METHODOLOGY FOR APPLYING COMPUTATIONAL TECHNIQUES IN ADVANCED MANUFACTURE OF COMPOSITES THROUGH ARTIFICIAL VISION

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ABSTRACT

In this paper is presented a computational framework that allows an efficient closed control loop for resin infusion process. First it is proposed a camera as a sensor of a resin infusion process. This sensor permits to define the pixels as nodes, generating a proper discrete space as FE used in simulations. The use of multiple cameras allows monitoring real 2.5D moulds. Therefore, a direct relationship exists between simulation and real process.

In The second part of the paper it is introduced a novel concept called *Configuration Spaces*. It introduces a novel representation form of LCM processes that permits an easy understanding and analysis of the filling process. This technique represents the filling process, instead of customary Cartesian axis, in terms of LCM parameters. In this paper is proposed the filling time of each node as a configuration parameter. The resulting configuration space is called *Flow Pattern time Spaces* (FPTS). In this space, the flow fronts are ever straight lines or circles. The filling time is obtained through simulation. Hence, after to choose the filling strategy, a FPTS that represents the optimal filling process that we want to reproduce in the real mould is obtained using the camera mesh. If the real filling process coincides with the optimal filling process, the flow front must be represented as a straight line in the FPTS. This representation form is not limited for the type of process, dimension of the mould and complexity of the gates and vents. Some examples of each case are shown in this paper.

1. INTRODUCTION

Resin infusion process is one of the common techniques used in the industry for large composite parts production. This technique uses vacuum pressure to drive the resin into a laminate. Preform is laid dry into the mould and the vacuum is applied before the resin is introduced. Once a complete vacuum is achieved, resin is sucked into the laminate via placed tubing. This negative pressure allows the top half of the mould to be made of a flexible material, thus reducing costs permitting manufacturing parts of practically any size; see Figure 1. It also implies that the top half can be transparent or translucent.

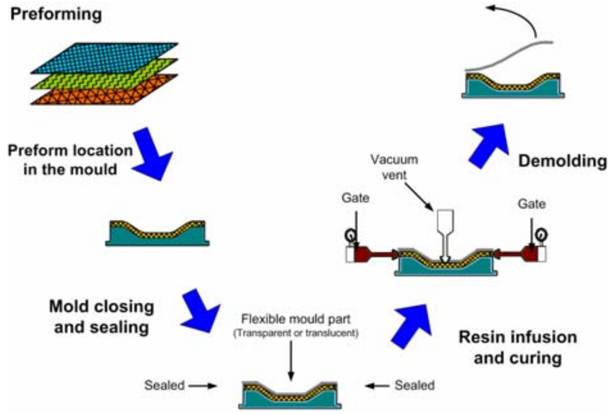


Figure 1. Resin Infusion Process stages

This process, as well as in all LCM processes, the resin impregnation of the fiber is described using the flow through porous media theory. The pressure-driven flow phenomenon is described by the well known Darcy's law. Analytical treatment of the flowing evolution is difficult except for a few simple geometries. Therefore, numerical methodologies for flow simulation were developed in past decades for RTM and extended to other processes more recently. The most common form for the flow numerical simulation is to use a discretization approach with finite elements.
The use of Darcy's law requires information about the material modelling. A major aspect to model is the perform permeability that characterizes the resistance offered by the porous medium to fluid flow. Therefore, for accurate description and design of the infusion process, characterization of the textile permeability is essential. Many research efforts are focused to an exact characterisation of permeability. However, this goal is complex due to its dependence on a multitude of parameters such as preform architecture, fibre volume fraction, etc. In addition, in the resin infusion process, compaction of the preform affects thickness, fibre volume fraction and permeability. In summary, the pressure driven infusion process is highly complicated since the mould and process design are not intuitive and may be variable due manufacturing conditions.
Off-line control strategies or passive control systems is one of the first possibilities to develop an efficient resin infusion process. In this case, a database of possible flow scenarios is generated from numerical flow simulations [1, 2]. However, passive control systems cannot ensure complete success and full reliability due to various aspects of the process such as edge effect, wrinkling of the vacuum bag, local preform heterogeneities, exact assignment of various material properties, etc. In order to overcome the off-line control problems, recent research works developed advanced on-line control systems. These systems are based on real-time simulations to take decisions during resin infusion [3, 4]. The use of this technique implies that must be fast enough to match mould filling times. In this sense, in many on-line control systems, proxy simulators instead of numerical simulation are used to predict flow progression. Unfortunately, this methodology also requires knowing previously material properties.
Typical on-line control system is basically compound of the controller and the process in a feedback structure. Actuators and sensors are also required to force and to measure system variables respectively. The desired output of a process is also called the reference for the control system, see Figure 2.

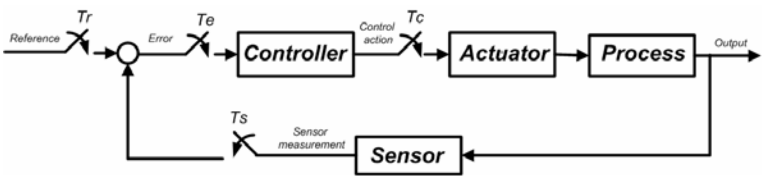


Figure 2.Closed control-loop

The sampling rate defines the number of samples per time taken from a continuous signal to generate a discrete signal. In the control loop depicted in Figure 2, *Ts* is the sensor sampling rate, *Tr* is the reference sampling rate, *Tc* is the control action sampling rate and *Te* is the error sampling rate. These periods depend on the computational costs of all the tasks involved in the control loop. In LCM processes, the flow front velocity imposes the sampling rate for reliable control laws. It implies that for a generic application using a specific parameter process, the computational costs of the control loop tasks must be the lesser possible. Therefore, the goal of our research is to obtain a computational framework that allows an efficient closed control loop for resin infusion process. In this paper, we do not attempt to solve all the required items to

obtain an efficient control loop; just some of them have been worked out and implemented.
This paper is organized as follow, in section 2, we propose a camera as a sensor of a resin infusion process. It is possible due to the top half of the mould can be made of a transparent or translucent material. In contrast to [5, 6] and in our previous work [7], cameras permit to define the pixels as nodes, generating a proper discrete space. The previous pixel association allows defining the sensed Finite Elements to be used in simulations. Moreover, the use of multiple cameras joined with artificial vision techniques allows monitoring real 2.5D moulds as a FEM simulation does.
In section 3 is introduced a novel computational technique for the representation of LCM filling process variables called *configuration spaces*. These spaces are commonly used in mobile robots, [8], permitting to represent the robot motion planning, instead of a customary Cartesian axis, in terms of configuration parameters as turning radius, path length, velocity, etc. The application of this technique in LCM processes is named *Flow Pattern Configuration Spaces* (FPCS). It allows an easy understanding of the process as well as a fast computation of the algorithms. In particular, it is proposed a configuration space called *Flow Pattern Time Spaces* (FPTS). In this space, one of the parameters is selected based on the radial flow behaviour. Hence, the angle defined by an interest point, such is the nozzle injection or the vacuum vent, to the evaluated point location is selected. The second parameter is selected through simulation results, that is, the filling time of each node. The main property of this space is that translates the flow fronts in straight lines or circles, depending on the FPTS representation mode.
In section 4 it is presented how to use this methodology in control applications. Conclusions and future works are presented in section 5.

2. SENSING RESIN INFUSION PROCESSES WITH ARTIFICIAL VISION.

Artificial vision is a sensor that samples the light scene. It is typically used in the industry for quality inspection. The use of this device as a sensor for mould filling processes is actually a research field for resin infusion processes [5, 6, 7]. In this works, the camera is defined as a grid of customary sensors used in RTM where the pixels acts as a punctual sensors. These studies do not exploit the amount of properties that the artificial vision has. In this sense, the CCD sensor can be considered as a matrix of nodes that produces a space discretization. It implies that it is possible to relate the image pixels as Finite Elements. The resulting mesh can be used in the proxy or on-line FEM simulations. Also is possible to relate an off-line mesh with camera pixels. In both cases, a direct relationship between FEM or proxy simulations and the real process is defined. The mould complexity for 2.5D resin infusion process can be easily solved including multiple cameras and calibrated them with stereovision techniques [9]. As a result, a 2.5D mould mesh is obtained where the camera acts as finite element sensor. Therefore, considering the CCD sensor as a rectangular matrix of nodes, the relationship between the neighborhood photodiodes-pixels-nodes establishes the typical definition of the Finite Elements; see Figure 3.
The CCD sensor permits to construct whatever meshes distribution using the pixels as nodes, Figure 3. (left), or grouping using some pixels as nodes, Figure 3. (right).
The translation between both processes is quite simple. Given a CCD with *P,Q* pixels, Figure 4 (left), and knowing the typical definition of Finite Elements in a mesh, Figure 4. (right), just only need to relate the number of each pixel with each Finite Element. In this sense, the simplest appropriate mesh is to obtain a uniform node distribution in a symmetrical mesh. Therefore, the pixels of the CCD sensor can be related to define the Finite Elements as can be seen in Figure.5.

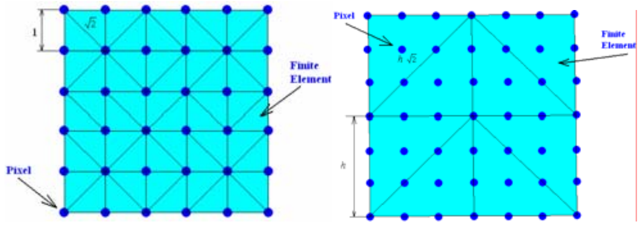


Figure 3.Finite Elements without (left) and with (right) grouping pixels into FE.

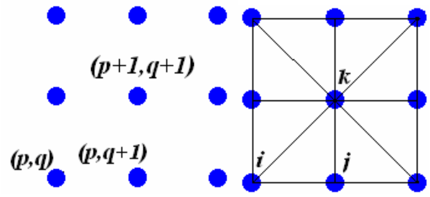


Figure 4. CCD to Finite Elements Discretization

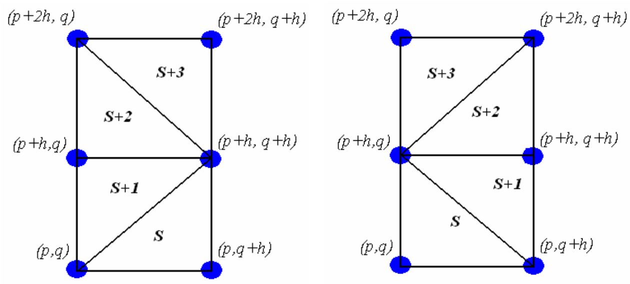


Figure 5. Finite Element Generation. Column k (left), and column k+1 (right).

where h is the distance between the pixels selected as nodes. The nodes are related in a different way for each column to obtain a symetrical mesh distribution, see Figure 5. The pixels that are inside of each Finite Elements are related to them. Hence, this algorithm establishes a non-dimensional mesh in the CCD camera sensor. The dimensions of the Finite Elements are selected to $\sqrt{2}\cdot h$ in the diagonal axis and h in the vertical and horizontal axis. The value of h depends on the distance between CCD light sensors and the number of pixels used to define the Finite Elements.
The resulting non-dimensional mesh is projected to the scene obtaining a space discretization with Finite Elements. Therefore, the mould allocated in the scene is meshed by the camera. The projection permits to identify the real node coordinates. For instance, a 2D mould allocated in parallel with the CCD sensor, just only needs to scale the non-dimensional mesh using the camera parameters and the distance to the mould. For a 2.5D mould, it is necessary to include multiple cameras, calibrating the field of view using, for instance light-sheet triangulation, relating the pixels of the cameras with stereovision techniques [9]. This issue permits a full 2.5D mould mesh generation.
In the same sense, it is also possible establishing the opposite process, which is, given a mould mesh; relate some pixels to each Finite Element. In this case, first the mould must be located in the image. The technique of finding some objects in the image is well-known as *matching*. There are several techniques to locate an object in an image, for instance, using the geometry, contour, area, etc [9]. After the mould is located in the image, each pixel can be associated with each FE in order to make comparisons between simulations and actual filling. In Figure 6 (left) is shown an example of this

relation between pixels and Finite Elements. The filled pixels determines the percentage at which each Finite Element is filled, see Figure 6. (right).

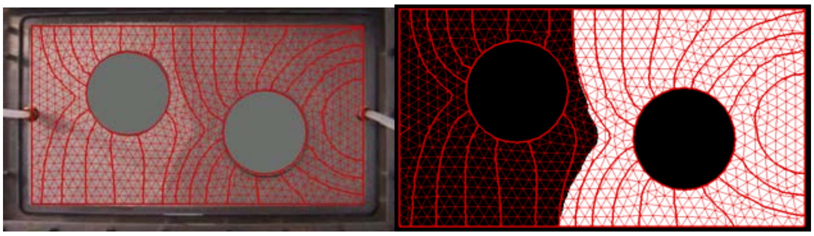


Figure 6 Example of FEM-CCD associations

3. MOULD FILLING TRACKING WITH FLOW PATTERN TIME SPACES

The camera vision permits to relate the actual process with the previous FEM simulation. Hence, it is possible to use the simulation for the on-line control process. Although this is possible, it is not useful because the sampling rate decrease until unacceptable values, even if proxy simulators are used. In addition, it requires to known material properties. For this reason, in [4] is proposed an on-line permeability estimator but it also introduces additional computational cost.

Since on-line FEM or proxy simulations requires high computational costs, the proper flow front behaviour reference is obtained in a previous off-line process simulation, see Figure 6, but it is necessary a low computational cost strategy to define the on-line control actions result of the comparison between the real and simulation (reference) behaviours. In order to obtain a computational framework that can be used for these intend in on-line control systems, it is proposed a novel technique called *configuration spaces*. This technique permits to represent the actual filling process in terms of configuration parameters, instead of a customary Cartesian axis. The application of these spaces in LCM processes is called *Flow Pattern Configuration Spaces* (FPCS). For the definition of these spaces, it is necessary to choose the configuration parameters. In this sense, one of the parameters commonly used in LCM processes is the filling time. It is well-known that the optimal filling process requires that the flow front achieves the vent at the same time, see Figure 7. If the vent is a curve, the flow front must be achieving the entire vent at the same time. Therefore, one parameter of the FPCS is the time at which the flow achieves each node. The other parameter is the angle defined by an interest point, that is, the nozzle injection or the vacuum vent, to the evaluated point location. This configuration space is called *Flow Pattern Time Space* (FPTS). Therefore, given a simulation results, one parameter is computed as an angle formed between the interest point and each node, θ. The normalized filling time, τ, in the interval [0…1] is the second parameter. Through these configuration parameters, there are two possibilities to represent FPTS, called FPTS-2D and FPTS-1D where the flow fronts are translated to exact circles or exact straight lines respectively. In Figure 8 shows the required computation to obtain the FPTS.

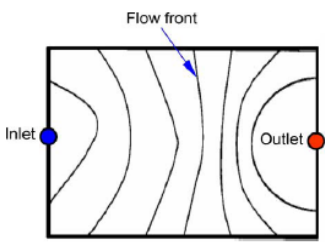


Figure 7 Example of optimal vent oriented fluid flow pattern

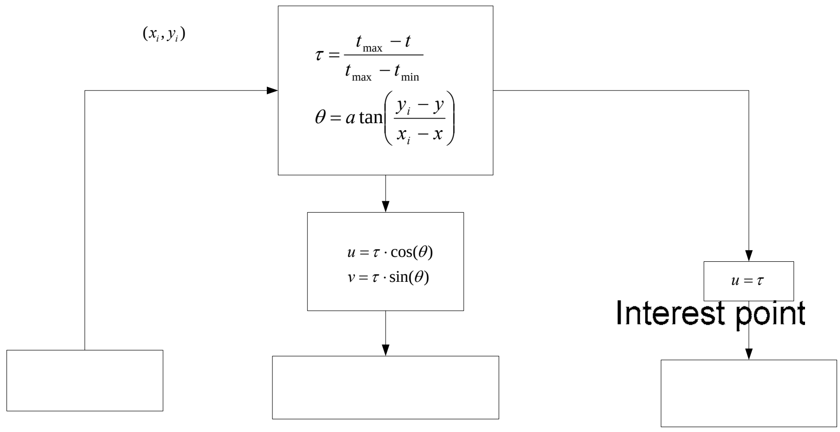


Figure 8 Variable computation required in the FPTS

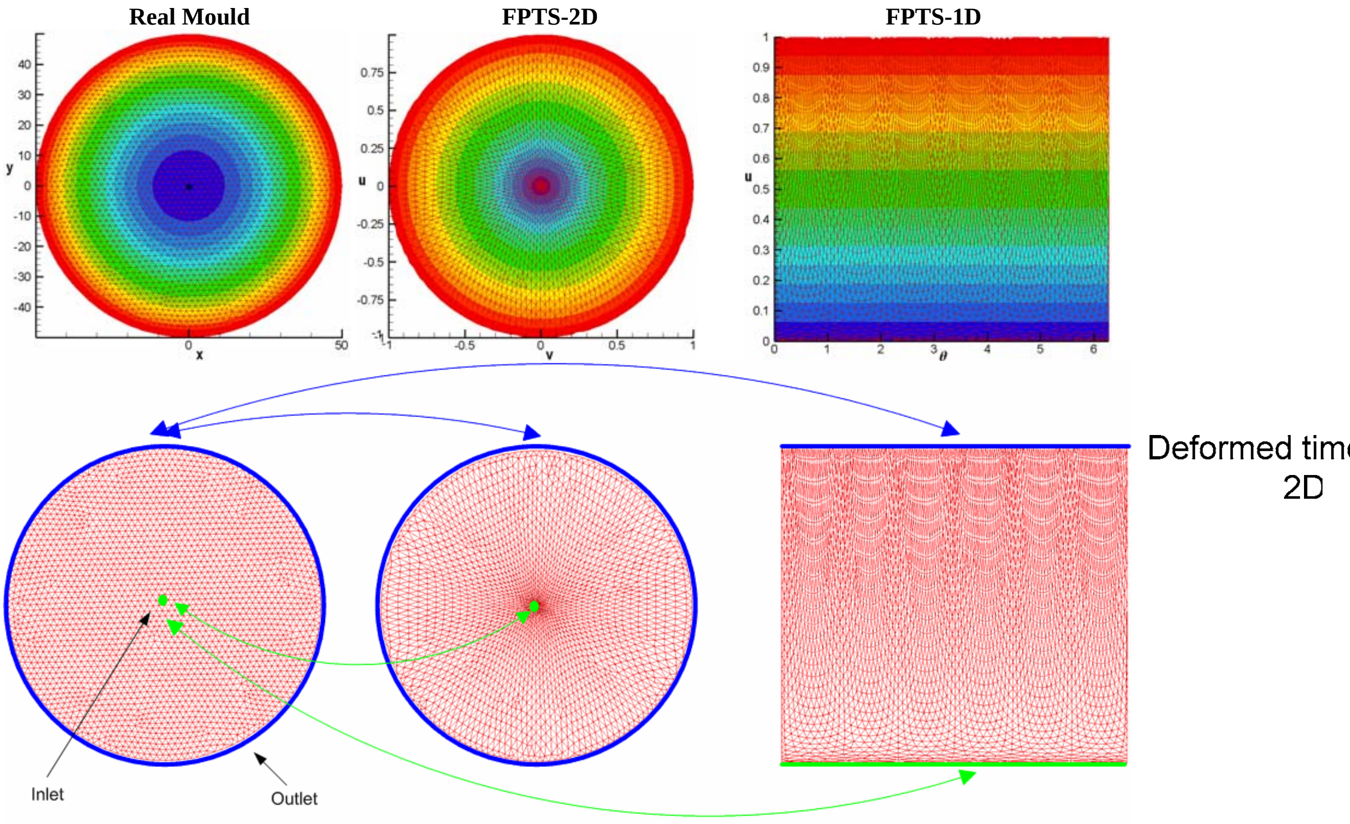
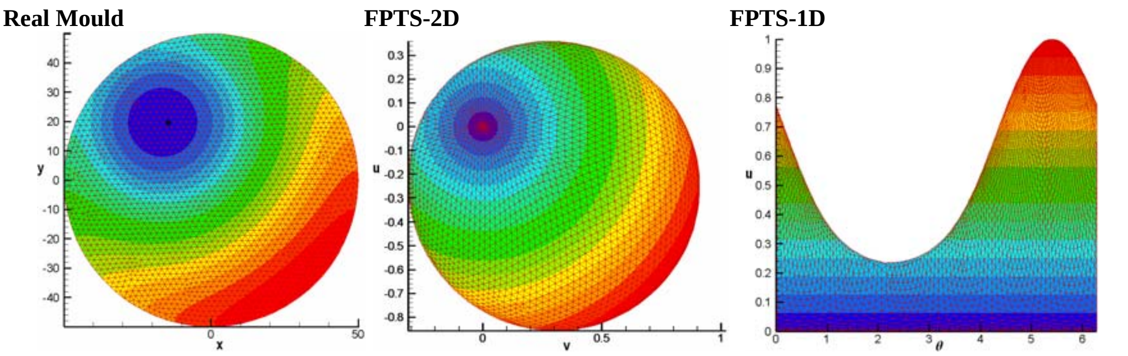


Figure 9 FPTS's (Up) and the correspondence between them (Down)

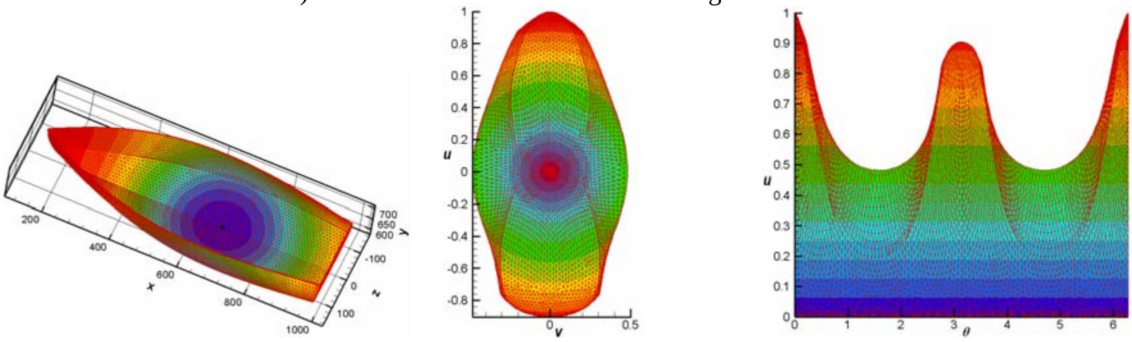
Figure 9 (Up) shows an example where the vent is allocated in the mould perimeter. In Figure 9 (Down) is showing the correspondence of inlets and outlets in FPTS's.

If the gate location is changed, the mould geometry in the FPTS's changes but not the flow front representation that ever is exact circles and lines respectively. This representation form is not limited for the dimension and complexity of the mould, even if the gate is not a point, see Figure 10.

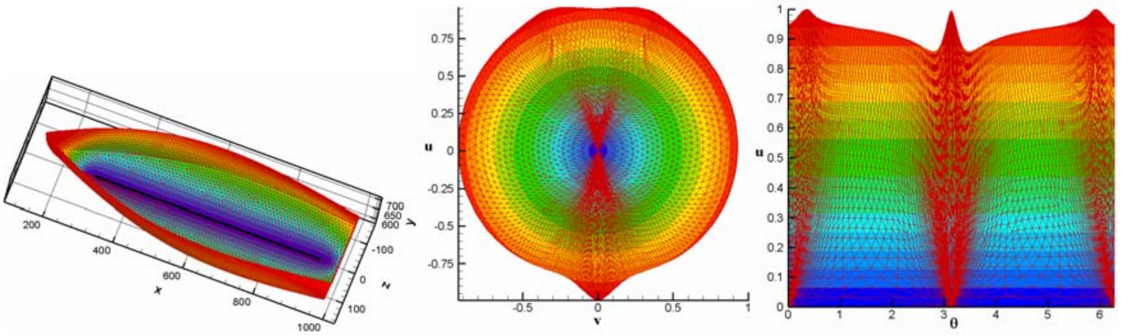
This technique also can be used for the customary configuration of VARTM processes, that is, the inlet gate is allocated in the mould contour and the outlet into the mould. In this case, the last node filled in the simulation process is considered the optimal outlet and then, the interest point in the FPTS. Figure 11 shows an example.



a) Circle mould with not centered inlet gate location



b) 2.5D complex hull mould with inlet point gate



c) 2.5D complex hull mould with line shaped inlet gate

Figure 10 some examples of Flow Pattern Time Spaces

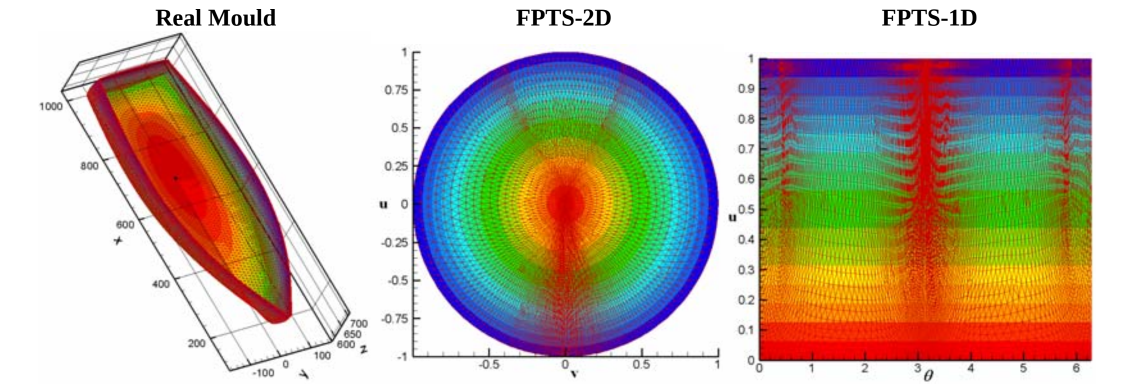


Figure 11 FPTS with VARTM configuration

4. A FILLING CONTROLLER STRATEGY BASED ON FPTS

Through the methodology explained in section 2, cameras mesh the mould to fill. Therefore, the monitorized mesh in the on-line control system is available for the FEM simulations. Hence, the mould filling process is off-line optimized through simulations using this mesh in order to define the optimal filling strategy. When this process is finished, the simulation of the optimal filling strategy is used to obtain the FPTS. The controller uses this representation system as a reference, that is, the flow front must appear in the FPTS as a straight line or a circle if the filling process corresponds to the optimal simulated process in each time instant. On the contrary case, the controller must be applying the respective control actions. As an example, it is proposed the rectangular mould shown in the next figure.

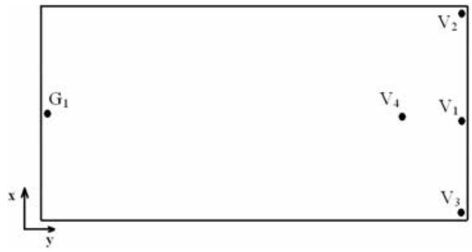


Figure 11 rectangular mould with RTM configuration

where G_1 is the gate and V_1, V_2, V_3, V_4, are the possible vents that the controller can be select. These vents are obtained through simulation. In this sense, some possible race tracking scenarios are simulated. In Figure 12 are shown the simulation results where the shadowed zone determines different areas of high permeability. In these simulations, the last node filled is considered as optimal vent. These nodes are defined as interest point for the FPTS representation.

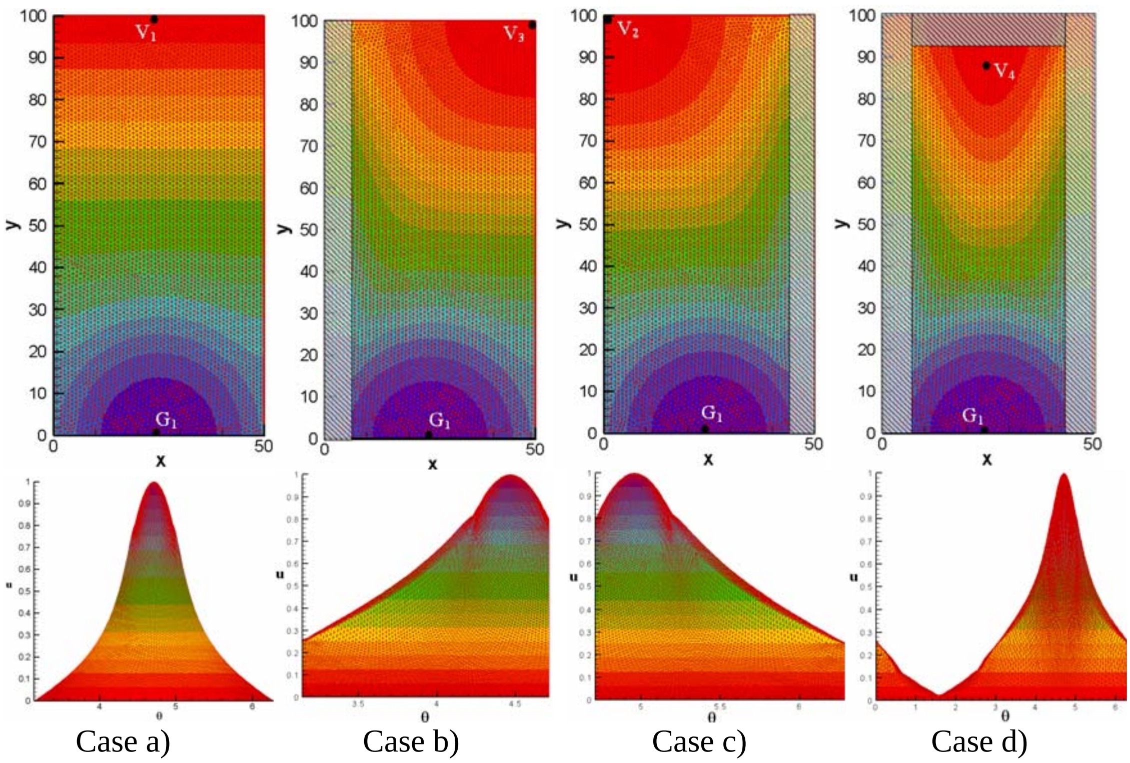


Figure 12 Different race tracking scenarios and FPTS defined for V1, V2, V3 and V4

Each FPTS stores inherently the simulation information. It is easy to identify which simulated case matches the actual filling process. For instance, Figure 13 represents the filling case a) in every FPTS defined for each vent.

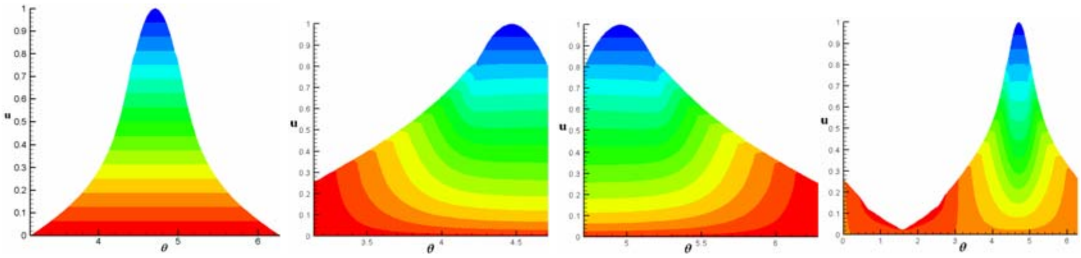


Figure 13 Filling case a) with V1, V2, V3 and V4 vents FPTS representations.

Therefore, the controller algorithm must measure the differences of every flow front with a straight line in each time instant representation form. It can be computed as

$$Q = \frac{\sum_{n=1}^{Vn} \bar{\tau} - \tau_n}{N} \qquad (1)$$

where τ_n are the flow front nodes, $\bar{\tau}$ is the median of all the flow front nodes and N are the number of flow front nodes. The controller chooses the optimal vent in each time instant. Figure 14 shows a time instant example.

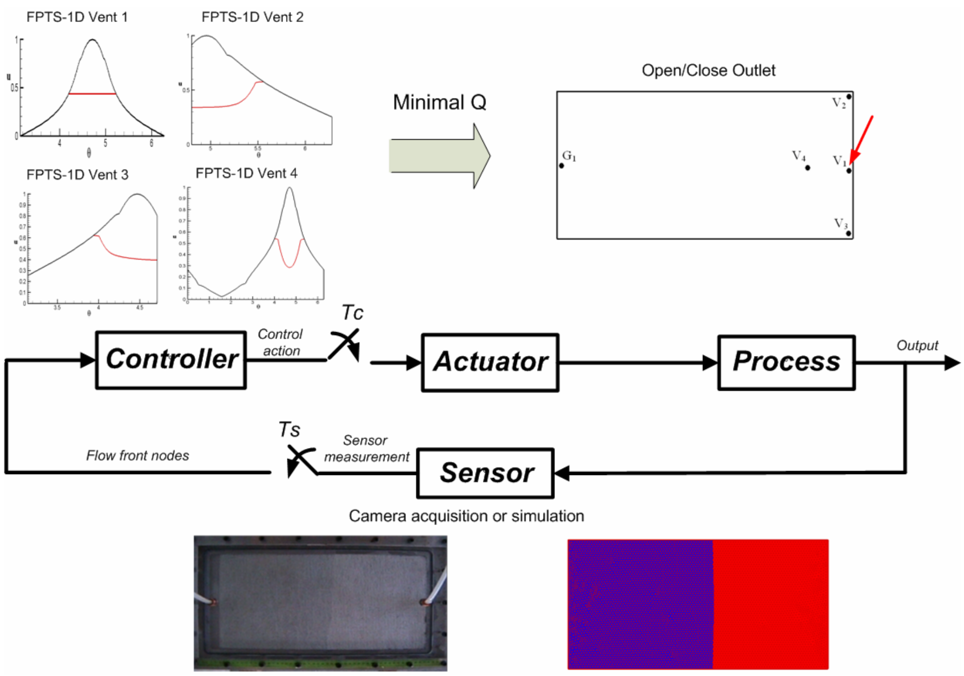


Figure 14 On-line control loop with camera vision and FPTS

5. CONCLUSIONS AND FUTURE WORKS

In this paper is presented a computational framework that allows an efficient closed control loop for resin infusion process. First it is proposed a camera as a sensor of a resin infusion process. This sensor permits to define the pixels as nodes, generating a proper discrete space as FE used in simulations. The use of multiple cameras allows monitoring real 2.5D moulds as a FEM simulation does. Therefore, a direct relationship exists between simulation and real process, permitting to use the algorithms developed for FEM in the real process as the same manner.

In The second part of the paper it is introduced a novel concept called *Configuration Spaces*. It permits to represent the filling process, instead of customary Cartesian axis, in terms of LCM parameter. In this paper is proposed the filling time of each node as a configuration parameter to develop the *Flow Pattern time Spaces* (FPTS). This space is a new filling process representation where the flow fronts are ever straight lines or circles. This filling time is obtained through simulation of the real mould discretization obtained by the cameras. Hence, after to choose the filling strategy, a FPTS that represents the optimal filling process that we want to reproduce in the real mould is obtained. In these FPTS, if the real filling process corresponds with the optimal, the flow front must be represented as an exact straight line or a circle.
The use of FPTS or more generally Flow Pattern Configuration spaces in LCM processes is not limited for the type of process. In this paper we show examples of VARI, VARTM and RTM. Also is not limited for the dimensionality of the mould and the complexity of gates and vents. This issue establishes that FPCS can be a new alternative representation for LCM filling process that can permit to analyze the filling process in an easy manner than the customary Cartesian coordinate system. In addition, FPCS can be extended with other LCM variables such as Incubation time, Distance, Flow Front Velocity, etc. This is our immediately future work.

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