# Automatic Control of Vacuum Infused Processes

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Thesis to obtain the Master of Science Degree in

**Mechanical Engineering**

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**November 2017**

# Abstract

This work presents automatic control solutions for vacuum infused processes using artificial vision. Current vacuum infusion processes control solutions are dependent on skilled labour and based on open loop control structures. In addition, they rely solely on valve actuation, which decreases the possibilities for an accurate process control.

The accurate control of the resin flow speed through the fibrous material is crucial for the manufacturing of high quality composite materials. Therefore, an adaptive control solution is proposed to address the time-variant dynamics and the need for a versatile and accurate solution. This controller regulates the resin flow speed by adjusting the pressure difference inside the part mold, using an adaptive PI controller with parameters that adapt to the plant dynamics at each time instant.

The proposed solution starts with the identification of an appropriate dynamic model for the system, then an adaptive controller is designed and tested in an experimental Vacuum Assisted Resin Transfer Molding laboratory setup.

**Keywords**: Vacuum Infusion, Process Automation, Automatic Control, Adaptive PID, VA-RTM.

# Resumo

Este trabalho apresenta soluções de controlo automático para processos de infusão a vácuo, usando visão artificial. As soluções atuais de controlo de processos de infusão a vácuo dependem de mão-de-obra qualificada e baseiam-se em estruturas de controlo em anel aberto. Além disso, estas soluções actuam apenas nas válvulas de alimentação, o que reduz as possibilidades de projectar uma solução de controlo de maior precisão.

O controlo preciso da velocidade do fluxo de resina através do material fibroso é crucial para a fabricação de materiais compósitos de alta qualidade. Uma solução de controlo adaptativo é proposta para abordar a dinâmica não-linear do sistema e a necessidade de uma solução versátil e precisa. O controlador regula a velocidade do fluxo de resina, ajustando a diferença de pressão dentro do molde da peça, usando um controlador PI com parâmetros que se adaptam à dinâmica do sistema ao longo do tempo.

A solução proposta inicia-se com a identificação de um modelo dinâmico do sistema, posteriormente o controlador é projetado e testado numa instalação experimental de infusão a vácuo em ambiente laboratorial.

**Palavras-chave**: Infusão a vácuo, Automação de processos, Controlo automático, PID adaptativo, VA-RTM.

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# List of Acronyms

| | |
|---|---|
| **CAPIV** | Automatic Control of Vacuum Infused Processes |
| **IDMEC** | Institute of Mechanical Engineering |
| **INEGI** | Institute of Science and Innovation in Mechanical and Industrial Engineering |
| **LAETA** | Associated Laboratory for Energy, Transports and Aeronautics |
| **MSE** | Mean Squared Error |
| **PI** | Proportional Integral |
| **PID** | Proportional Integral Derivative |
| **RLS** | Recursive Least Squares |
| **RLSE** | Recursive Least Squares Estimator |
| **VA-RTM** | Vacuum Assisted Resin Transfer Molding |
| **VIP** | Vacuum Infused Process |
| **ZOH** | Zero-Order Hold |

# 1. Introduction

This work is integrated in a project promoted by the Associated Laboratory for Energy, Transports and Aeronautics (LAETA) and it is being developed in cooperation between the Mechanical Engineering Institute (IDMEC) and the Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI) research units. Their goal is “to transfer new technologies, to implement new engineering procedures of project, design, manufacturing and testing of products and to promote the dissemination of knowledge and the education and training of technicians and engineers to overcome existing lacks in education and to acquire new competences” [1].

This work consists in the design of an automatic control solution for the manufacturing of high quality composite materials in vacuum infused processes, which depends heavily on the accurate regulation of the resin flow speed through dry fibers. This is accomplished by applying an adaptive controller to the pressure difference inside the mold and monitoring the resin flow position through artificial vision.

The development of this control solution is based on an experimental setup located in the facilities of INEGI. This experimental setup replicates a Vacuum Assisted Resin Transfer Molding (VA-RTM) process.

The adaptive controller structure consists of a Proportional Integral (PI) controller with time-varying parameters dependent on the evolution of the system dynamics which is identified online through a Recursive Least Squares (RLS) algorithm.

## 1.1. Context

### 1.1.1. Composite materials

A composite material is a material made from two or more materials with significantly different proprieties that, when combined, produce a material with different proprieties than the individual components.

There are two main categories of constituent materials: matrix and reinforcement. The matrix acts as a binder for the reinforcement while controlling the physical shape and dimensions of the part. Its primary purpose is to transfer the load, or stress, applied to the part, to the reinforcement. The matrix also protects the reinforcement from adverse environmental effects. The reinforcement’s function is to enhance the mechanical properties of the composite and is typically the main load bearing element. Reinforcements are usually in the form of fibers. Matrix and reinforcement materials can be polymers, metals, ceramics, or carbon.

The mechanical proprieties of the composite materials result from the individual proprieties of each component and from the type of bond formed by them. The matrix material can be a metal, a ceramic or a polymer.

A composite material with a polymer matrix is usually made with thin layers of polymer fibers, forming a fiber reinforced composite material. These thin layers of fibers are called laminate, they make up for most of the volume, being the main component of the final product. By adjusting the number of layers and their orientation it is possible to achieve a desired thickness and different mechanical proprieties.

The use of composite materials, specially carbon fibers and glass fibers, allows for great improvements in several industries, mainly due to their high strength-to-weight ratio. They are widely used in the nautical and automotive industries, mainly in boat hulls, car chassis and body parts. Nowadays the use of composite materials in the energy sector is increasing, due to its wide application to wind turbine blades [2].

### 1.1.2. Relevant manufacturing processes

The most relevant manufacturing methods used to manufacture fiber-reinforces polymers include:

- Manual Lay-Up
- Spray-Up
- Filament Winding
- Resin Transfer Molding
- Vacuum infusion

Manual lay-up (Figure 1) is the most basic process for this type of materials. It is highly reliable but requires a significant amount of supervision and skilled labor during a long period of time. It consists of placing previously cut pieces of fiber over the mold by hand, and infusing them with resin by pouring it over. The resin impregnated matrix material needs to be hand-rolled to remove any air bubbles trapped inside and to guarantee an even thickness and distribution. This process can also be accomplished using pre-impregnated fibers, which simplifies it by removing the need for separate handling of the matrix and reinforcement.

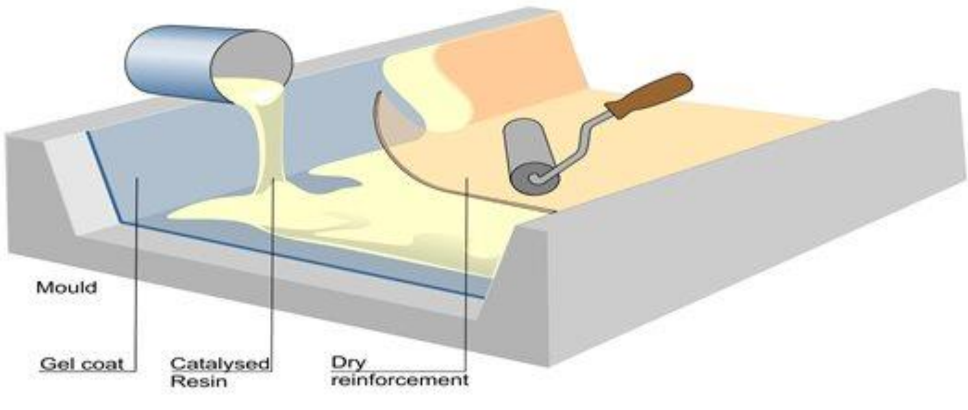


Figure 1 - Manual lay-up [3]

In spray-up (Figure 2), a spray gun applies simultaneously the resin and chopped pieces of fiber, impregnating them as they get to the mold, which requires a lower time expense and increases the process efficiency. This process also needs subsequent hand-rolling for the removal of air pockets and surface homogeneity.

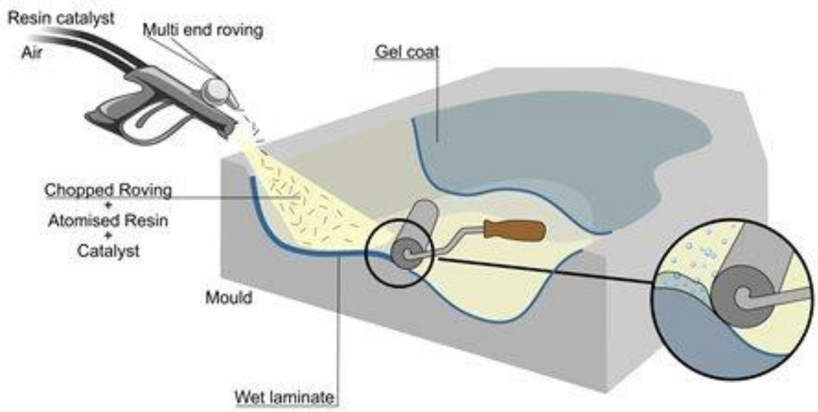


Figure 2 - Spray-up [3]

Filament winding (Figure 3) uses a rotating mold to wind impregnated fibers around it. The fibers are continuously fed into a resin bath before being wound around the mold, which ensures their impregnation. This process has a great increase in efficiency as the fibers and resin application can be automated, however, it is limited to axisymmetric parts as the resin impregnated fibers must be wound up around a mandrel.

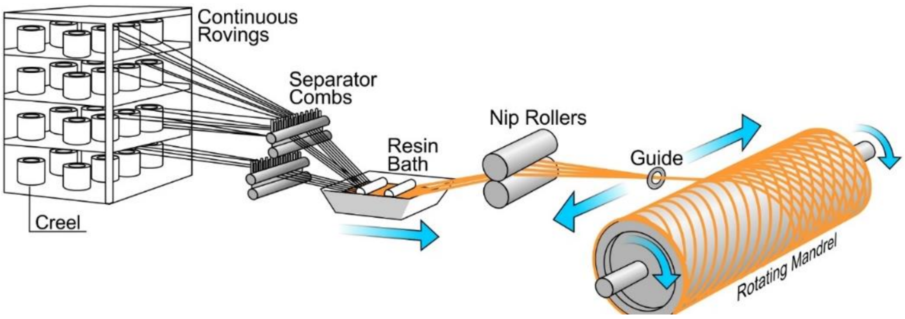


Figure 3 - Filament winding [3]

In Resin Transfer Molding (RTM) the dry fibers are loaded inside a closed rigid mold (Figure 4), which is filled with resin either by letting gravity push it through the fibers or with the help of a pump. This process allows for a higher fiber to resin ratio, which affects positively the mechanical proprieties of the manufactured parts.

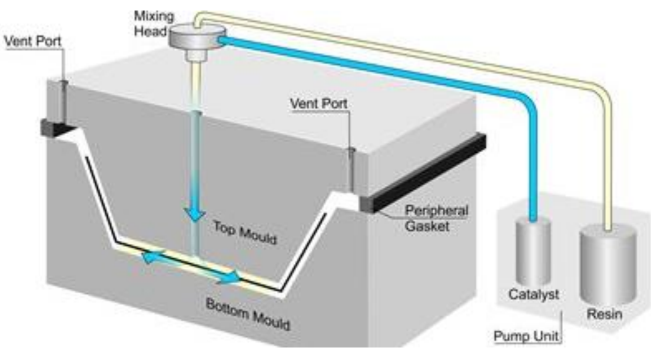


Figure 4 - Resin Transfer Molding [3]

### 1.1.3. Vacuum infusion processes

Vacuum Infusion Processes (VIP) are a subcategory of closed mold processes that distinguish themselves by using vacuum to infuse resin into the laminate. A great advantage of the VIP (Figure 5) is the manufacturing of parts with very high fiber content.

The first step in the preparation of these processes is loading the fabric fibers and core materials into the mold. Next the dry material is sealed using a vacuum bag or a counter mold. A high vacuum pump is used to remove all the air in the cavity and consolidate the fibers. Still under vacuum, resin is infused into the mold cavity to wet out the fabric fibers.

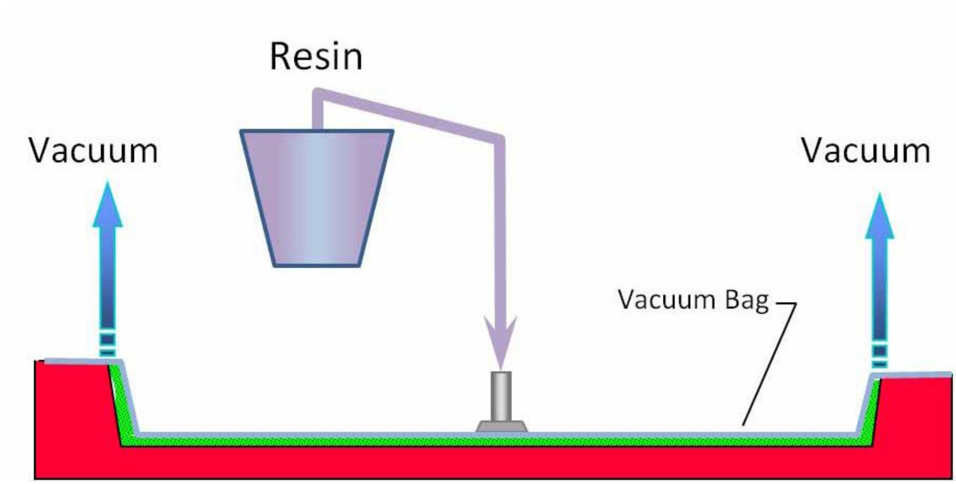


Figure 5 - Vacuum Infused Process [4]

The vacuum infusion process is a very simple concept, however, it requires detail planning and process design, so the parts can be infused in a reasonable amount of time without any dry spots. The quality of an infusion depends on several factors that need to be controlled by skilled workers. Therefore, the decisions made by the workers are critical in making good parts, which makes this process highly dependent on skilled labour.

### 1.1.4. Vacuum Assisted Resin Transfer Molding

There is a variant to the vacuum infused processes category called Vacuum Assisted Resin Transfer Molding (VA-RTM). In this process, the fibers are placed inside a rigid mold which has an inlet connected to a resin container and an air outlet connected to a vacuum pump, typically placed on opposite ends of the mold, as seen in Figure 6:

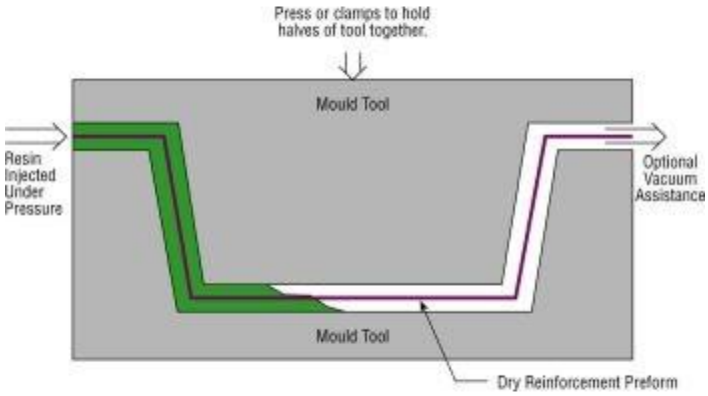


Figure 6 - Vacuum Assisted Resin Transfer Molding [5]

This process allows for better control of the resin flow when compared to a normal vacuum infused process. The rigid mold ensures that the resin only flows through the fibers, whereas the vacuum bag can create resin pockets above the fibers, causing unexpected variances in the resin flow.

## 1.2. Related work

This chapter addresses the present state of control strategies applied to VIP in composite materials manufacturing.

### 1.2.1. Manufacturing problems

The quality of a part manufactured by VIP is dictated by the amount of resin that penetrates the fibers. A perfect infusion is one where the fibers are completely immersed in resin. The main defects that occur in VIPs are dry spots, micro voids and macro voids. These defects lead to areas in the fibers that do not have hardened resin binding them and therefore have lower mechanical resistance and increased risk of cracking or fracture [6].

Nowadays the VIPs are highly dependent on human supervision. In order to avoid dry spots or voids, the speed of the resin flow is carefully monitored as both high and low flow speeds lead to flawed parts.

The main disadvantages of human supervised VIPs are the costs of skilled labor, the long time spent in each infusion and the high number of parts that are discarded due to flawed infusions. This leads to financial losses and inefficiencies that can be improved using automatic control strategies.

### 1.2.2. Control solutions

Some attempts to solve these problems rely on open loop control strategies, where the control action is not related to the system state or any disturbances. These solutions are more common in processes where the system dynamics can be easily calculated and predicted to a certain extent, leading to a model that becomes the basis for the controller design.

The development of open loop control strategies of vacuum infused processes starts with the analysis of the desired geometry and the injection strategy deliberation (i.e. the placement of the resin injectors). The resin infusion is analyzed in a simulation that predicts the formation of dry spots, macro and micro voids. With the simulation results, the injection strategy is tuned, and the formation of defects is minimized. However, despite having a reduced need for parameter adjustment, the presence of a skilled laborer is still required to supervise the process in case of an anomaly.

Another approach to this problem is to have feedback on the system state measured by sensors, thus closing the control loop. The use of feedback can overcome disturbances by having the control action based on the error between a reference and the actual system state. As in the open loop approach, the closed loop controllers also require a previous study of the systems dynamics. Despite being more complex, this approach allows for more accurate control solutions [7].

### 1.2.3. Previous contributions

This work is part of a research project whose goal is the development of automatic control strategies for vacuum infused processes. It relies on previous contributions by Silva [8] and Sousa [9].

Silva has developed an experimental setup that consists of a rectangular mold with sensors and actuators that allow for the study of vacuum infusions in a controlled environment. His work consists in developing the experimental setup that serves as basis for this project and modelling its dynamics using a white-box modelling approach. The obtained dynamic model was based on the physical principles involved in the VIP and resulted in the following differential equation:

$$\frac{dx_{ff}}{dt} = \frac{C_r}{x_{ff}} \cdot (\mathrm{P}_e - P_v + a_c) \tag{1}$$

Where $x_{ff}$ is the resin flow position; $\mathrm{P}_e$ and $\mathrm{P}_v$ are the pressure at the resin inlet and at the air outlet, respectively; $C_r$ and $a_c$ are variable parameters that correct the non-linearities in the system [8].

Sousa developed a pressure control subsystem in the resin container and applied a PI controller to the overall system in a first attempt to control the process. The pressure control was accomplished by regulating the connection of the resin container to a vacuum pump and the ambient air, separately, through a valve action in each connection. This resulted in a controlled subsystem with a significantly faster dynamics than the overall system, which enables the development of active control solutions applied only to the pressure difference and the resin flow position, bypassing the pressure control inside the resin container [9].

## 1.3. Problem resolution

These previous contributions have found that the speed of the resin flow through the fibers is the factor that most influences the overall quality of the manufacturing process. This premise directed the previous control solutions towards maintaining the resin flow speed at a constant value. It has also been found that the resin flow speed is highly influenced by the pressure difference between the resin container and the vacuum at the air outlet [8] [9].

The vacuum infusion processes are difficult to model and control due to the unpredictability of the system dynamics. It varies with factors that cannot be predicted, and has a time-variant behavior throughout the infusion.

This work proposes to solve this problem by implementing an adaptive PI controller to the pressure in the resin container, which identifies the system dynamics online and adjusts the parameters of a PI controller accordingly.

## 1.4. Research methodology

This work is integrated in the project Automatic Control of Vacuum Infused Processes (CAPIV) that has been developed by LAETA. It is based on experimental results of a setup located in INEGI facilities, thus continuing the previous contributions towards this common goal.

The experimental setup mimics the behavior of manufacturing a typical part through a VA-RTM process. This allows for better study of the process, as it provides a simplified and controlled environment.

There are three main stages in designing this controller:

1. System identification and dynamics modelling
2. Controller design and simulation
3. Experimental testing

### 1.4.1. System identification

This first step consists in analyzing the system inputs and outputs and finding an accurate transfer function.

As previous contributions to this project adopted a white-box modelling approach struggled to replicate the system behavior, in this work a black-box modelling approach will be used to complement it. However, as part of the white-box modelling results are taken into consideration, this approach can also be considered as a grey-box modelling. The analysis is made through *Matlab* software using information from several sensors located in the experimental setup.

In systems identification, the main requirement is that the most important operating regions of the system are persistently excited. Despite being aware that more experimental results lead to a more accurate identification, in this project they need to be well planned as they are costly and time consuming [10].

The experiments consist of a series of infusions where the pressure difference (system input) varies in steps and ramps, allowing the use of basic system identification tools as well as more advanced ones, such as *Matlab System identification toolbox.* The dynamic modelling combines these techniques with empirical judgement and critical reasoning about the system and the experimental results.

### 1.4.2. Controller design and simulation

In controller design, model structure and model parameters highly influence the controller performance. Therefore, after having obtained a dynamic model that reasonably resembles the dynamics of the real system, a controller is designed taking into account some desirable specifications.

The most important goal of the controller is to meet the performance requirements set beforehand. It is also recommended that the controller solution chosen is as simple as possible to allow for an easy implementation and adaptation to similar processes.

After having outlined a control strategy and a preliminary controller, the controller is tested and improved based on a simulation model implemented in *Simulink.*

### 1.4.3. Experimental testing

The controller performance validation consists in comparing the controlled output with a desired reference. This comparison is performed using an experimental setup located in the INEGI facilities that replicates the VA-RTM process.

## 1.5. Objectives

This project presents a solution for the control of the resin flow speed in a Vacuum Assisted Resin Transfer Molding process. This is achieved by applying the methods described in the previous section to an experimental setup.

- Development of a dynamic model for the process
- Design the overall control system
- Implement and test the controller at an experimental setup

### 1.5.1. Experimental results

The overall controller performance is evaluated by applying it to the VA-RTM process replicated in the experimental setup. Although the main goal of this work is the regulation of the resin flow speed, the control action is applied to its integral, the resin forefront position, to avoid having a derivative inside the control loop. This means the controller is required to follow a positional reference in the shape of a ramp, whose slope reflects the desired speed. Considering the sensor resolution is 1 mm, the controller is meant to follow the set reference with an error lower than 2 mm and settle into that range before the resin reaches 10% of the full length of the part.

## 1.6. Document structure

This document presents an experimental approach to the automatic control of the resin flow in a VA-RTM process. This document is divided in 6 chapters with the following structure:

Chapter 1 introduces the project, provides the composite material manufacturing context, and presents the approach adopted in this work.

Chapter 2 addresses the experimental setup in which the dynamic modelling and controller testing are based on. Here, the components of the setup are explained to better understand the influence of each detail. Also, the data resulting from the sensors and the input expected by the actuator are discussed.

Chapter 3 presents the dynamic modelling of the process. Here the data collected from the experimental setup is analysed to reach a model that mimics the system behaviour with a high degree of accuracy.

Chapter 4 describes the control strategy adopted to regulate the behaviour of the system. Its structure is developed according to the model previously obtained in chapter 3.

In chapter 5, the performance of the controller designed in chapter 4 is analysed. Its results are discussed to assess the success and overall quality of the controller when applied to a real process.

Chapter 6 summarizes this work contributions, provides critical judgement towards the results obtained, and proposes improvements for future contributions to this project.

# 2. Experimental setup

A considerable part of this work relies on the analysis of experimental data obtained from an experimental setup of a Vacuum-Assisted Resin Transfer Molding process that has been specifically designed for this project. Its main purpose is to provide a controlled environment to minimize the influence of unpredictable or uncontrollable factors. It is of most importance to ensure that all experiments are performed under similar conditions so that they can be compared [8].

The setup is composed mainly by the following parts:

- Acrylic mold
- Vacuum pump
- Resin container
- Pressure sensors
- Valves
- Camera

## 2.1. Setup description

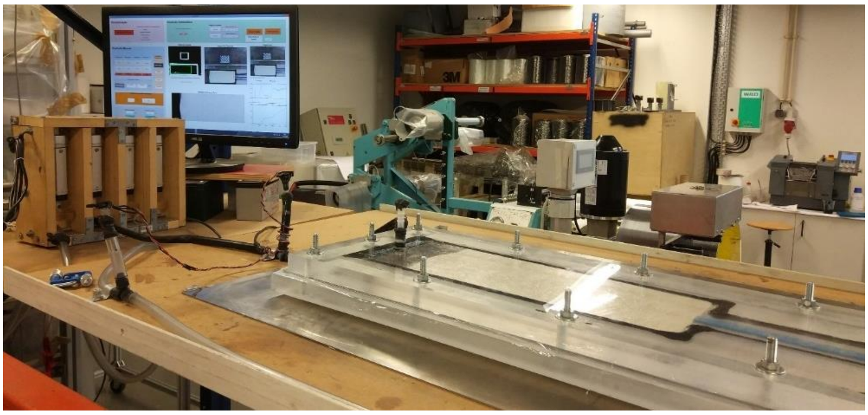

Figure 7 - Experimental setup

The experimental setup (Figure 7) assembly is depicted in the Simulink block diagram presented in Figure 8:

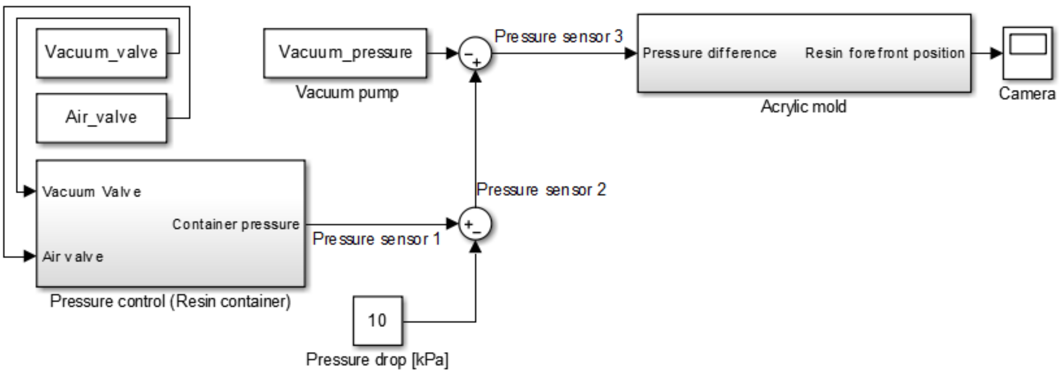


Figure 8 - Simulink block diagram of the experimental setup

The resin flow forefront position is measured by a common webcam placed above the acrylic mold. The position is influenced mainly by the pressure difference between the mold inlet (connected to a resin container) and its outlet (connected to a vacuum pump). The resin container has its own pressure control subsystem (Figure 9) that adjusts the pressure at the resin inlet by regulating the state of two valves, connected to the vacuum pump and the ambient air, separately.


Figure 9 - schematic representation of the pressure control subsystem [9]

In this setup, the mold (Figure 10 and Figure 11) is made of transparent acrylic to enable the observation of the infusion state, providing feedback to the system and closing the control loop. It consists of two flat pieces spaced by narrow metallic plates around the edges and attached by 12 evenly distributed bolts and nuts also placed around the edges, forming a rectangular cavity whose thickness can be adjusted by varying the number of plates.

Figure 10 - Acrylic mold, bottom piece

The top piece of the mold has one hole at each end for the resin input and the air output, connected to the resin container and the vacuum pump, respectively.

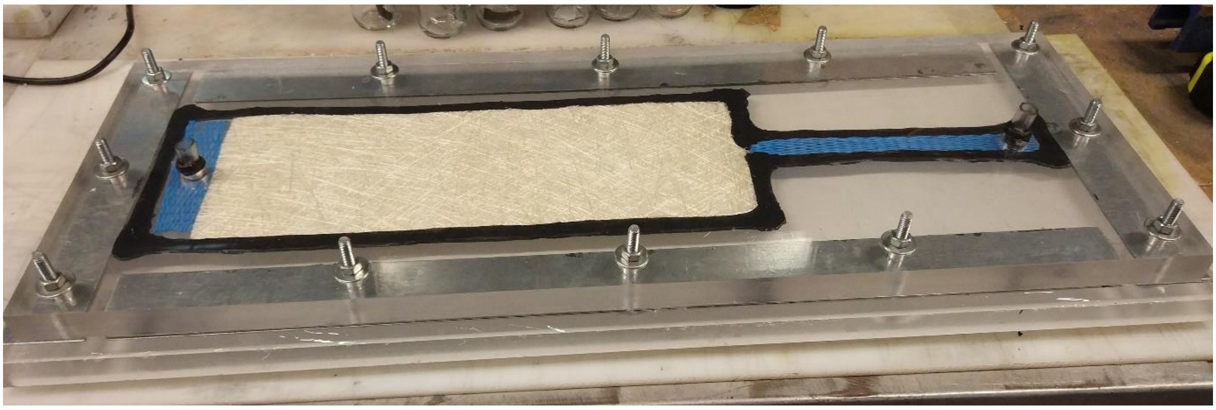

Figure 11 - Acrylic Mold, full assembly

The vacuum pump (Figure 12) can set a pressure of 10 kPa and is connected to one end of the mold and to the resin container, to impose a near-vacuum pressure in the mold and to enable for the pressure control in the resin container.

Figure 12 - Vacuum pump

The resin container valves actuate according to a control system previously developed by Sousa (2017). The dynamics of this subsystem are significantly faster than the one of the development of the resin flow forefront, which means that its delay can be neglected [9].

## 2.2. Sensors and actuators

The artificial vision for the output measurement and the input pressure control subsystems have been previously developed by Silva (2016) and Sousa (2017).

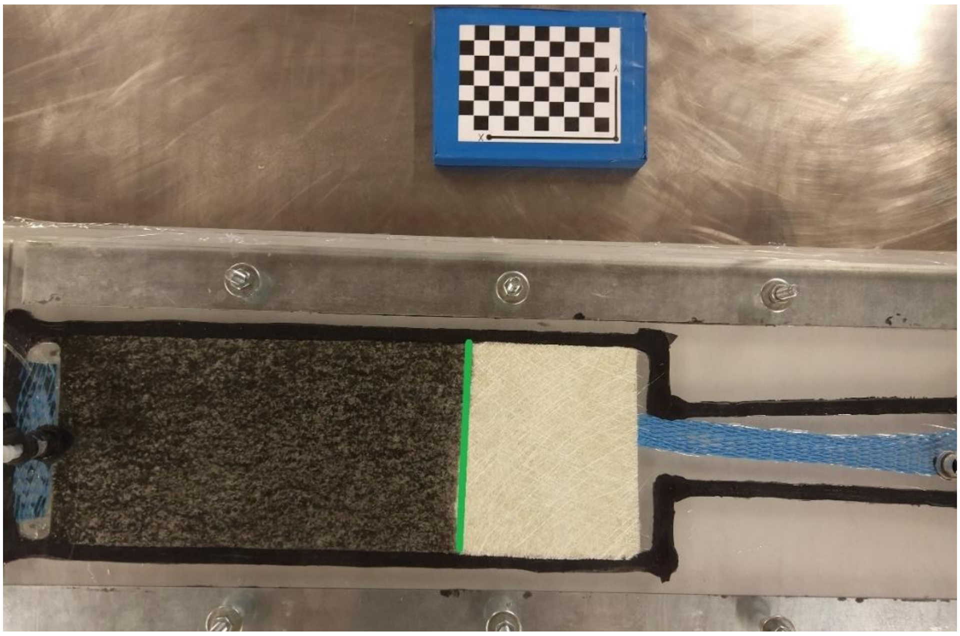

Figure 13 - Camera view

The camera is a common webcam placed above the mold that captures the resin forefront position in real time, as seen in Figure 13. An artificial vision algorithm is adopted to identify the resin flow forefront position by applying a threshold to the acquired image, distinguishing the white fibers from the resin mixed with a coloring agent. The artificial vision subsystem is applied to a 400 mm long Region Of Interest (ROI) and is capable of identifying the resin forefront position with a resolution of 1 mm [8].

Figure 14 - Pressure sensor

The pressure is measured at three points in the system: inside the resin container, at the air outlet and at the resin inlet close to the mold. The pressure sensors (Figure 14) located at the mold inlet and outlet allow for the measuring of the pressure difference, which is the main influencing factor of the resin flow speed. The sensor located in the resin container is part of the actuation subsystem.

Figure 15 - Actuation valve

The control action is made through the resin container, by imposing a desired pressure inside it. This is achieved by manipulating two separate valves (Figure 15) that connect the container to the vacuum pump and the ambient air [9].

## 2.3. Variables description

The system dynamics can be described by two main variables: pressure difference inside the mold and resin forefront position.

Although the main goal of this project is to control the resin flow speed, the control strategies are applied to the resin flow position, to avoid noise amplification that results from computing its derivative over time. Therefore, the resin forefront position is considered to be the system output, i.e. the variable meant to be controlled. It is measured by the camera, which can identify positional variations inside a 400 mm long region of interest with a 1 mm precision.

The difference between the pressure at the resin inlet and at the air outlet is the main influencing factor of the resin flow behavior, which makes it the system input, i.e. the controllable variable. The pressure difference is influenced by the constant low pressure applied by the vacuum pump and the variable pressure inside the resin container, where a pressure control subsystem is in place [9].

# 2.4. Pressure control subsystem

The pressure difference is the difference between the pressure at the resin inlet and at the air outlet. In order to control it, a pressure control subsystem has been developed by Sousa (2017). The pressure at the air outlet is determined by the vacuum pump and it is approximately 10 kPa. The pressure at the resin inlet is a result of the imposed pressure in the resin container associated with a pressure drop that occurs between the two locations (Figure 16).

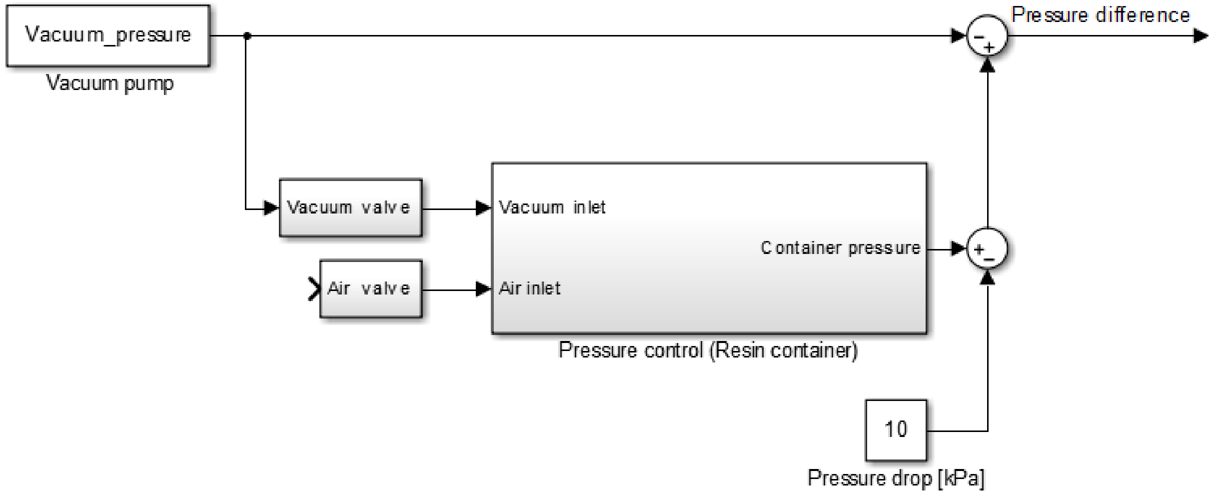


Figure 16 – Simulink block diagram of the pressure control subsystem

The resin container has two separate valves connected to the vacuum pump and the ambient air. The pressure inside is controlled by manipulating their state. The resulting pressure difference varies between 0 kPa and 80 kPa.

As the dynamics of this subsystem is considerably faster than the advance of the resin flow, this subsystem can be bypassed and its influence in the overall dynamics can be neglected [9].

# 3. System identification

This chapter presents the development of a dynamic model that accurately describes the system dynamics. In order to reach it, the followings steps are considered:

1. Defining the inputs and outputs from the system meant to be identified
2. Processing and selecting the relevant data
3. Analyzing the system responses
4. Assume a plausible model structure
5. Identifying the model parameters
6. Validating the model

The system identification resulted in a dynamic model with three main characteristics:

- first order integrator dynamic behavior
- time-variant parameters
- dependence on external factors

Despite not having reached a parametric model that fits all the experimental data, the model structure is adequate to describe the VA-RTM process general behavior and serves as basis for a control solution. Its open loop transfer function is described in equation (2):

$$\hat{G}(s) = \frac{1}{T(x) \cdot s} \qquad ; \qquad T(x) = C \cdot x \tag{2}$$

## 3.1. Data

The data analyzed in this section results from infusions performed in the experimental setup described in chapter 2. For each infusion it is possible to collect the following data over time:

- Resin forefront position
- Pressure at the resin inlet
- Pressure at the air outlet

As previously stated, the goal of this project is to control the speed of the resin flow, whose main influencing factor is the pressure difference inside the mold. Therefore, the system input is that same pressure difference, which can be manipulated by maintaining the vacuum pressure at a constant value and adjusting the pressure inside the resin container. As the subsystem that controls the pressure difference has been developed by Sousa (2017), it can be bypassed, and the pressure difference is considered the input to the system.

The resin flow speed control is achieved through the regulation of the resin forefront position. The resin flow speed can be regulated and maintained near a specific value by making the resin forefront position follow a ramp shaped reference, whose slope reflects the desired speed.

This identification requires a set of experimental data that excites the most relevant regions of operation. It is done in two distinct stages. The first one is to compare the system response to constant inputs, each at a different value. And secondly the system is subject to steps with different sizes throughout the infusion.

## 3.2. First-order integrator dynamics

This section presents the analysis of the resin flow response to a constant pressure difference input., which led to the assumption of a first-order dynamics

The first sets of experimental data to be considered are three infusions where the pressure difference remains constant.

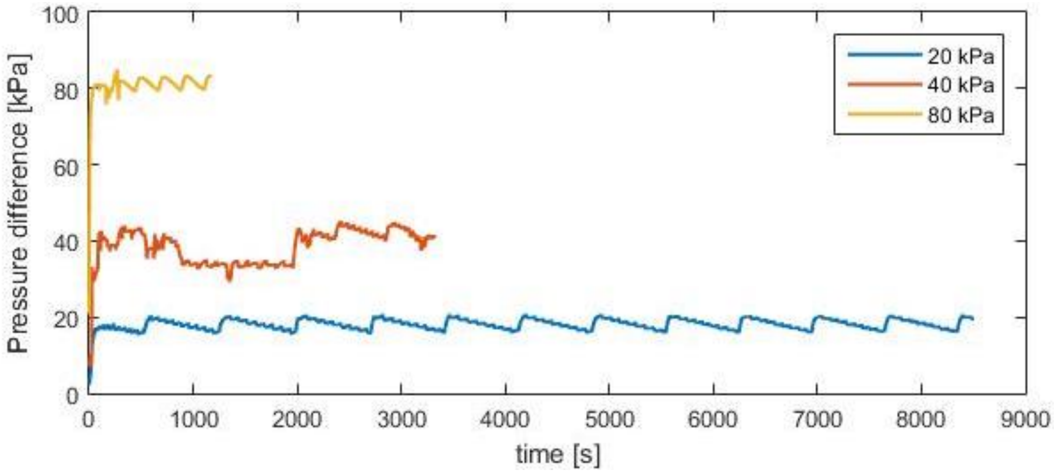


Figure 17 - Pressure difference: Constant inputs

The pressure difference remains constant throughout each infusion, at approximately 20 kPa, 40 kPa and 80 kPa. Although a small variance at the input can be observed (Figure 17), it has no considerable influence in the resin flow and it only happens due to the vacuum pump bang-bang controller.

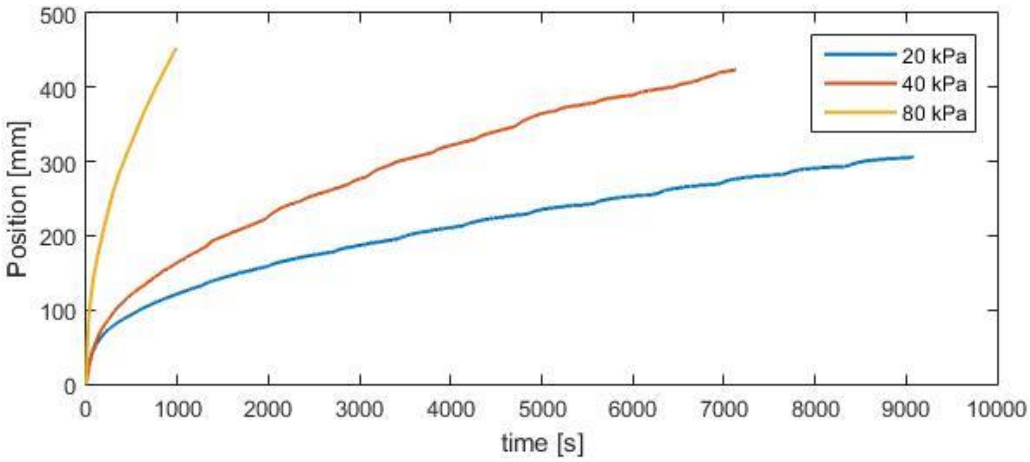


Figure 18 - Forefront position: Response to constant inputs

With a relatively constant input, the resin forefront position increases through the whole experiments (Figure 18), which leads to the hypothesis that the system presents a first-order integrator dynamics.

## 3.3. Time-variant parameters

The three experiments presented earlier are combined into a piecewise linearized model to better understand their joint dynamics:

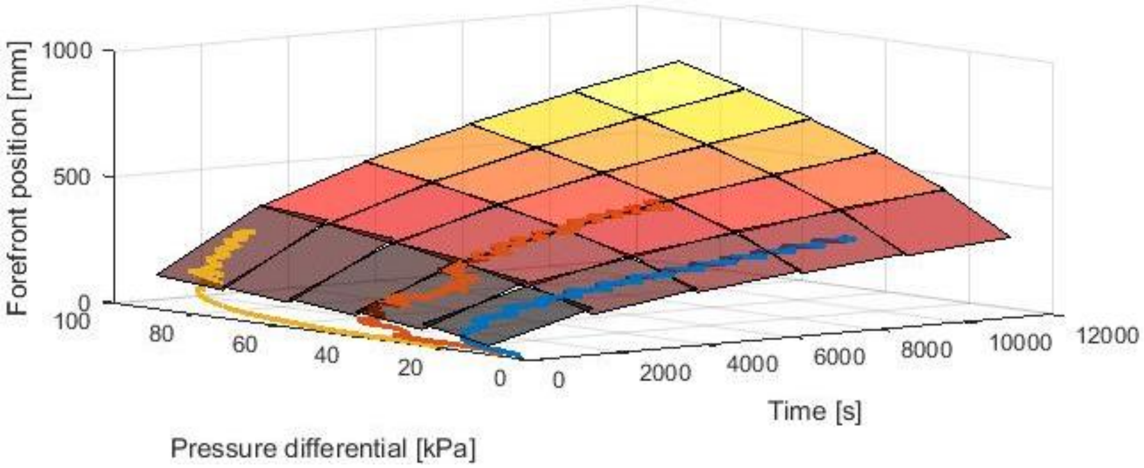


Figure 19 - Piecewise linearization (5x5)

This representation of a linearization (Figure 19) indicate that the system dynamics are time-variant. The forefront position increases according to the pressure difference, but its growth rate decreases with the advance of the resin flow, as seen in Figure 19 confirmed in a more detailed linearized extrapolation (Figure 20):

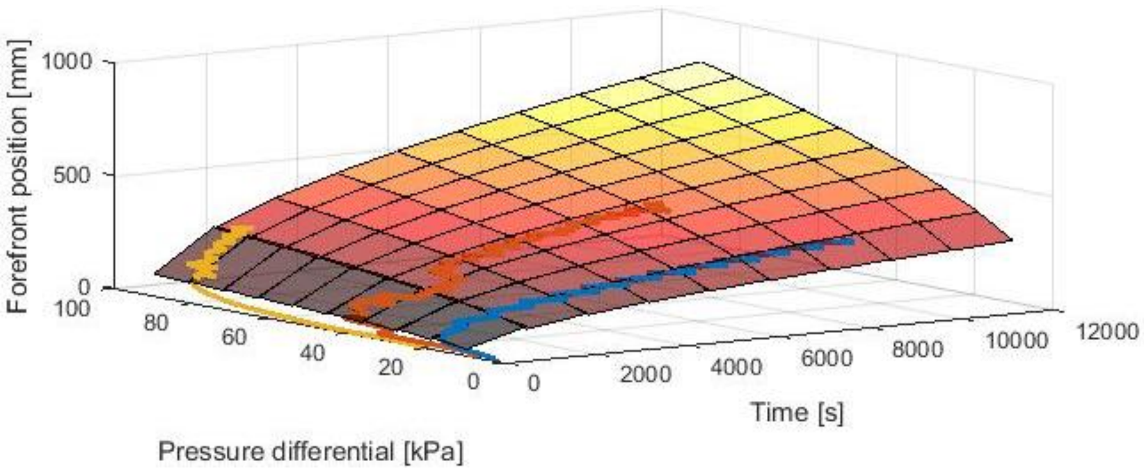


Figure 20 - Piecewise linearization (9x9)

Considering the continuous increase with a constant input and the time-variant growth rate, the following model structure is assumed:

$$\hat{G}(s) = \frac{1}{T(x) \cdot s} \qquad ; \qquad T(x) = C \cdot x \tag{3}$$

Here, the estimated transfer function consists of an integrator with a proportional component that varies in inverse proportion with the resin forefront position, $x$, in $mm$ and a coefficient of proportionality $C$. The function $T(x)$ represents the time-variant behavior present in the system.

## 3.4. Validation

After observing responses to constant inputs, a series of experiments are performed to validate the model structure. These experiments analyze the system response to steps in the input variable, which are designed to stimulate the most regions of operation and to achieve a more complex output signal that allows for better behavior analysis.

The proposed model response is compared to the experimental data and its parameters are adjusted to better fit the system response by minimizing the Mean Squared Error (MSE):

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)^2 \tag{4}$$

Where $\hat{Y}_i$ is the model output and $Y_i$ is the measured system response.

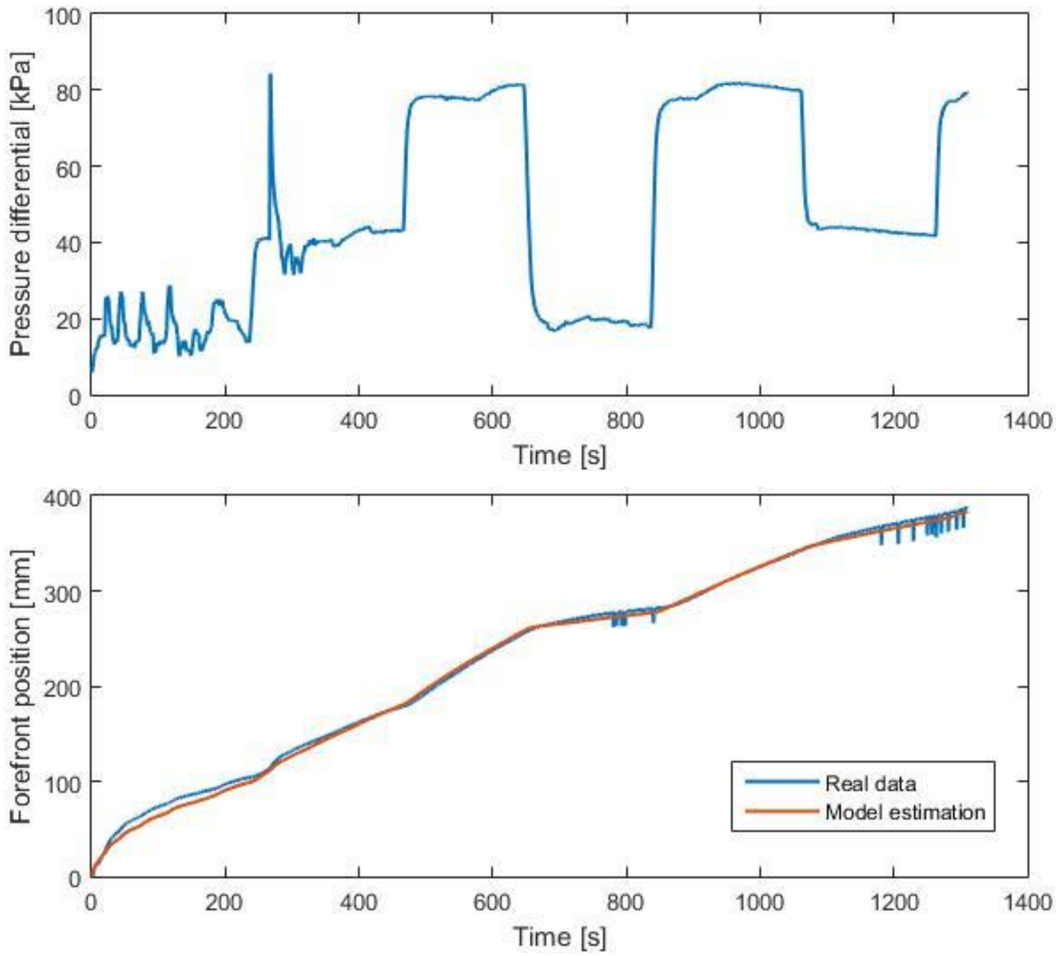

Figure 21 - Experiment 1

The minimum $MSE$ obtained for the infusion shown in Figure 21 is 20.11 $\boldsymbol{mm^2}$, which resulted from a parameter $C$ of 0.82. The estimated open loop transfer function applied to this infusion is:

$$\hat{G}_{OL}(s) = \frac{1}{0.82\ x \cdot s} \quad (5)$$

The validity of the proposed model is evaluated by comparing the responses of the model and the real system to the same input. The model is applied to 5 infusions and adjusted to each infusion by computing the parameter $C$ that minimizes the mean square error. This analysis lead to the results presented in Table 1:

| | **PARAMETER C** | **MEAN SQUARED ERROR ($mm^2$)** |
|---|---|---|
| **EXPERIMENT 1** | 0.82 | 20.1 |
| **EXPERIMENT 2** | 1.41 | 48.6 |
| **EXPERIMENT 3** | 0.66 | 33.7 |
| **EXPERIMENT 4** | 0.93 | 51.2 |
| **EXPERIMENT 5** | 0.86 | 2.1 |

Table 1 – Model parameter $C$ estimation results

Table 1 shows the parameter $C$ and the mean squared error of a model adjustment to its corresponding experiment. The structural hypothesis proposed earlier provides models that fit the experimental data with a low $MSE$. However, the parameter $C$ varies from 0.66 to 1.41 which indicates a possible inability to reach a parametric model that fits all experimental data.

## 3.5. Consistency and repeatability

The assessment of the consistency and repeatability between experiments is accomplished by applying a fixed model parameter to the experiments from section 3.4 and analyzing the variation in the $MSE$. In addition, the responses of two different experiments with highly similar inputs were compared to further confirm this assumption.

When a fixed model parameter $C$ is computed to fit all data, the results in Table 2 are obtained:

| | **PARAMETER C** | **MEAN SQUARED ERROR ($mm^2$)** |
|---|---|---|
| **EXPERIMENT 1** | 0.89 | 125.6 |
| **EXPERIMENT 2** | 0.89 | 3372.1 |
| **EXPERIMENT 3** | 0.89 | 1459.7 |
| **EXPERIMENT 4** | 0.89 | 118.2 |

| | | |
|---|---|---|
| **EXPERIMENT 5** | 0.89 | 12.9 |

Table 2 - MSE comparison with fixed parameter $C$

Table 2 indicates that the dynamics do not vary in the same manner across experiments and thus the performance is dependent from external factors.

The assumption that the dynamics depend on uncontrollable external factors can be verified by comparing two experiments with nearly equal inputs (Figure 22 and Figure 23).

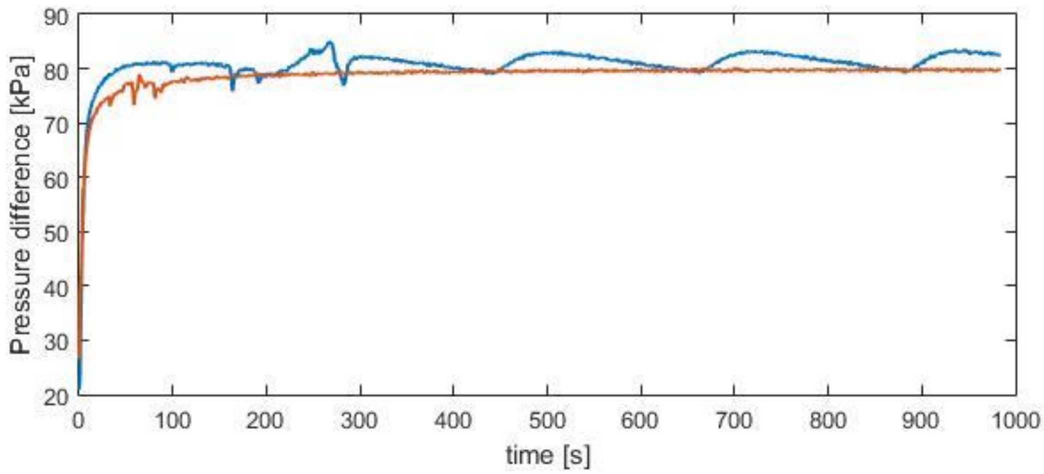


Figure 22 - Similar inputs comparison - Pressure difference

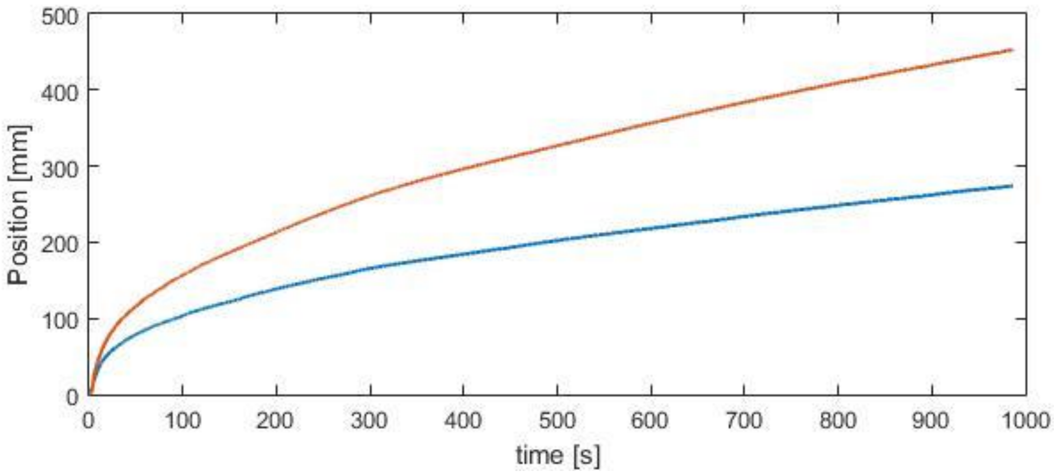


Figure 23 - Similar inputs comparison – Forefront position

This comparison shows that the responses to similar inputs differ significantly, thus proving that the repeatability of the experiments is compromised and beyond the reach of this experimental setup.

# 4. Controller design

This chapter presents the controller design for the VA-RTM process experimental setup. It consists of an adaptive control structure that estimates the system parameters online through a Recursive Least Squares Estimator (RLSE), which are applied in the adjustment of a PI controller parameters.

As demonstrated in chapter 3, although having a common structure, the dynamics of the system differ unpredictably between experiments and vary throughout the infusion, which supports the need for an adaptive controller, which relies on the model structure reached in the previous chapter.

The controller aims to regulate the resin forefront position by comparing it to a ramp shaped reference and using the error between them as a basis to correct it. As there is some degree of uncertainty in the calculation of parameter C, the controller must adapt to the changes in the plant dynamics.

The control action regulates the pressure difference in order to minimize the difference between the resin forefront position and a ramp shaped reference input.

An adaptive controller is one that adjusts its parameters to a dynamic model identified online. A typical adaptive controller structure can be seen in Figure 24 with two main components: the estimator and the controller [11].

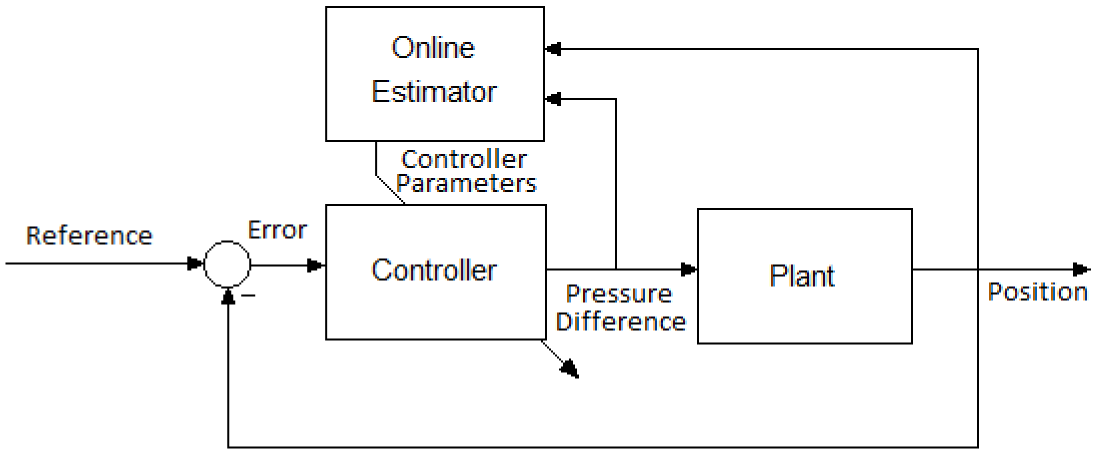


Figure 24 - Adaptive controller structure

## 4.1. Online estimator

The purpose of an online estimator is to identify the plant dynamics at each instant. It computes an approximation to the plant dynamics based on the input and output responses. For this application, as the artificial vision acquires a discrete data set, a Recursive Least Squares Estimator (RLSE) is selected for the online estimation of this process.

As the system dynamics are estimated recursively, the system input and output need to be converted into discrete variables. This discretization is accomplished through a Zero-Order Hold (ZOH), which holds each sample value for one sample interval, thus creating a discrete signal. As the RLSE is based on the dynamic model structure from chapter 3, the dynamic model also needs to be discretized.

The discrete model structure is achieved by applying a $\mathcal{Z}$ transform with a ZOH, with a sampling time $T_0$, to the continuous model structure:

$$\hat{G}(s) = \frac{1}{T \cdot s} \tag{6}$$

$$H\hat{G}(z) = \frac{z-1}{z}\,\mathcal{Z}\left[\frac{\hat{G}(s)}{s}\right] = \frac{T_0}{T(z-1)} \tag{7}$$

$$H\hat{G}(z^{-1}) = \frac{T_0 z^{-1}}{T(1-z^{-1})} \tag{8}$$

The RLSE algorithm computes the minimization of a cost function which represents the error between an estimated model and the measured response and returns the parameters that minimize that cost function at each iteration [10].

The RLSE presents the problem in the following form:

$$y(t) = \varphi_1(t)\theta_1 + \varphi_2(t)\theta_2 + \cdots + \varphi_n(t)\theta_n = \varphi(t)^T\theta \tag{9}$$

Where $y(t)$ is the system output, $\varphi_n(t)$ are the known functions that compose the model structure, also called regressors, and $\theta_n$ are the unknown parameters associated to those functions. To compute the estimated parameters, the following notation is introduced:

$$\Phi(t) = \begin{pmatrix} \varphi^T(1) \\ \vdots \\ \varphi^T(t) \end{pmatrix} \tag{10}$$

$$P(t) = (\Phi^T(t)\Phi(t))^{-1} \tag{11}$$

$$\varepsilon(i) = y(i) - \hat{y}(i) \tag{12}$$

$$K(t) = P(t)\varphi(t) \tag{13}$$

The estimated parameters at each time instant are computed recursively according to equation (14):

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)\,\varepsilon(t) \tag{14}$$

When applying this algorithm to the system in study, the parameter $T$ is identified at each instant, which solves both the issues of lack of repeatability and time-variance.

## 4.2. Control action

A Proportional Integral Derivative (PID) controller structure (Figure 25) is selected to outline the control action of this process. This controller is widely used across several industrial process applications due to its versatility and robustness.

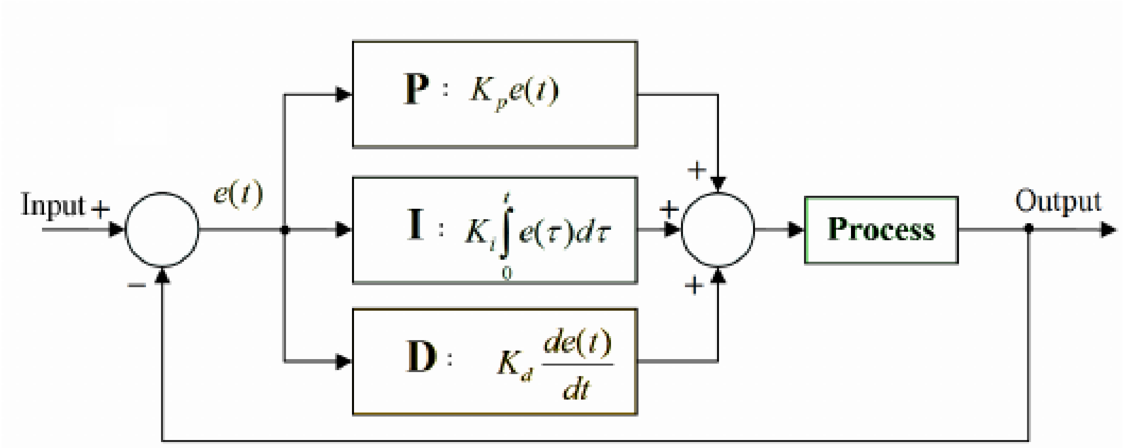


Figure 25 - PID controller structure

The PID controller applies a correction according to the error between the desired reference and the measured output, computed in equation (15):

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} e(t) \tag{15}$$

In this process, as the resin flow progresses slowly, and the feedback has a discrete measurement, the derivative term is neglected, leading to a Proportional Integral (PI) control action computed in equation (16):

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \tag{16}$$

The parameters $K_p$ and $K_i$ determine the controller behavior and they are adjusted according to the plant dynamics identified by the online estimator.

Also, when applying a controller with an integral component, the system saturation needs to be taken into account. In the experimental setup, the pressure difference imposed by the vacuum pump and the resin container saturates at 0 KPa and 80 kPa. To avoid the integral error accumulation due to the controller saturation, an anti-windup feature is added to the controller [12].

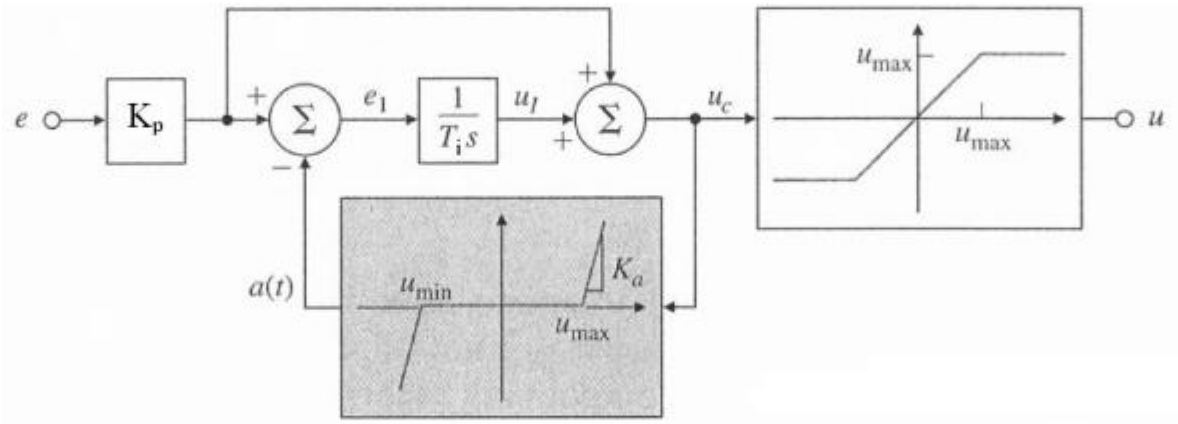


Figure 26 - Anti-windup block diagram structure [12]

The anti-windup component (Figure 26) prevents integral error accumulation by removing the integral computation when the controller output exceeds the saturation limits.

To further improve the controller and prepare it for the experimental setup application, the performance is evaluated in a simulation environment, which allows for the fine-tuning of its parameters. The controller structure and the theoretical parameters are tested according to the model developed in chapter 3 with the addition of sensors and actuators delay of 1 and 4 seconds, respectively [9].

The basis for the preliminary controller performance assessment is a Simulink model, shown in Figure 27, which represents the dynamics identified in chapter 3 as well as estimated time delays and arbitrary noise signals to increase its similarity to the real system.:

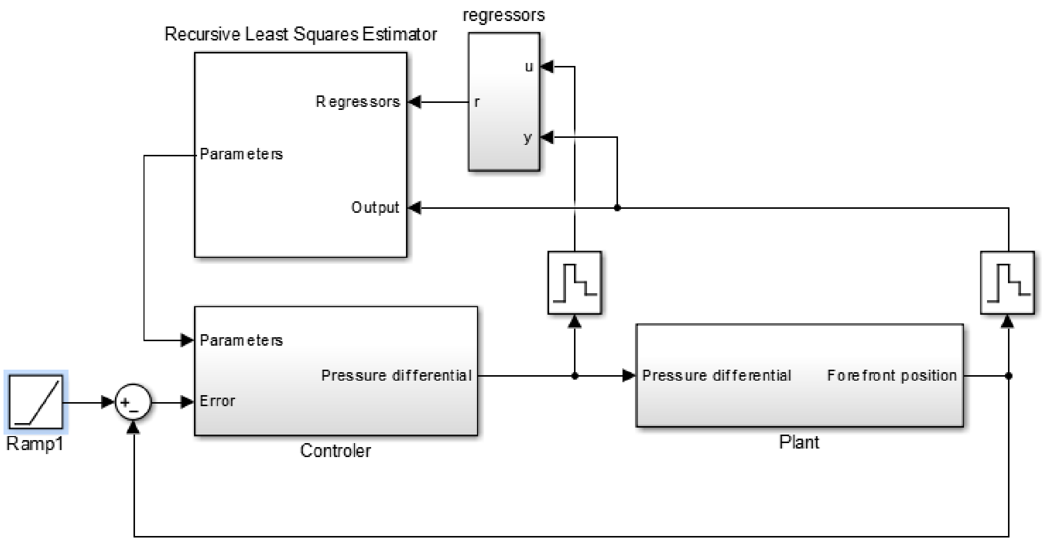


Figure 27 - Simulink model

## 4.3. Controller details

The adaptive PI controller parameters, $K_p$ and $K_i$, vary according to the estimated dynamics to ensure that the system response behaves as designed.

The system dynamic parameters are estimated by applying the RLS algorithm to the structure determined in equation (8), with the regressors according to Figure 28:

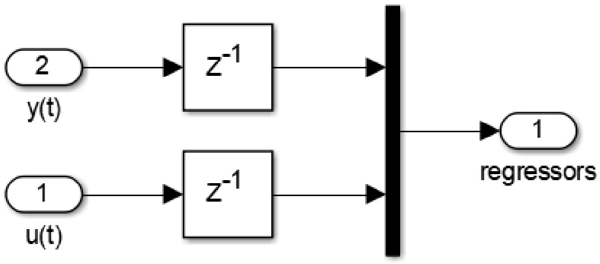


Figure 28 - Regressors selection in *Simulink*

The RLSE returns two parameters $\theta_1$ and $\theta_2$ that are associated to each regressor. According to equation (8), one of the estimated parameters is the sampling time, $T_0$ and the other is the desired parameter $T$.

The resin flow desired behavior is calculated through the *PID tuner* tool in *Matlab* for different regions of operation and extrapolated in order to be adjustable to any plant dynamics. The ideal controller parameters vary in direct proportion with the estimated parameter $T$.

The *PID tuner* tool calculations result in gains that relate the estimated parameter $T$ and the controller parameters, which are 0.6 for $K_I$ and 0.03 for $K_P$. However, the tuning performed in simulation lead to improved controller parameters that are better suited for its real-world application: 0.3 for $K_I$ and 0.005 for $K_P$, as shown in Figure 29.

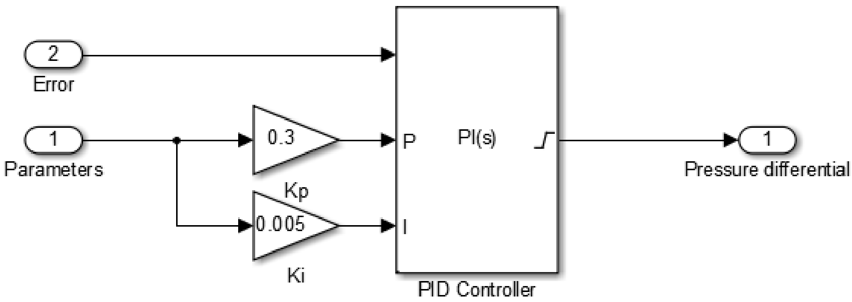


Figure 29 - Simulation controller

# 5. Experimental results

This chapter presents the experimental results of the adaptive controller developed throughout this work.

The most important data sets to consider and analyze are:

- The control action imposed in the mold
- The resin flow position evolution compared to the reference
- The error between the reference and the resin forefront position

## 5.1. Infusion details

When applying the adaptive controller to the experimental setup, there are a few details that need to be taken under consideration, especially at the beginning of the infusion.

As the resin flow is controlled through the pressure inside the resin container, the feeding tube must be free of air pockets. Otherwise the control action does not affect the resin flow in a consistent way due to the compression of the remaining air inside the tube. Also, if the control action is applied before the resin reaches the region of interest captured by the camera, the error between the forefront position and the reference increases significantly before the infusion begins, which leads to an undesired overshoot as the controller tries to compensate for an increasing positional error that does not represent a true error.

To overcome these issues, an alternative control action is implemented for the transient region. This transient controller sets the pressure difference at 20 kPa until the resin forefront reaches 20 mm, at which point the adaptive controller is applied as well as the ramp shaped reference. Although this compromises the first 20 mm of the infusion, it prevents both the air pockets and the overshooting.

Another detail that has to be taken into account is the influence of the controller saturation. The maximum pressure that can be applied to the resin container is the atmospheric pressure, at 100 kPa. When taking into consideration the pressure drop from the container to the mold, it is clear that the experimental setup is unable to impose a pressure difference greater than 80 kPa, as the vacuum pressure remains close to 10 kPa.

## 5.2. Relevant experiments

### 5.2.1. Controlled infusion 1

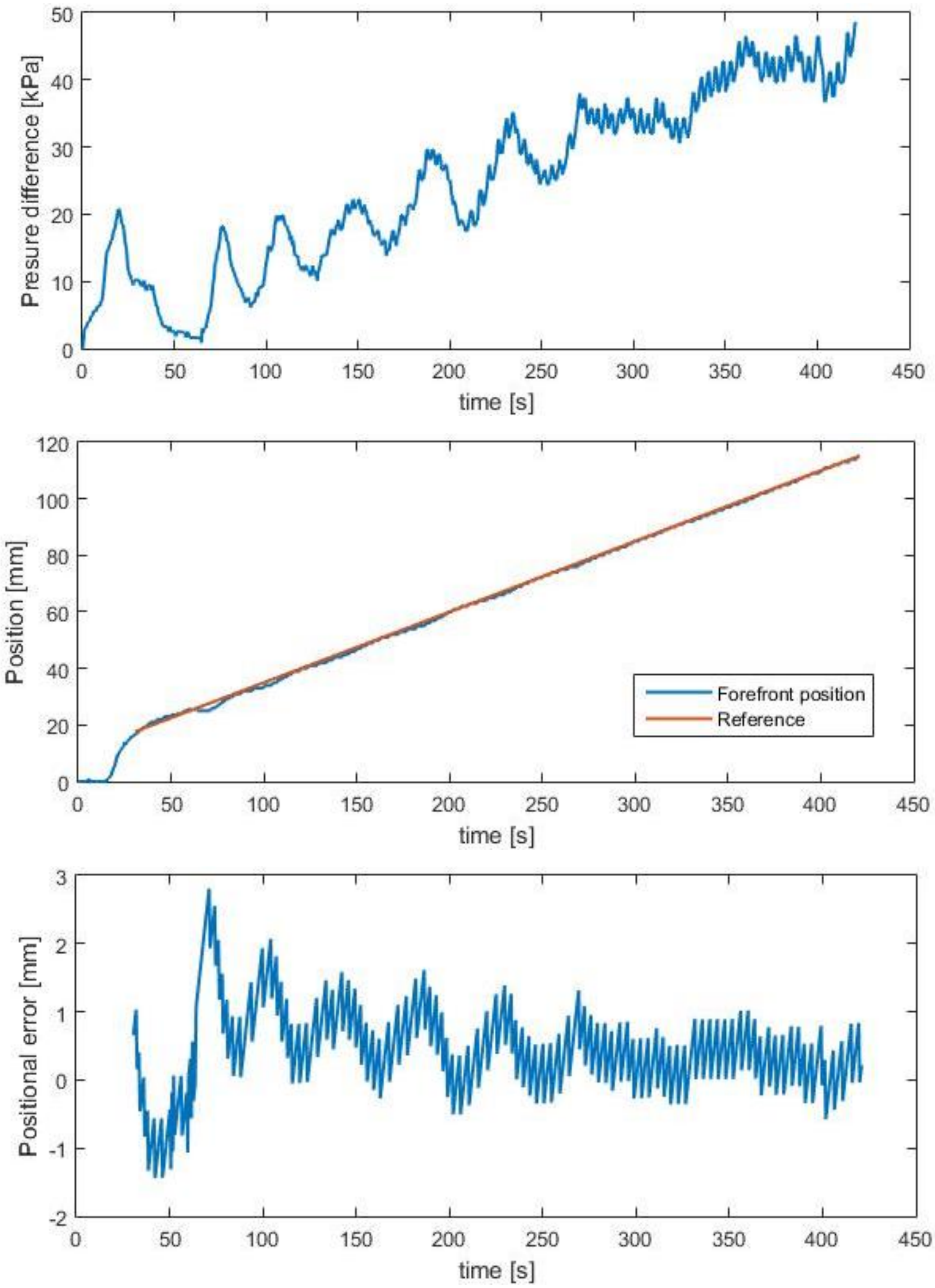


Figure 30 - Controlled infusion 1

The infusion presented in Figure 30 stopped due to an unrelated computer issue at 115 mm, before the system reached its saturation limit. However, its results are relevant to demonstrate the successful control of the resin flow. In this infusion the control action oscillates due to a strong integral component. The effects of this oscillation are visible in the forefront position and in the positional error. Despite the oscillation, the positional error settles below 2 mm after 104 seconds, at 34 mm.

### 5.2.1. Controlled infusion 2

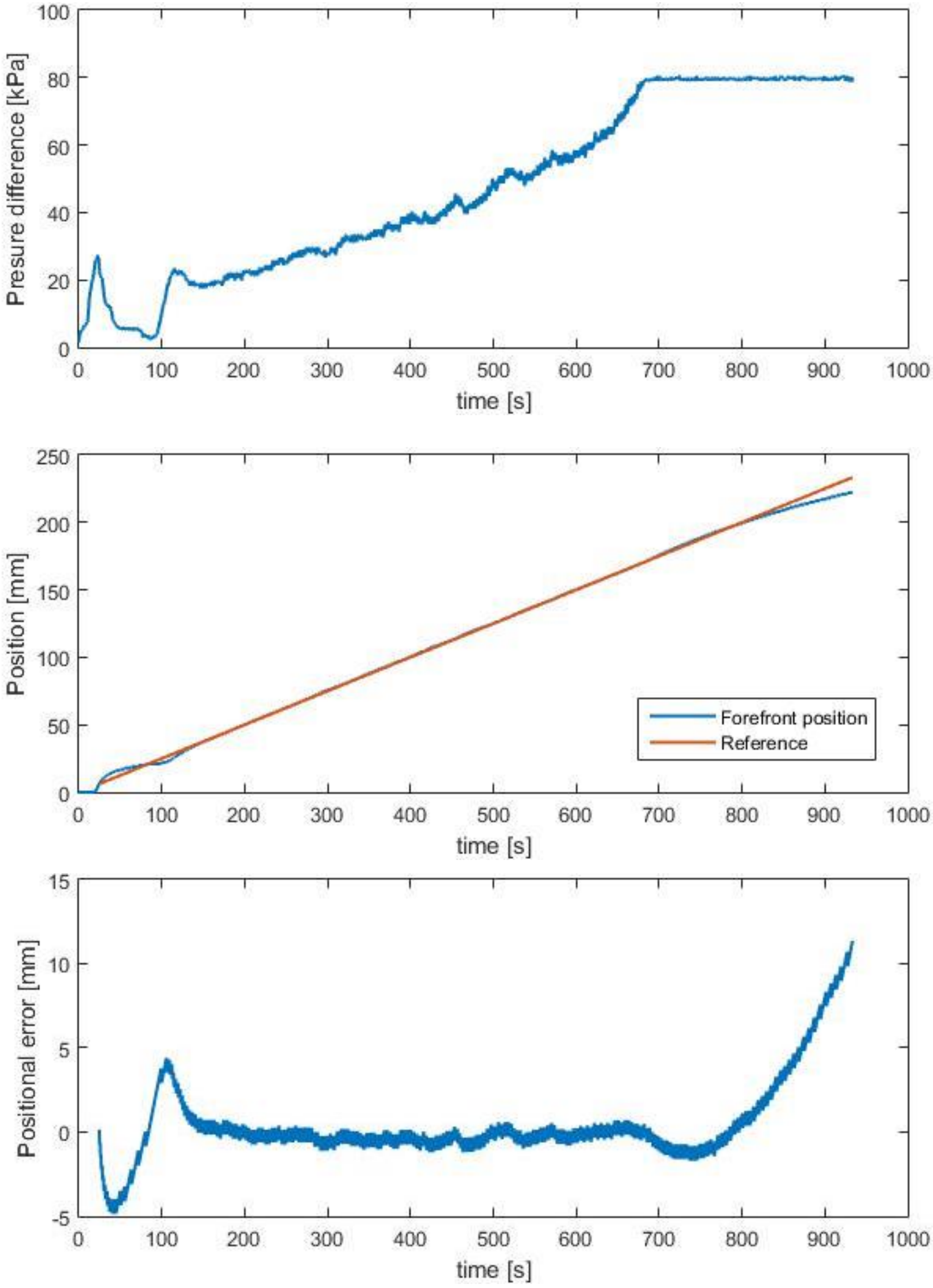


Figure 31 - Controlled infusion 2

The infusion presented in Figure 31 shows very low oscillation in the control action. The positional error settles below 2 mm after 124 seconds, at 29 mm, which shows a successful control of the resin flow. The system saturates at 685 seconds when the position is at 170 mm, however, the error only exceeds the 2 mm limit at 824 seconds, which occurs at 204 mm.

## 5.3. Evaluation

The control solution designed for this process provides a smooth growing control action, which is more evident in 5.2.1, where the pressure difference increases gradually throughout the experiment, after the transient region.

In both experiments the resin flow position settles into a 2 mm range from the ramp shaped reference, which reveals an accurate position control. That settling occurs before the resin flow reaches 10% of the part length, 40 mm.

The experimental data from the controlled infusions show a smooth control action and an accurate positional reference following, that translates to a successful resin flow speed control.

# 6. Conclusions

This work provides a successful control strategy for the resin flow speed control in VA-RTM processes.

The development of this control solution resulted from the identification of the system dynamic model, the design of an adaptive controller and its application to an experimental setup.

## 6.1. Contributions

The main contributions provided by this work are:

- A dynamic model structure that fits the VA-RTM process
- An adaptive PI controller capable of regulating accurately the resin forefront position
- A successful application of the designed controller to a physical process

The dynamic modelling of this process showed a time-variant behavior and lack of consistency between experiments. The time-variant behavior is overcome by adjusting the model dynamics to the progression of the resin flow. The discrepancies between infusions are not possible to work around, as the process dynamics vary according to factors beyond the reach of this experimental setup.

Despite not having reached a parametric model that can fit all data with a low MSE, the model structure is suitable fit was found, depending on the parameters used, which can serve as basis for an adaptive controller.

The control solution developed for this process is an adaptive controller. It is based on a PI controller structure with parameters that adjust to the online identified process dynamics, which is achieved through a recursive least squares estimator.

The controller is successfully applied to the experimental setup with all the adjustments it requires, such as transient control and parameter tuning. The real-world results show a controlled resin forefront position that settles within a 2 mm range of its reference before it reaches 10% of the part full length, 400 mm. When controlling at a 0.25 mm/s speed the system reaches its saturation limit when the resin forefront position is at approximately 200 mm.

## 6.2. Future work

In order to further develop a solution for the VA-RTM process, the following improvements are proposed:

- Connect the resin container to a high-pressure pump
- Validate this project premise
- Adapt the controller to a real-life application

The improvement in the pressure control is done by having the resin container connected to a vacuum pump and a high-pressure pump. This allows for a faster pressure control and surpasses the saturation issue, allowing for a control in a wider operation range.

This can only be applied to closed mold processes. In vacuum infusions where the materials are enclosed by vacuum bags or other type of non-rigid mold, imposing a high pressure in the resin container can cause a significant portion of the resin to flow above the fibers, which originates flaws in the manufactured parts.

This project is based on the premise that the resin flow speed control improves the quality of the manufacturing of composite materials through the VA-RTM process. The validation of that premise is accomplished by manufacturing resin infused composite materials in the experimental setup and evaluating their quality.

The assessment of the overall value of a VA-RTM process control solution, is accomplished by adapting the controller structure and parameters to a real-life application and compare the active and passive control solutions in terms of quality, efficiency and costs.

# 7. References


[1] "LAETA," Setembro 2017. [Online]. Available: www.idmec.ist.utl.pt/laeta/.

[2] "Mar-bal, inc.," Setembro 2017. [Online]. Available: http://www.mar-bal.com/language/en/applications/history-of-composites/.

[3] "Nuplex Industries Ltd.," Setembro 2017. [Online]. Available: http://www.nuplex.com/composites.

[4] "MFG | Molded Fiber Glass," Agosto 2017. [Online]. Available: http://www.moldedfiberglass.com.

[5] "Net Composites," Julho 2017. [Online]. Available: https://netcomposites.com.

[6] D. a. R. P. Nielsen, Intelligent model-based control of preform permeation in liquid composite molding processes, with online optimization, 2001.

[7] P. K. Mallick, Fiber-reinforced composites: materials, manufacturing, and design, 2007.

[8] F. Silva, "Modelação Dinâmica de um Processo de Infusão a Vácuo," 2016.

[9] B. Sousa, "Controlo Automático de um Processo de Infusão a Vácuo," 2017.

[10] M. Ayala Botto, Identificação de Sistemas Dinâmicos, 2002.

[11] K. a. W. B. Åström, Adaptive Control, 2008.

[12] M. Ayala Botto, Controlo de Sistemas, 2017.