitor temperature.

Figure 26 - Type K Thermocouple.

This sensor has the necessary characteristics to satisfy the operating conditions of the process, like resistance to high temperatures for extended periods of time [26], [27]. The thermocouple creates a potential difference according to the temperature measured at the metal junction terminal. However, this output is in the order of milivolt so a signal amplifier is used to amplify the signal between the sensor and the microcontroller. The thermocouple amplifier is represented in Figure 27.

Figure 27 - Thermocouple amplifier MCP9600 [27].

Another advantage of using this device is the linearisation of the results obtained from the thermocouple sensor [26]. This simplifies data processing and removes the concern of implementing a signal conditioning circuit at the output of the thermocouple sensor. Furthermore, this device is also responsible for converting the analogue signal, obtained by the thermocouple, into a digital signal.

Therefore, temperature measurement can be made directly from the thermocouple amplifier by the microcontroller. Temperature data is transferred to the microcontroller through I^{2}C communication protocol.

This device stores temperature data in three different registers that contain the values of the cold and hot junction temperatures and the difference between them. In Figure 28 a block diagram of the thermocouple module temperature registers is represented. The temperature values stored in these registers can be sent to the microcontroller via I^2C communication protocol. It is noteworthy that this thermocouple module has integrated cold-junction compensation which means that the temperatures given are absolute [26].

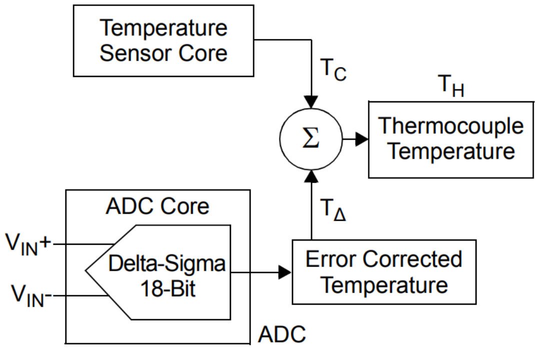
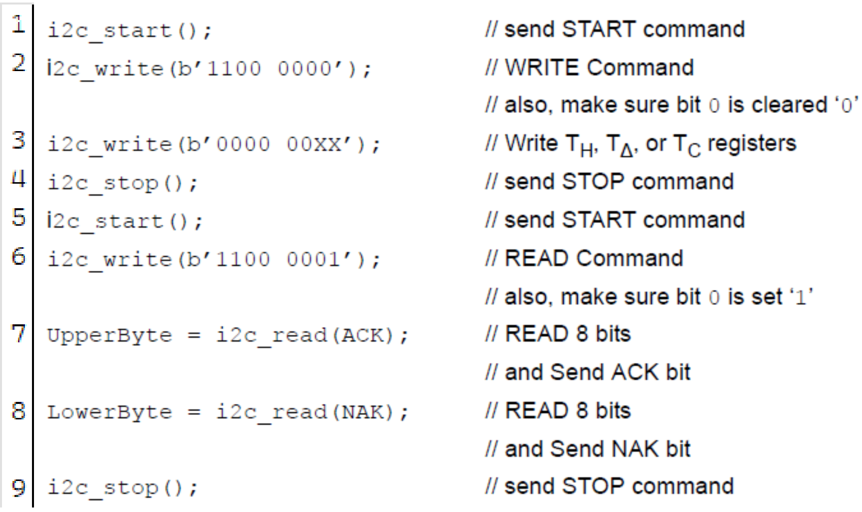


Figure 28 – Block diagram of thermocouple module temperature registers [26].

Regarding the configuration on the thermocouple sensor register it was used the predefined settings as these are already suitable for the application, type K thermocouple selected. The Analog-to-Digital Converter, ADC, measurement resolution is also left with the predefined setting which sets an 18-bit resolution. This parameter can be changed by accessing bits 5 and 6 of the device configuration register.

To access the information on the registers it is required to follow the manufacturer's instructions on the datasheet as shown in Figure 29.



```
1 i2c_start();                      // send START command
2 i2c_write(b'1100 0000');          // WRITE Command
                                    // also, make sure bit 0 is cleared '0'
3 i2c_write(b'0000 00XX');          // Write TH, TΔ, or TC registers
4 i2c_stop();                       // send STOP command
5 i2c_start();                      // send START command
6 i2c_write(b'1100 0001');          // READ Command
                                    // also, make sure bit 0 is set '1'
7 UpperByte = i2c_read(ACK);        // READ 8 bits
                                    // and Send ACK bit
8 LowerByte = i2c_read(NAK);        // READ 8 bits
                                    // and Send NAK bit
9 i2c_stop();                       // send STOP command
```

Figure 29 - Pseudo routine to set a register pointer and read a two-Byte Data [26].

The Hot-Junction temperature (T_H), Junctions temperature delta (T_Δ) and Cold-junction temperature (T_C) are the registers which contain the data from the temperature readings. These registers can be accessed through lines 7 and 8 after defining the respective pointers in line 3 from Figure 29.

Temperature is transmitted to the microcontroller as a byte so the microcontroller is responsible for converting to its corresponding temperature value according to the datasheet [26]. A formula, for positive Celsius temperatures, is provided for that as represented in Equation (13), where T is temperature and *UpperByte* and *LowerByte* represent the two bytes read from the register. It should be noted that these are 16-bit registers and as such it is necessary to divide the data into two bytes, where the lower half is considered *LowerByte* and the upper half *UpperByte*.

$$T = (UpperByte \times 16 + LowerByte/16) \tag{13}$$

Regarding the temperature monitoring, these two devices suppress the system's requirements. The temperature actuator, which work in parallel with the temperature sensor, are described below.

Figure 30 shows the flowchart for temperature control.

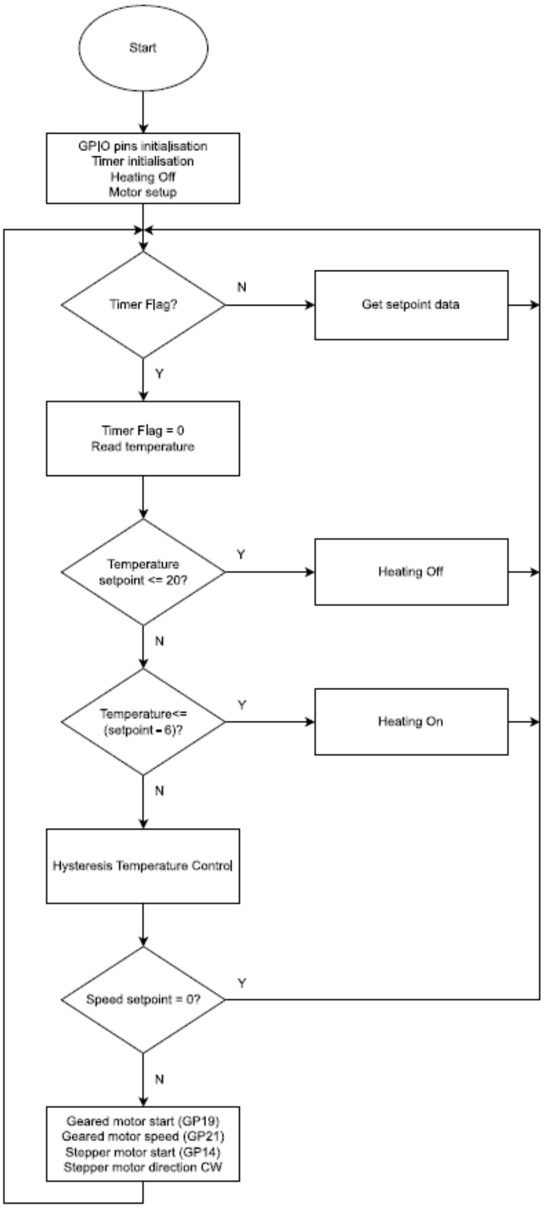
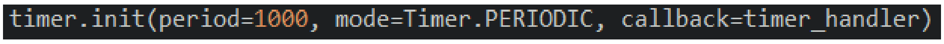


Figure 30 – Temperature control strategy flowchart.

First, the necessary GPIO pins are initialised, and the desired values are assigned so that the heating system and motors are switched off. Then, the main cycle is responsible for evaluating the system temperature according to the setpoint desired. This is performed every second as soon as the timer flag is activated. In Figure 31 is represented the timer configuration, where the *period* argument sets the period desired in milliseconds, the *mode* argument defines the timer to run periodically, and *callback* refers to the handler of the timer interrupt. The flag is changed in the timer interrupt handler as represented in the flowchart in Figure 32.



```
timer.init(period=1000, mode=Timer.PERIODIC, callback=timer_handler)
```

Figure 31 – Timer configuration for temperature readings every second.

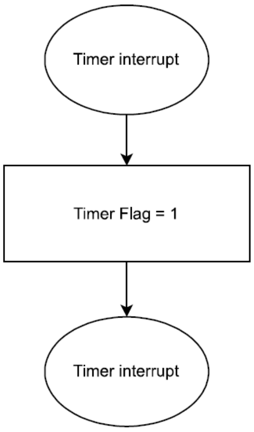


Figure 32 – Timer interrupt handler flowchart.

While the timer flag is not active, the system proceeds to read the temperature and speed setpoint parameters values sent by the computer in the UART channel. In Figure 33 is represented the flowchart of getting the setpoint parameters values.

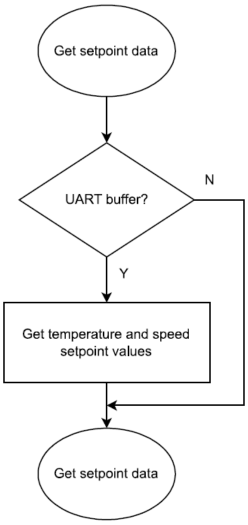


Figure 33 – UART buffer setpoint values read flowchart.

The hysteresis temperature control is represented in Figure 34.

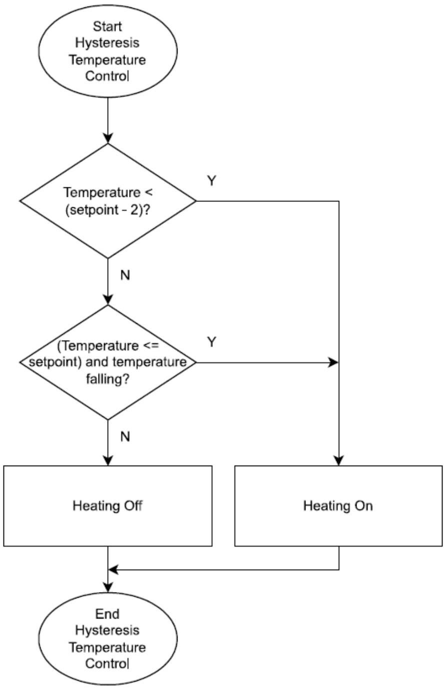


Figure 34 – Hysteresis temperature control flowchart.

The hysteresis temperature control allows to maintain the system's temperature at the desired values. The heating cartridges are powered on as long as the temperature recorded is below the setpoint temperature minus two Celsius degrees, and switched off when the system's temperature is decreasing and reaches the setpoint temperature.

When the system temperature has reached the desired setpoint value then it can start the motors to produce the composite prepreg.

4.2.1. TEMPERATURE ACTUATORS

Since the temperature is a parameter to control in the system it is necessary to have some actuators responsible for temperature variation. The system temperature will vary according to the heat provided to it. For this matter, as heat sources of the system, heating cartridges were chosen. These are power resistors that can produce high amounts of heat and are reliable, hence the application of these devices in the system. In Figure 35 is represented the heat cartridges used.

Figure 35 – 220 V 490 W Heat Cartridge.

The heat cartridge chosen is rated to 220 V and 490 W [28]. In order to achieve the temperature more effectively, four heat cartridges were used. First, this allows a more homogeneous distribution of the heat generated as well as less heating time. It is noteworthy that the heat cartridges have to be installed in parallel, otherwise it is not possible to achieve the rated power of the heat cartridges. The Figure 36 shows how the heated cartridges were connected.

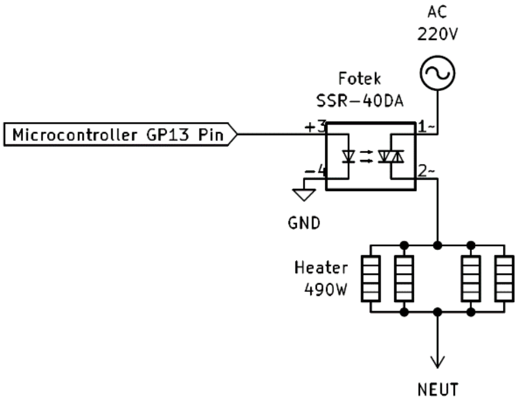


Figure 36 - Heat cartridge electric circuit.

In this configuration each heat cartridge is powered at its rated voltage and can deploy its rated power. The fact that the cartridges are grouped in pairs is due to their arrangement in the heating chamber. Each pair is located in an aluminium wall of the heating chamber. In Figure 37 is represented the location and arrangement of the heat cartridges highlighted in red.

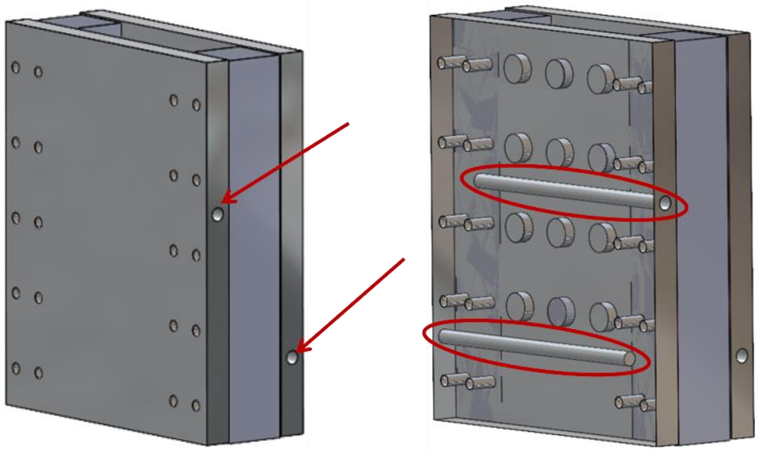


Figure 37 – Position of heating cartridges on the heating chamber.

Furthermore, the distribution of the heat cartridges in the heating chamber was taken into account in order to distribute the heat produced uniformly. Figure 38 has a representation of the distribution of the heat cartridges in the heating chamber.

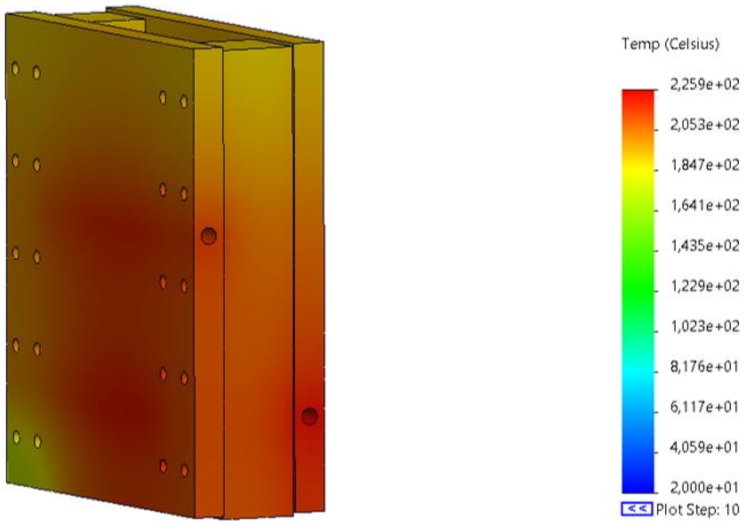


Figure 38 - Thermal simulation of heating chamber with heat cartridges.

As can be seen in Figure 36 the heat cartridges are grouped in pairs so that each pair is placed in a wall of the heating chamber. The control of the power supply to the heat cartridges is done through a SSR. The SSR chosen is the FOTEK SSR-40DA represented in Figure 39. It is controlled by a Direct Current (DC) input voltage 3 V to 32 V and its output is 24 V to 380 V Alternating Current (AC) [29]. This allows to isolate the control circuit from the power circuit.

Figure 39 - SSR used for heat cartridge power supply control.

As previously mentioned, the use of SSR allows to isolate the control circuit from the power circuit. This is from high importance since, firstly, the two circuits work on different voltage levels between the different components of the circuit. Second, the control circuit works with DC and the power circuit works with AC.

Regarding the SSR chosen, it has a zero cross trigger method. This method consists of turning on and off the output when the voltage of the supplied sine wave is zero [29]. In Figure 40 is illustrated an application of this method.

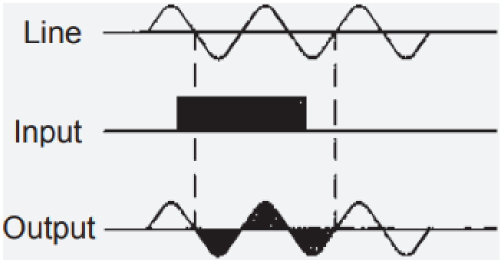


Figure 40 - Zero crossing SSR trigger method [29].

In order for the fibre to go through the heating chamber where the melted polymer is located, a pulling system is required. Besides that, it also needs to wind the produced composite tape to later be stored before use.

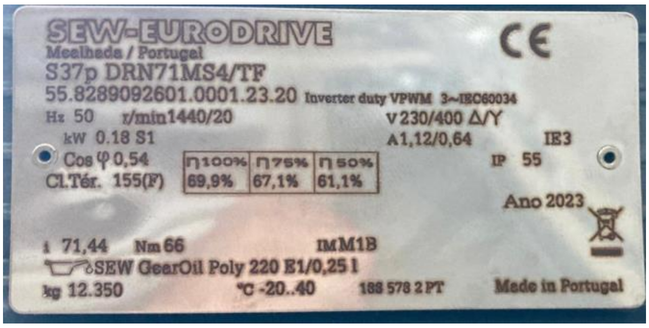
4.3. WINDING SYSTEM

After impregnating the fibres in the heating chamber, it is necessary to pull the composite tapes. Hence, it is required a motor capable of pulling the composite tapes after impregnation. In addition, it can also be used for winding them up for storage. Since the melted polymer has high viscosity and the fibres run a sinuous path inside the heating chamber, it is necessary to choose a motor capable of producing high torque [30]. Hence the chosen motor for this application is a geared motor. The choice of this type of motor is due to the high torque produced compared to the power of the engine. This is due to the fact that the motor has coupled a geared system capable of reducing the motor output speed and, in turn, increases the output torque. Regarding this application, the main focus is on the outcome at the geared system output rather than fixating the gear ratio. Other options involve high power motors, which require more energy. This option would make it difficult to implement the system since it would require powerful energy source.

The geared motor is composed of an induction motor and a gearbox. This gearbox is directly coupled in the motor shaft. This allows to be possible to obtain, at the output of the motor and gearbox system, different speed, and torque values from the ones the motor is capable of producing on its own. The gearbox relation determines the new output parameters which could be higher or lower from the motor. In this case, it is favourable a lower output speed and higher torque.

Figure 41 - Geared motor [31].

For this project, a geared motor from SEW-Eurodrive is chosen as represented in Figure 41. The principal characteristics of this motor are represented in Figure 42. The choice of this motor was due to several factors, including the low power, high torque produced and high service factor. Regarding the control and power of the motor it is necessary to use a frequency driver. The frequency driver characteristics are described further down in this section. It is noteworthy that the frequency driver available to implement in the system imposes a limit on the motor power of 0,37 kW. Therefore, this is an important factor to consider when choosing the motor. Concerning this, the chosen motor has a nominal power of 0,18 kW has represented in Figure 42.



SEW-EURODRIVE
Mealhada / Portugal
S37p DRN71MS4/TF
55.8289092601.0001.23.20 Inverter duty VPWM 3~IEC60034
Hz 50 r/min 1440/20
V 230/400 Δ/Y
kW 0.18 S1
A 1,12/0,64
IE3
Cos φ 0,54
Cl.Tér. 155(F)

η100%	η75%	η50%
69,9%	67,1%	61,1%

IP 55
Ano 2023
i 71,44
Nm 66
IM M1B
SEW GearOil Poly 220 E1/0,25 l
kg 12.350
°C -20..40
188 578 2 PT
Made in Portugal

Figure 42 – Geared motor characteristics.

Other characteristic that was taken into account was the torque produced by the gear system. As can be seen in Figure 42, this geared motor can achieve 66 Nm of torque. The system torque requirement was determined experimentally using a suspension scale. With the system, under the production conditions, ready to produce, a suspension scale was attached to the material that was extracted from the heating chamber. Then, the scale was pulled until the fibres started to move through the heating chamber and the value obtained in the scale was registered. Finally, multiplying the value obtained with the gravitational acceleration, 9,81 m/s^2, it is obtained an approximate value for the torque required to move the material through the system. This way, from this hypothesis the torque required by the system is approximately 60 Nm, since the value obtained by the suspension scale is around 6 to 6,5 Kg.

Finally, the high service factor of this motor, 1,55, allows the motor to safely handle overloads for short periods of time [32]. This is convenient as more torque is needed at the beginning of the manufacturing process.

As previously mentioned, to control the geared motor is necessary a variable frequency driver (VFD). This device establishes the interface between the control unit and the motor. The frequency driver is responsible for controlling the speed and direction of rotation of the motor. It achieves this by changing the power frequency input to the motor. For this, a variable frequency driver ABB ACS101-K75-1 was used. The driver is represented in Figure 43.

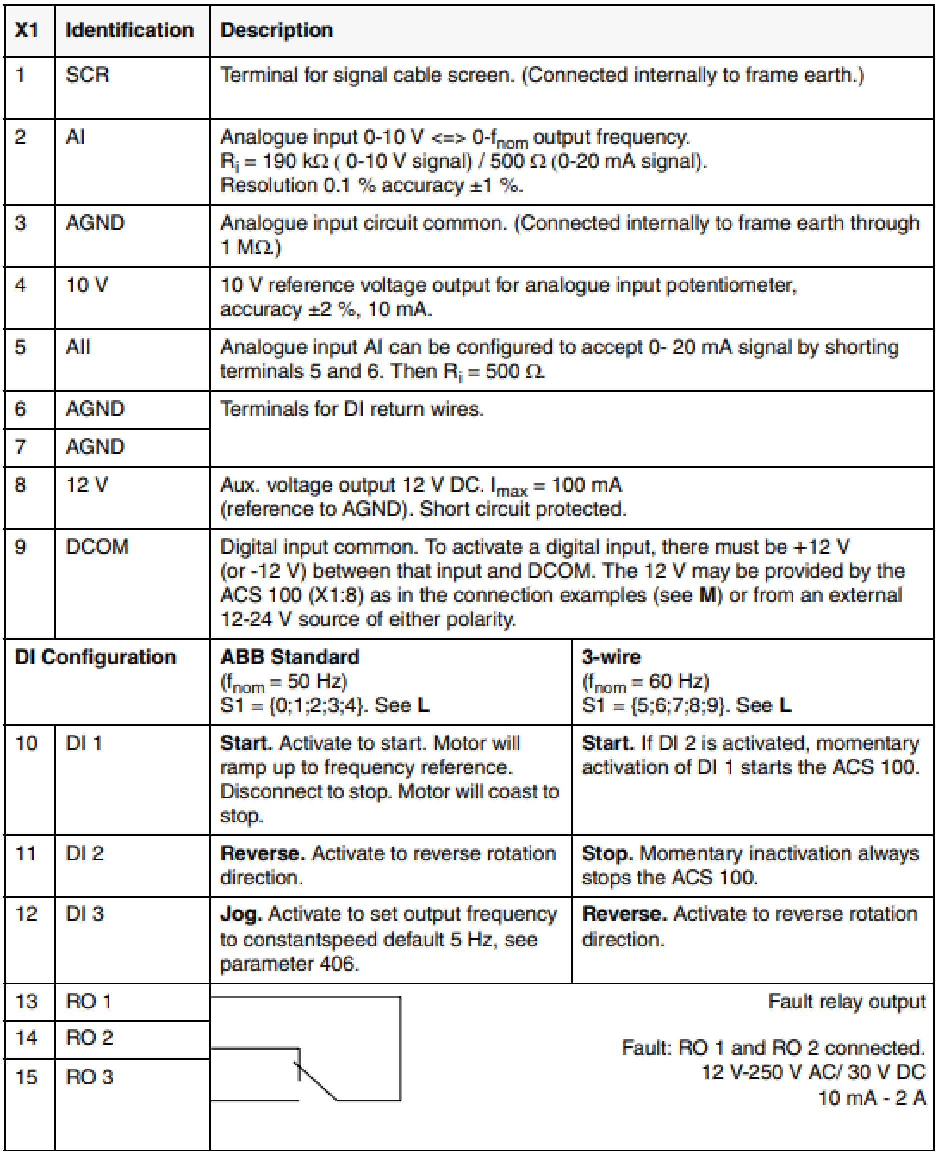
Figure 43 - ABB Variable Frequency Driver [33].

This device can control motors up to 0,37 kW of nominal power which is taken into consideration when choosing the motor. As for output specifications, it can supply up to 2,2A at a commutation frequency of 4 kHz which is enough for the geared motor needs [34].

In order to better perform there are some configurations needed to be made in the controller. These configurations consist of filling the engine performance parameters in the controller so that the power sent is adequate for the motor. Nominal ratings of current, speed and frequency drive are some of the parameters that are required to fill in the driver when connecting the motor.

Moreover, this driver allows remote control from a microcontroller since it has a control terminal where it is possible to send commands to control the motor. The functions of each channel are described in Table 5. The start, stop and direction of rotation commands are digital signals, and the frequency output command is analogue.

Table 5 - Control terminals from ABB Variable Frequency Driver [34].



X1	**Identification**	**Description**	
1	SCR	Terminal for signal cable screen. (Connected internally to frame earth.)	
2	AI	Analogue input 0-10 V <=> 0-f_{nom} output frequency. R_i = 190 kΩ (0-10 V signal) / 500 Ω (0-20 mA signal). Resolution 0.1 % accuracy ±1 %.	
3	AGND	Analogue input circuit common. (Connected internally to frame earth through 1 MΩ.)	
4	10 V	10 V reference voltage output for analogue input potentiometer, accuracy ±2 %, 10 mA.	
5	AII	Analogue input AI can be configured to accept 0- 20 mA signal by shorting terminals 5 and 6. Then R_i = 500 Ω.	
6	AGND	Terminals for DI return wires.	
7	AGND		
8	12 V	Aux. voltage output 12 V DC. I_{max} = 100 mA (reference to AGND). Short circuit protected.	
9	DCOM	Digital input common. To activate a digital input, there must be +12 V (or -12 V) between that input and DCOM. The 12 V may be provided by the ACS 100 (X1:8) as in the connection examples (see **M**) or from an external 12-24 V source of either polarity.	
DI Configuration		**ABB Standard** (f_{nom} = 50 Hz) S1 = {0;1;2;3;4}. See **L**	**3-wire** (f_{nom} = 60 Hz) S1 = {5;6;7;8;9}. See **L**
10	DI 1	**Start.** Activate to start. Motor will ramp up to frequency reference. Disconnect to stop. Motor will coast to stop.	**Start.** If DI 2 is activated, momentary activation of DI 1 starts the ACS 100.
11	DI 2	**Reverse.** Activate to reverse rotation direction.	**Stop.** Momentary inactivation always stops the ACS 100.
12	DI 3	**Jog.** Activate to set output frequency to constantspeed default 5 Hz, see parameter 406.	**Reverse.** Activate to reverse rotation direction.
13	RO 1	Fault relay output Fault: RO 1 and RO 2 connected. 12 V-250 V AC/ 30 V DC 10 mA - 2 A	
14	RO 2		
15	RO 3		

These commands can be controlled from a microcontroller however, the logical high-voltage level for the driver is 12 V and the microcontroller is not able to generate this voltage level. Transistors should therefore be used as switches, as shown in Figure 44.

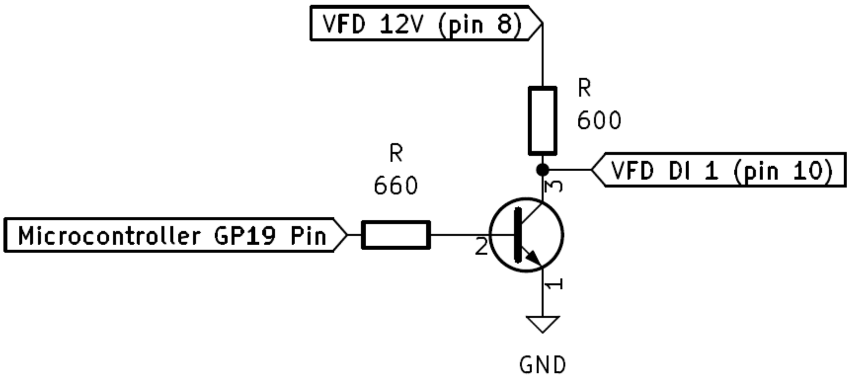


Figure 44 - Transistor circuit as switch.

For example, to start the motor it is necessary to apply 0 V to the VFD DI 1 pin. The transistor circuit as a switch, from Figure 44, is used to control the voltage on this pin which is connected where *Variable Frequency Driver Pin (VFD)* label is represented. A microcontroller pin operates the base of the transistor in order to control the voltage value on the variable frequency driver. If there is no input from the microcontroller, the transistor acts as an open switch and the VFD DI 1 pin has 12 V. Whereas a positive input allows the transistor to conduct current and as such acts as a closed switch, with the VFD DI 1 pin having approximately 0V which results in the motor start.

With the combination of these technologies, geared motor, variable frequency driver and microcontroller it is possible to control the motor speed and, consequently, the processing speed of the system.

4.4. WINDING GUIDING SYSTEM

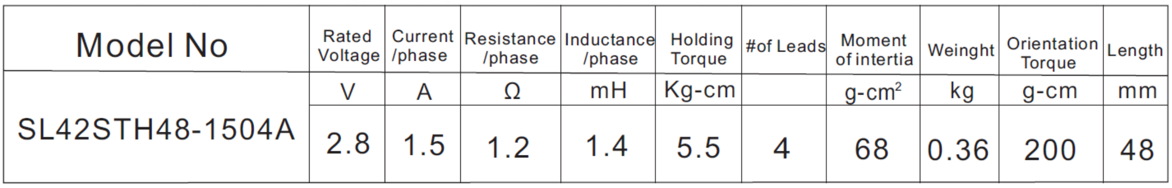
The produced tapes must be stored after production. This way, the motor pull system is used to wind up the tape. However, there are some aspects to take into account when winding the pre-impregnated tapes. The main one being saving space for storing the reel. Regarding this a winding guiding system is installed in order to control the pre-impregnated tape path when winding. This allows to save space and avoid knots in the produced tape. The winding system then consists of a mechanical steering system coupled to a stepper motor. The system described is represented in Figure 45.

Figure 45 - Steering system for prepreg tape winding.

This system has to be in synchronization with the winding system otherwise the prepreg tape winding will not be optimal.

The mechanical steering system travels on a shaft that is coupled to the stepper motor. This shaft is responsible for converting the rotational motion produced by the motor in linear movement. Hence the speed of stepper motor has to be synchronized with the winding motor speed in order to the guiding system performs a translation movement increment at each winding rotation executed. For this it was chosen NEMA 17 type stepper motor, SL42STH48 – 16184A. Table 6 shows the main characteristics of the stepper motor.

Table 6 –Main characteristics of stepper motor.



Model No	Rated Voltage	Current /phase	Resistance /phase	Inductance /phase	Holding Torque	#of Leads	Moment of intertia	Weinght	Orientation Torque	Length
SL42STH48-1504A	V	A	Ω	mH	Kg-cm		g-cm^2	kg	g-cm	mm
	2.8	1.5	1.2	1.4	5.5	4	68	0.36	200	48

It should be noted that it is necessary a stepper motor driver in order to control the stepper motor speed with a microcontroller. This is due to the current necessary to drive the stepper motor. The driver used is the DRV8825 and is represented in Figure 46. This driver allows to control the stepper motor through commands sent by the microcontroller. Besides that, it allows to control the stepper motor through different stepping techniques in order to achieve a smooth movement.

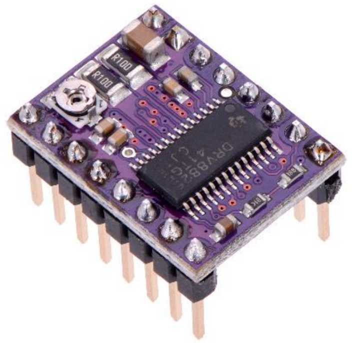


Figure 46 - Stepper motor driver DRV8825 [35].

Furthermore, the choice for a stepper motor allows some simplification of the positioning system since it is possible to determine the position of the motor rotation through tracking the number of steps executed instead of the implementation of a feedback mechanism.

Regarding this, it is important to establish an absolute position which will be the zero position. This way, this position will serve as a starting point for counting the steps taken by the motor. For this, an endstop sensor is placed at a boundary of the course and defined has the zero position for the stepper motor.

Figure 47 – Endstop sensor [36].

In order to control all these systems and devices from a remote location it is possible to establish a wireless data protocol such as Bluetooth.

4.5. MOTORS CONTROL

The motors implemented in the system require different control strategies due to their nature and function. First there is the geared motor responsible for pulling the material through the different stages of the system. Then, there is the stepper motor that assists the geared motor in arranging the material winding.

4.5.1. GEARED MOTOR CONTROL

The geared motor is responsible for pulling the carbon fibres through the system and winding them for storage. Hence the geared motor requires speed control provided by a variable frequency controller like the ABB ACS101-K75-1, presented in Section 4.3.

This frequency controller allows two modes of control, one local and the other one remote. The local mode allows to change the motor speed via the console provided by the controller as represented in Figure 48. It also allows to start and stop the movement of the motor as well as change the direction of rotation.

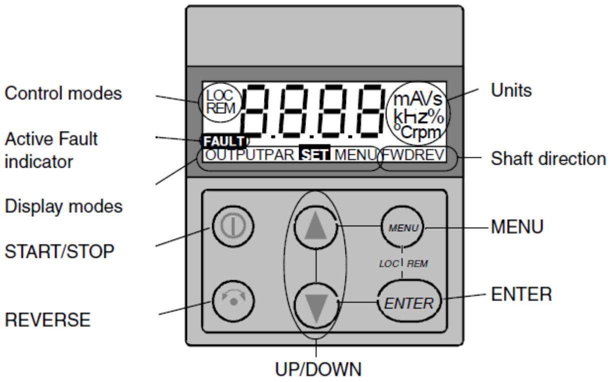


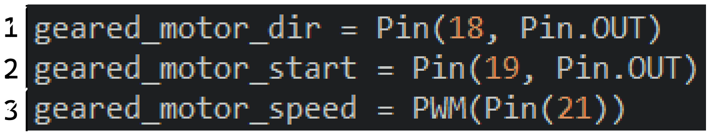
Figure 48 – Console of the variable frequency controller which allows local control of the motor [34].

The display shows information relating the motor parameters. The speed can be represented as frequency or current that is being supplied to the motor. The motor speed is changed by varying the frequency of the signal sent by the controller to the motor.

Regarding the remote control mode, it is necessary to use the controller bus of the variable frequency controller to establish connection with the microcontroller. As previously mentioned in Section 4.3, it is necessary use transistors as switches to command the controller due to the different voltage levels in these two devices. This way, a configuration like the one represented in Figure 44 is used on pin 2 of the variable frequency controller.

The pin 2, AI, from the variable frequency controller allows to control the output frequency of the controller and consequently the motor speed. For that it is necessary to apply a PWM signal to the base terminal of the transistor to control the current that this pin will receive. This current serves as a reference for defining the desired frequency for the motor as described in Table 5. The variation in the duty-cycle of the PWM signal, applied to the transistor, is responsible for the variation of the current at the variable frequency controller pin and consequently the speed of the geared motor.

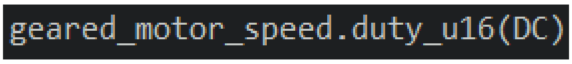
Three pins are required to control the geared motor. Two as simple digital outputs where the output varies between high or low logic value to control the start, stop and rotation direction of the geared motor. The third one is configured with a PWM output to control the motor speed. The *machine* library of Micropython assists in the configuration of the microcontroller pins through its classes. The *Pin* class allows to configure the pins as output and the *PWM* class, that generates a PWM signal, as the pin output. Figure 49 shows the configuration used for the geared motor control pins.



```
geared_motor_dir = Pin(18, Pin.OUT)
geared_motor_start = Pin(19, Pin.OUT)
geared_motor_speed = PWM(Pin(21))
```

Figure 49 - Configurations of the pins that control the geared motor.

The geared motor speed can be controlled through the manipulation of the duty-cycle value of the PWM signal of the speed control pin as represented in Figure 50.



```
geared_motor_speed.duty_u16(DC)
```

Figure 50 – Variation of duty-cycle to control the geared motor speed.

4.5.2. STEPPER MOTOR CONTROL

In order to organise the winding of the pre-impregnated tapes on a reel, it is necessary to use a stepper motor associated with a guiding system. A DRV8825 stepper motor driver is used to interface the stepper motor with the microcontroller. This driver allows the stepper motor control through two pins of command, one for establishing the direction of rotation and the other for the speed of rotation. Depending on the logic state of the direction pin, the motor rotates clockwise or counterclockwise. The motor speed is controlled by the STEP pin of the DRV8825 driver. When there is a change in logic state on this pin, it energizes one of the motor windings, causing the motor rotor to rotate. This means that the speed at which the motor rotates is directly influenced by how quickly the logic value on this pin changes. Hence, applying a variable frequency signal to this pin it is possible to control and adjust the rotational speed of the motor.

The microcontroller is responsible for controlling the logic state of the direction pin to control the rotation direction of the motor as well as the speed through the frequency control of the driver STEP pin signal. The connections between the microcontroller with the driver and the stepper motor are represented in the Figure 51.

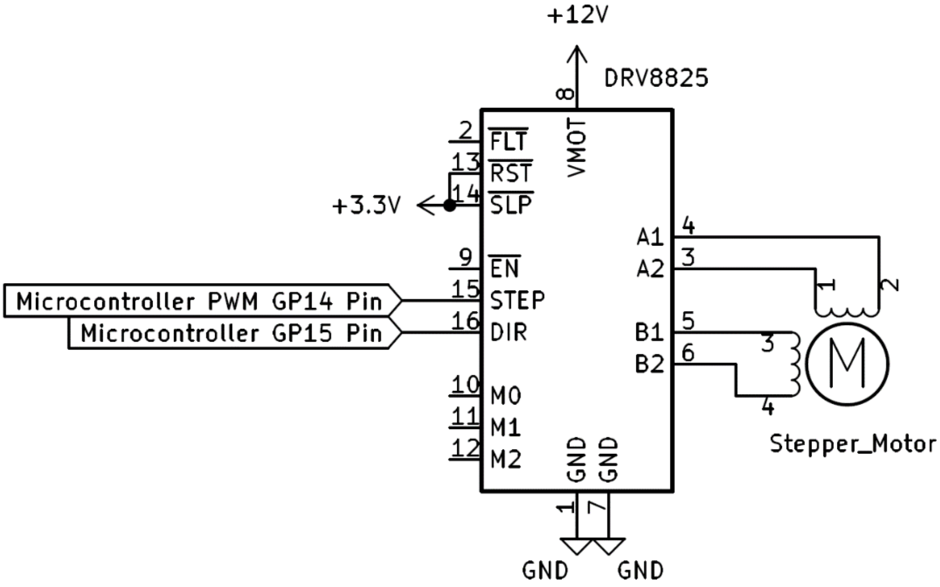


Figure 51 - Connections between stepper driver, stepper motor and microcontroller.

It is noteworthy that in order to power the motor is necessary to use an external DC power source since the microcontroller cannot provide enough power to the motor.

The position of the motor rotor is not relevant to this application however, it is important to have an absolute position to know when the motor achieves the limit position of the winding system travel course. This is responsibility of the endstop sensor that indicates the microcontroller when the winding guide trolley achieves the limit of the course through a change of logic value when pressed. The microcontroller has an external interrupt active for this sensor which answers the generated interrupt when the sensor changes the logic state. The flowchart of Figure 52 represents the external interrupt event generated by the endstop sensor.

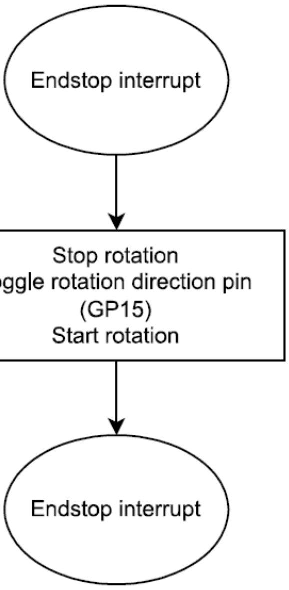
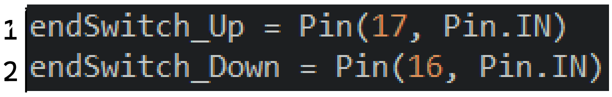


Figure 52 – Endstop interrupt flowchart.

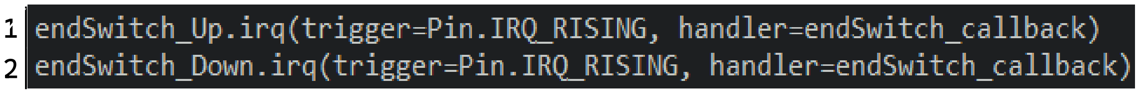
First it is necessary to define the endstop sensor pins as input GPIOs. This is done using the *Pin* class from the *machine* library of Micropython as represented in Figure 53.



```
endSwitch_Up = Pin(17, Pin.IN)
endSwitch_Down = Pin(16, Pin.IN)
```

Figure 53 - Configuration of endstop pins as input GPIOs.

After that, the external interrupt can be configured through the *irq* method from the same *Pin* class. As arguments of this method are defined the trigger event and the handler function that handles the interrupt when it occurs. In this case, the interrupt is set to occur when an upward flank of the pin logic value is detected and the *endSwitch_callback* function as the interrupt handler. This configuration is represented in Figure 54.



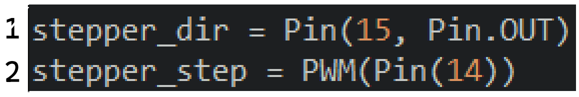
```
endSwitch_Up.irq(trigger=Pin.IRQ_RISING, handler=endSwitch_callback)
endSwitch_Down.irq(trigger=Pin.IRQ_RISING, handler=endSwitch_callback)
```

Figure 54 – Endstop external interrupt configuration.

Finally, the *endSwitch_callback* function has to be defined and execute the logic intended for the interrupt handler as represented in the flowchart of Figure 52.

The first thing to do is to configure the direction and step pins for the motor driver and then set a motor starting position. This is done by moving the motor until the trolley reaches course limit, stopping the motor at that point and setting its position. After that, the motor is on hold until the initialisation of the production. When this is permitted, the motor’s rotation speed is set, with the direction of rotation being dependent on the interrupt events from the endstop sensors.

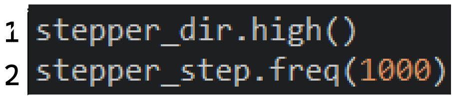
Like the other peripherals connected to the microcontroller, the pins for motor control must also be configured as output pins. In this case two are required, one for rotational direction and one for motor speed control. With regard to the direction pin, only its logical state needs to be controlled and as such the Pin class is used giving the corresponding pin of the microcontroller the function of an output pin. On the contrary, the pin dedicated to motor speed control will have to alternate its logic state at a given frequency. Thus, it is advantageous to configure this pin to output a PWM signal using the *PWM* class of the *machine* library. These configurations are respectively represented in Figure 55.



```
stepper_dir = Pin(15, Pin.OUT)
stepper_step = PWM(Pin(14))
```

Figure 55 – Configurations of the pins that control the stepper motor.

By using the *machine* library classes there are several methods available to manipulate the states and settings of the pins. Figure 56 shows how to change the logic state of the motor rotation direction pin, to a logical high level, and how to change the frequency of the PWM signal by varying the argument of the *freq* method of the *PWM* class, respectively.



```
stepper_dir.high()
stepper_step.freq(1000)
```

Figure 56 - Methods to change logical value of a GPIO pin and a PWM output signal pin.

A spool is attached to the geared motor where the composite tape will be wound and then stored. The stepper motor is used to guide the material produced so that it is wound along the entire length of the spool. Hence, the two motors speed are synchronized so that the stepper motor advances 2 cm per revolution of the geared motor. To do this, the relation represented in Equation (14) must be respected, where s_{stm} is the stepper motor speed in rpm and s_{gm} is the speed of the geared motor in rpm.

$$s_{stm} = 20 \times s_{gm} \tag{14}$$

The stepper motor speed has to be higher than the geared motor due to the motion translation system, as represented in Figure 45. This system is coupled to the stepper motor and is responsible for converting the rotational motion of the motor to a linear motion.

4.6. BLUETOOTH DATA TRANSFER

The final solution of this project aims not only to parameterize the process but also to acquire data from the process remotely. As such it is necessary to implement a wireless protocol to meet this requirement. This way it is designed a Bluetooth interface where it is possible to alter the process parameters and send data from the running process. Parameters like temperature and speed can be changed remotely through Bluetooth connection between microcontroller and a computer or smartphone.

The wireless protocol implemented is based on Bluetooth and it requires a Bluetooth module connection with the microcontroller. The module chosen to the project is the HC-05 Bluetooth module represented in Figure 57.

Figure 57 - HC-05 Bluetooth module [37].

This module is connected to the microcontroller through four pins, two of which are for powering the Bluetooth module. The other two are responsible for establishing communication with the microcontroller through UART, hence it is necessary to connect the TXD and RXD pins to the microcontroller’s UART RX and TX pins respectively. Figure 58 represents the connections necessary to establish to effectively use this module with the microcontroller.

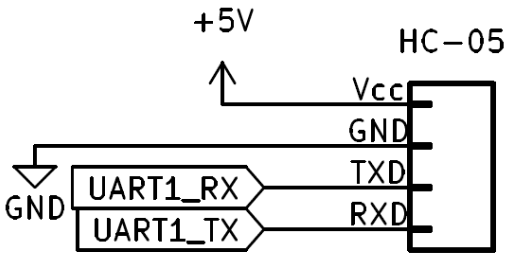
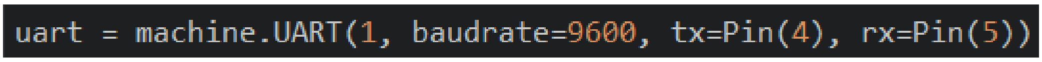


Figure 58 – Connections between the HC-05 Bluetooth module and the Raspberry Pi Pico.

It is through the UART that the microcontroller receives the process setpoint data update from the Bluetooth module. It then updates the process control data and changes the control commands if necessary. It is also through this module that the process data is transmitted to the computer. The process data is transmitted to the Bluetooth module via UART.

The UART needs to be configured in order to establish communication between the microcontroller and the HC-05 Bluetooth module. For this, the UART method configures the channel 1 as the selected channel to establish communication and the microcontroller pins 4 and 5 as the transmitter and receiver pins respectively, as represented by the arguments of the UART method in Figure 59. It is also necessary to establish a 9600 baudrate for the communication which is specified by the baudrate argument of the same method.



```
uart = machine.UART(1, baudrate=9600, tx=Pin(4), rx=Pin(5))
```

Figure 59 – UART channel 1 configuration.

Furthermore, to correctly transmit data between the microcontroller and the computer, it is necessary to establish a data transmission protocol. To do this, a data array was established consisting of the process temperature value, followed by an *S* character and the process speed value as represented in Table 7. When communication takes place between the microcontroller and the computer, these values are taken as the instantaneous values of the process parameters. On the other hand, when communication is the other way round, between the computer and the microcontroller, the values are taken as the setpoint values for the process parameters. Table 7 shows an example of this array.

Table 7 -Data transmission protocol.

Temperature Value	Division character	Speed Value
183	s	0

As represented in Table 7, the microcontroller sends to the computer the instantaneous values of process parameters which are 183 °C and 0 m/min, for temperature and process speed respectively.

4.7. GRAPHICAL USER INTERFACE (GUI)

To define and change the process data, a GUI is developed so that the data is presented in an appealing way. This requires displaying the process temperature and speed as well as the desired setpoint values. A script was developed in Python to fulfil these objectives.

To develop this GUI, a python module, *customtkinter*, is used to help develop a graphical interface. This module defines the application's visualisation window and other visual characteristics. It also has various options for user interaction, including text visualisation, data entry windows, buttons, and others. In Figure 60 is represented the flowchart of the developed script.

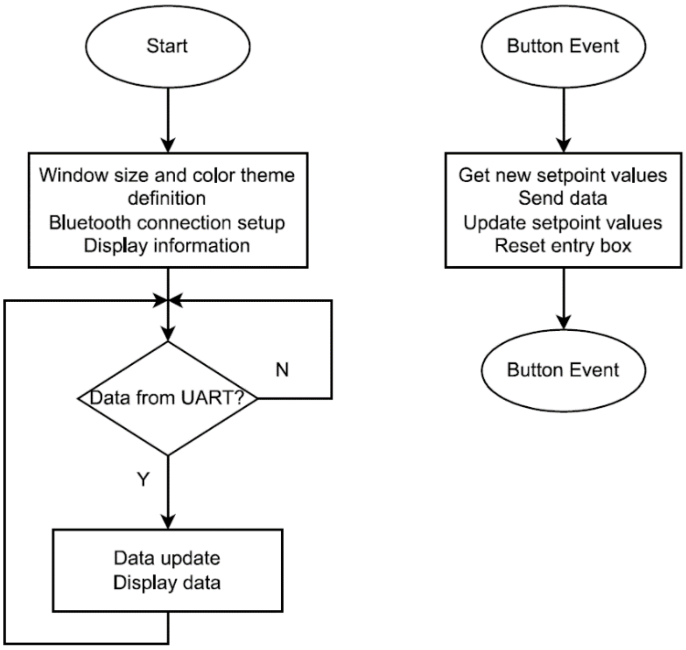
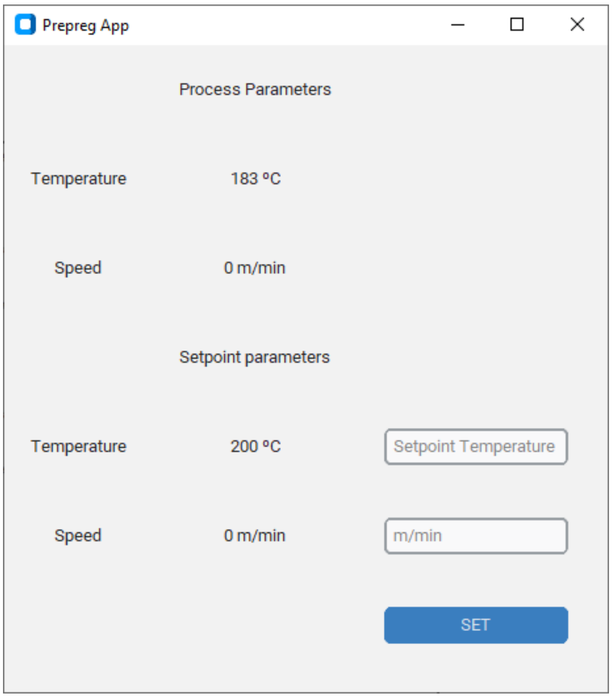


Figure 60 – GUI flowchart.

At start up, visual configurations for the application are defined such as application window size and colour theme. Besides this, the serial communication configuration is also configured in order to establish communication with the Bluetooth module. After the initial settings, the process information is displayed in the window according to the data received from the UART channel of the Bluetooth module. It also allows to input new setpoint values which are sent to the microcontroller. Figure 61 shows the solution's application.



Process Parameters

Temperature 183 ºC

Speed 0 m/min

Setpoint parameters

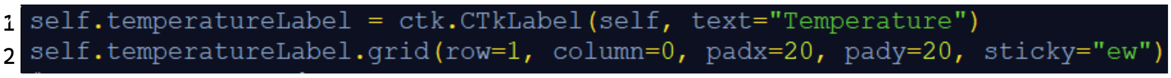
Temperature 200 ºC Setpoint Temperature

Speed 0 m/min m/min

Figure 61 – GUI window for visualisation and changing process parameters.

In the first lines of the application window is shown the process parameters data, temperature and speed, followed by the setpoint values desired in the last two lines. The two boxes on the right of the screen, in the setpoint parameters section, allows to change the process setpoint values by entering the desired values and sending them to the microcontroller via the *SET* button.

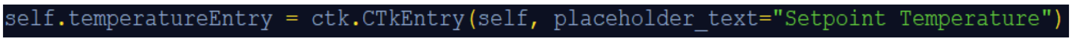
The information presented on the screen is possible by the methods of the *customtkinter* module. The *CTkLabel* method allows to display text in the window as represented in line 1 from Figure 62, specifically the *text* argument. In line 2, is defined the location of the text in the window grid.



```
1 self.temperatureLabel = ctk.CTkLabel(self, text="Temperature")
2 self.temperatureLabel.grid(row=1, column=0, padx=20, pady=20, sticky="ew")
```

Figure 62 – Text display functions from customtkinter for GUI.

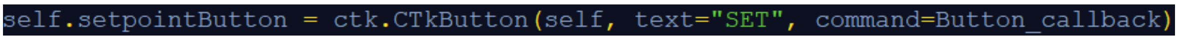
The *CTkEntry* method, represented in Figure 63, is responsible to define the data entry boxes, where the user can input values for the parameters setpoint. The *placeholder_text* argument allows to enter a place holder on the entry box to facilitate the user experience.



```
self.temperatureEntry = ctk.CTkEntry(self, placeholder_text="Setpoint Temperature")
```

Figure 63 – Text entry for GUI.

A button to send the process setpoint values to the microcontroller is created with *CTkButton*, as represented in Figure 64. The *text* argument allows to display a string inside the button and the *command* argument is an event callback after the button has been pressed. This button is a trigger to send the entry values to the microcontroller which is responsibility of the *Button_callback* function where this is performed.

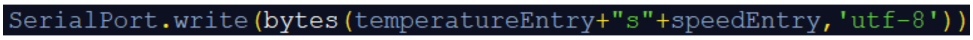


```
self.setpointButton = ctk.CTkButton(self, text="SET", command=Button_callback)
```

Figure 64 – Button configuration for GUI.

In order to establish Bluetooth communication with the microcontroller, it is necessary to use python's *Serial* module to establish serial communications. The connection port is then configured, as well as the Baudrate according to the device to be connected. In this case, the connection port is COM8 and the Baudrate value is 9600. The *Serial* module also provides the methods used to process and send the data transmitted between the devices.

The data transmitted also respects the protocol exemplified in Table 7. When the values are sent from the computer to the microcontroller, these are accepted as setpoint values to process control by the microcontroller. The *Button_callback* function gets the values from the entry boxes and send them to the microcontroller as shown in Figure 65.



```
SerialPort.write(bytes(temperatureEntry+"s"+speedEntry,'utf-8'))
```

Figure 65 – Serial data protocol for Bluetooth module.

5. RESULTS

After the design and project of the system it is necessary to validate it. This way, it is necessary to test the different components that satisfy the system requirements. This chapter describes the different tests and results of the developed solution.

5.1. TEMPERATURE CONTROL RESULTS

The main objective of the temperature control is for the system temperature to be as close as possible to the setpoint temperature. The first objective for the control unit is to approximate the system temperature to the setpoint temperature. Then, the system must be able to stabilize the temperature with little variation relative to the setpoint temperature. A satisfactory temperature interval variation would be in ±5°C of temperature setpoint value.

5.1.1. SYSTEM'S TEMPERATE CHARACTERIZATION

Regarding the control strategy for heating the system to the setpoint temperature, an on/off control technique was first evaluated. This is because it is necessary to understand the system's response to a simple control logic regarding changes in temperature.

Considering this, it was defined a test to increase the system's temperature in approximately ten Celsius degrees. This test allows to obtain a first impression of the system behaviour to temperature variation. In this regard, the system temperature is increased from ambient temperature, approximately 23 °C, to a setpoint temperature of 30 °C. For this, a simple on/off control was implemented where the system is powered until the setpoint temperature is reached. The results obtained from this test are represented in the graph of Figure 66.

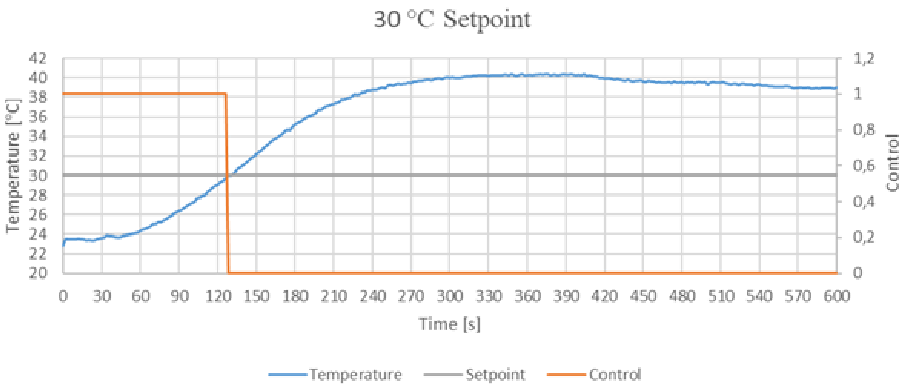


Figure 66 - System temperature evolution from ambient temperature to 30 °C.

From the observation of the graph, it is possible to conclude that the system cannot be controlled through an on/off strategy with the setpoint temperature being the cut-off condition. Despite the system having stopped powering the heating cartridges at the setpoint temperature, 30 °C, its temperature continued to increase due to the thermal inertia of the materials. While the system was supposed to stabilize the temperature at approximately 30 °C, it stabilized at 40 °C which represents an overshoot of approximately 10 °C. This must be considered when defining the system’s control strategy. This behaviour can have drastic consequences regarding the conservation of the properties of the polymeric material which is inside the heating chamber. The polymer should not achieve its degradation temperature, which is frequently near its processing temperature, hence the concern to control the temperature overshoot.

It is also noticeable from the graph of Figure 66 that after the system reaches its maximum temperature, its cooling rate is very low. This again highlights the thermal inertia of the system, but in this case related to cooling.

Another detail that demonstrates the system’s thermal inertia is the delay between the power of the heat cartridges and temperature variation from the initial temperature. In Figure 67 is represented in detail the evolution of temperature while the heat cartridges where being powered. It is possible to observe that, approximately, in the first 45 seconds the temperature remains relatively constant at initial temperature. After that, the increase in temperature is noticeable. This phenomenon highlights the thermal inertia of the system in terms of delayed system's response to the command to heat the system.

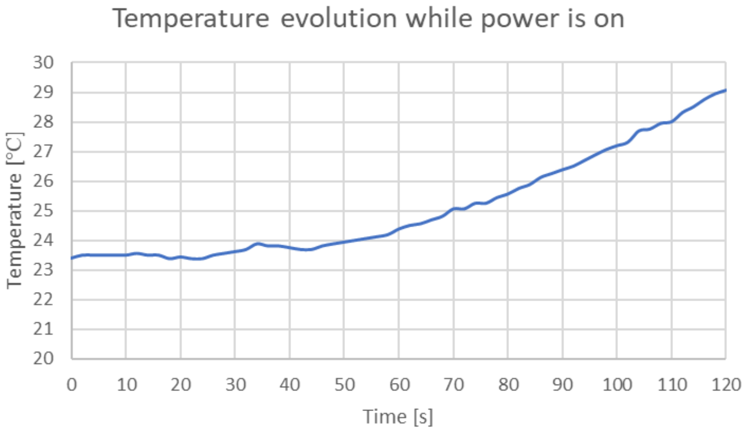


Figure 67 - Temperature evolution while the heat cartridges are powered on.

The thermal inertia observed is due to the material characteristics of the aluminium heating plates specifically the thermal capacity of this material. The thermal capacity of a material is defined as the amount of heat necessary to supply to the material in order to increase by one Celsius degree the temperature of one gram of the material [38]. Since the heating cartridges are inserted in the aluminium plates of the heating chamber, it is important to consider the specific heat of the aluminium. Due to the characteristics of the aluminium plates, namely their dimensions and high mass, the system has high thermal inertia since it stores heat energy from the heated cartridges. Besides this, there is also energy transfers between the other materials constituents of the heating chamber as well as heat losses to the surrounding air. All these characteristics influence the system's temperature behaviour.

In order to complement the characterisation of the system, a second test was performed. This test consisted in powering the system for a fixed period of sixty seconds and monitor the temperature. For this, three consecutive iterations were carried out in which the initial temperature is higher compared to the previous one. According to the specific heat capacity determined, a temperature variation of eight Celsius degrees could be expected. The results from this test are represented in Table 8.

Table 8 – Results from 60 seconds power test.

Test	Duration [s]	Initial θ [°C]	Máx θ [°C]	Δθ [°C]	$\Delta t_{Max\ \theta}$ [s]
1	60	19,5	28,75	9,25	283
2		26,94	35,06	8,12	241
3		33,81	41,69	7,88	230
Average		-	-	8,42	251,33

From this test it is possible to conclude that although the system was powered the same amount of time at each iteration, the temperature variation achieved is not the same. This can be justified by the laws of thermodynamics. Since the system is composed by the heating chamber and the surrounding air, which are at different temperatures, there are energy exchanges between them. In this case, this energy exchanges are considered energy losses.

Besides, it is possible to verify that the temperature increment at each iteration is smaller. This is due to the different initial temperature of each iteration. And according to thermodynamics laws, the greater the difference in temperature between two systems, the greater the rate of energy transfer between them. This test emphasize that temperature variation is not consistent, and temperature increment decreases at higher initial temperature.

From the tests carried out on the system it is possible to conclude that it presents high thermal inertia which is reflected in the slow response of the system to the control signal. In addition, it is necessary to take into account the thermal capacity of the system that reflects the temperature overshoot recorded. Finally, the temperature difference between the system and the ambient temperature also influences the rate of temperature increase of the system.

5.1.2. CONTROL STRATEGIES

Regarding the control strategy, it is necessary to take into account the characteristics of the system described above. There are several possibilities for temperature control, including on/off control and PID control. However, due to the characteristics of the system, high mass and thermal inertia, the hypothesis of an on/off control complemented by a hysteresis was explored [39]. The implementation of hysteresis aims to compensate for temperature overshoot effects in the system. Thus, it is necessary to define an adequate hysteresis interval for the system to reach the desired setpoint temperature and to keep it relatively constant, respecting the limits defined as satisfactory (± 5 °C of setpoint temperature).

This way, a control strategy consisting of two stages is developed. The first is related to heating the system to the setpoint temperature. The second is responsible for controlling the temperature in hysteresis range.

Regarding this, the first test consisted in evaluate the system's response at a higher temperature, near the processing temperature window of the thermoplastics. To minimize temperature overshoot, the setpoint temperature was defined at 200 °C and the power cut-off temperature ten Celsius degrees lower than the setpoint temperature. This way, the heated cartridges remain powered until the system's temperature reaches 190 °C. The temperature evolution from this test is represented in Figure 68.

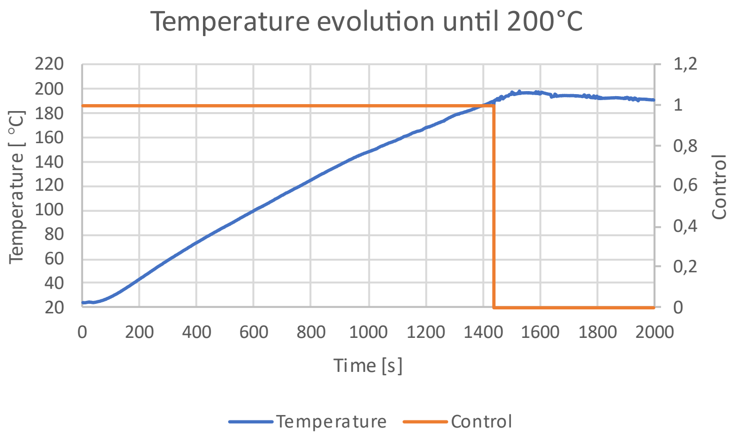


Figure 68 – Temperature evolution until 200 °C with cut-off delta of ten Celsius degree.

By analysing the temperature graph obtained it is possible to observe that through this technique no overshoot occurs. However, the system is unable to reach the desired temperature of 200 °C, so it will be necessary to adjust the cut-off temperature interval.

Thus, several iterations of this test were performed, varying the cut-off temperature value in order to find the most suitable value for the system. Monitoring the system's temperature at each iteration allows to establish the best value for the cut-off temperature. Since a ten Celsius degree difference between setpoint temperature and cut-off temperature was not able to reach the setpoint temperature, the starting value for the iterations was defined as half of its value, *i.e.*, five Celsius degrees. Each iteration varies the cut-off temperature by one Celsius degree according to the results obtained from the previous iteration. Finally, the test is completed once a temperature cut-off value is reached that fulfils the objective of not having an overshoot greater than five Celsius degrees from the setpoint temperature.

It is noteworthy that these iterations considered as the setpoint temperature 220 °C, which is a temperature value more representative of the processing temperatures of thermoplastics used in this manufacture process. The results obtained from the iterations are represented in Table 9.

Table 9 – Iteration results to determine cut-off temperature.

Iteration	Setpoint Temperature	Max θ [°C]
1	215 °C (θ_{ref} – 5 °C)	227,12
2	214 °C (θ_{ref} – 6 °C)	222,12
3	214 °C (θ_{ref} – 6 °C)	221,75

As previously mentioned, the iterations started at 215 °C, five Celsius degrees of interval between setpoint and cut-off temperature. The first iteration reached the desired setpoint temperature however it had an overshoot greater than the objective of the system. Thus, this value for the cut-off temperature had to be discarded and run a new iteration where the cut-off temperature is decreased by one Celsius degree corresponding to 214 °C.

In the second iteration the values obtained for the cut-off temperature already satisfy the objective of the system. The setpoint temperature was reached and the maximum temperature achieved was 222,12 °C. To validate this value, the conditions of this iteration were repeated in the third iteration. Again, the obtained results satisfied the objective of the solution. Therefore, a cut-off temperature that differs from the setpoint temperature six Celsius degrees is considered valid.

Finally, the system needs to be able to maintain the temperature within the specified temperature range, ± 5 °C from the setpoint temperature. For this purpose, a hysteresis temperature control is implemented in which the system's temperature does not vary beyond the desired temperature values range.

For hysteresis temperature control, several factors need to be considered. Firstly, the temperature range in which temperature variation is accepted, ± 5 °C from the setpoint temperature, as previously mentioned. Then, it is also necessary to define the intervals of change of control state according to the temperature evolution. Regarding this, 218 °C and 220 °C were defined as conditional temperatures. Being 218 °C the power off temperature when the system's temperature is increasing, in order to minimise the temperature overshoot beyond the desired range. And 220 °C is the power on temperature when there is a downward trend in temperature as represented in Figure 69.

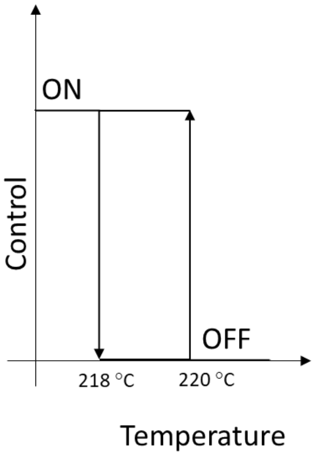


Figure 69 – Temperature hysteresis control.

This temperature hysteresis control is applied to the system and its temperature was monitored. The results obtained from this control test are represented in Figure 70.

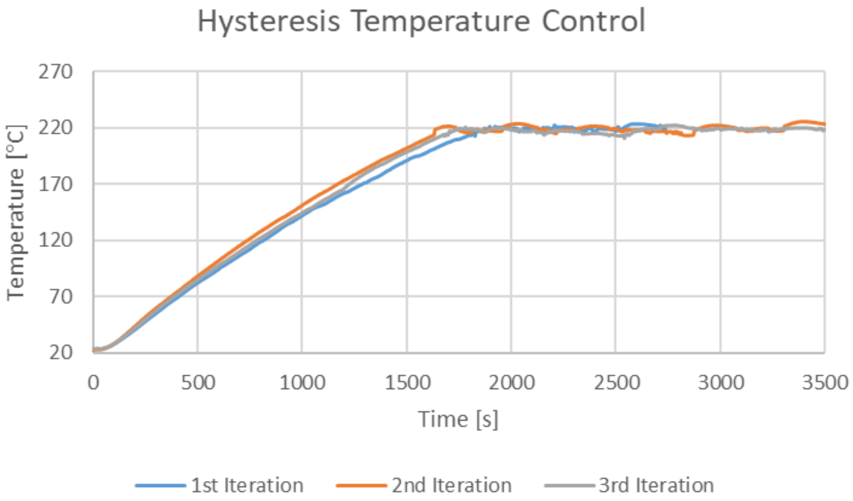


Figure 70 – Hysteresis temperature control results.

The hysteresis control strategy was executed three times and its ability to fulfil the system requirements was evaluated. Table 10 shows the maximum and minimum temperatures as well as the average temperature of the system with this control strategy.

Table 10 – Temperatures from hysteresis control strategy.

Iteration	**θ_{Max} [°C]**	**θ_{Min} [°C]**	**$\Delta\theta$ [°C]**	**Average θ [°C]**
1	223,38	214,81	± 4,29	219,57
2	223,94	215,06	± 4,44	218,95
3	222,62	211,19	± 5,72	217,48

It is noteworthy that with this strategy it is possible to comply in a satisfactory way with the system requirements. The temperature overshoot observed is acceptable since it is less then the setpoint temperature plus five Celsius degrees. The temperature variation registered at setpoint temperature averaged 4,81 °C which also complies with a variation of ± 5 °C from setpoint temperature. Finally, although the average temperature achieved is not exactly the setpoint temperature however it is very close.

6. DISCUSSION & CONCLUSION

This chapter focuses on the discussion and conclusions of the work carried out. It describes the solution implemented in order to fulfil the project's desired objectives.

6.1. DISCUSSION

Although composite materials are already present in industry, they are still the subject of new studies and search for new solutions. The use of new materials for their production poses new challenges for the manufacturing processes of composite materials. It is therefore necessary to support the development of technologies capable of satisfying new production methods.

The use of thermoplastics for the manufacture of composite materials requires a solution capable of controlling temperature as well as processing speed. In this regard, the solution presented in this work targets these requirements.

The production of thermoplastics composites requires temperature stabilisation in the range of processing temperature values characteristic of the material used. It is therefore desirable for the solution to reach the desired temperature and maintain it within a defined range of ± 5 °C. Given the characteristics of the solution's heating chamber, the temperature control system was able to fulfil the proposed objectives.

The viscosity of melted thermoplastics also presents a challenge in the production of these materials. Due to their high viscosity, it is difficult to pull fibres through the melted polymer. Hence it is necessary to implement a pulling system capable of exerting sufficient force to overcome this challenge. For this, a geared motor proved to be a good solution since these motors are capable of exerting high torques at the output of the geared system.

The material produced can be stored on reels, so the implementation of a material guidance system is advantageous. To this end, a mechanical system driven by a stepper motor was implemented.

The process is controlled by a microcontroller that receives the process setpoint parameters from a computer. Communication between these two units is via Bluetooth which allows remote control of the process. It also provides a window for visualising and adjusting process parameters. This is important as it allows the process to be adjusted for different thermoplastics which have different temperature and processing speeds.

It can be concluded that the solution developed fulfils the project's objectives.

6.2. FUTURE WORK

Regarding future work as improvement of this project there are some aspects that could be improved. For temperature control, other techniques, such as PID control, can be explored. It would also be advantageous to implement local control systems such as buttons and a display for manual work. The implementation of safety mechanisms such as emergency buttons can also be an improvement to the solution.

It would also be interesting to implement other functionalities in the GUI development. The introduction of processes with predefined parameters would allow for greater automation of the production process. Besides this, process data could be presented in other forms such as graphs.

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