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A FAST MARCHING-LEVEL SETS APPROACH FOR THE DISTANCE FIELD COMPUTATION AND ITS APPLICATION IN LIQUID COMPOSITE MOLDING PROCESS PERFORMANCE INDICATORS

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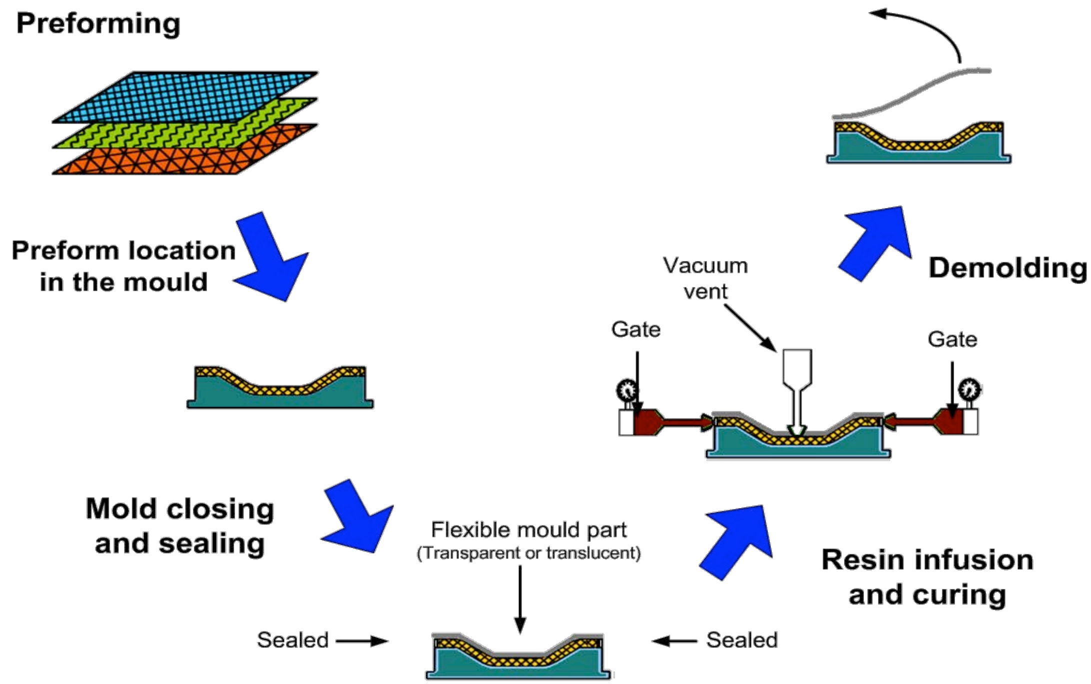
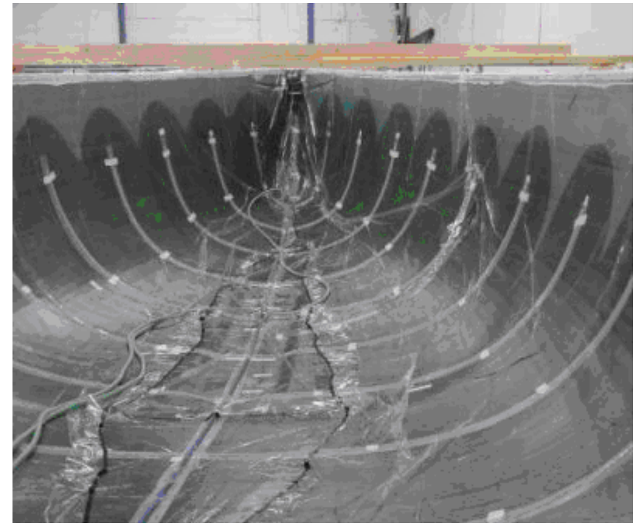
Content Outlook

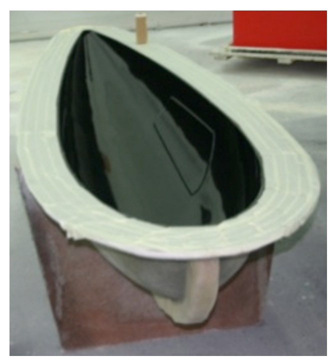
- Introduction. Problem
- Objectives and Motivation
- New techniques based on implicit geometric methods. Level Set Applications for process pre-Design.
- Level Sets as computational framework
  - Resin flow front shapes and velocity measurements during filling.
  - Material properties estimation. Mixed Numerical Experimental Technique based on CV-FEM and Artificial Vision.
- Conclusions / Future Work

LCM-Resin Infusion. Introduction



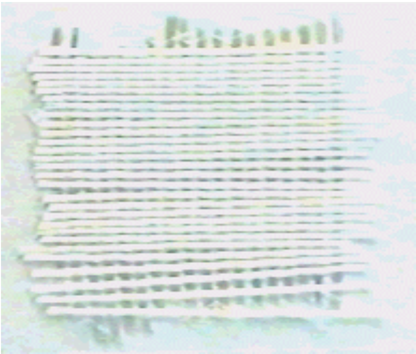


- ✓ flow fronts **filling time can be related to the distance** of the flow path.
- ✓ to prevent dry areas imposes that the flow has to be **vent-oriented** and avoiding flow encounters.
- ✓ desired resin flow pattern **achieves the vent uniformly**



Permeability and dynamic flow behavior. Introduction

Unidirectional Weave



0/90 Bi-directional Weave

Random Mat

- ✓ **Permeability** characterization is a key issue in LCM processing and will allow predicting the **flow behaviour** in porous media
- ✓ In spite of using accurate **computer simulations**, the modeling and **characterization of the materials** is usually a tedious and extensively work.
- ✓ In industrial manufacturing conditions, the **process disturbances** are not always predictable. A major quality part production concern is the permeability variations **along the flow path** yielding incomplete filling.

Objectives and Motivation

1. To develop **alternative computational tools** in **process design based on geometric methods** **and dynamic behaviour** instead of previous material characterization.

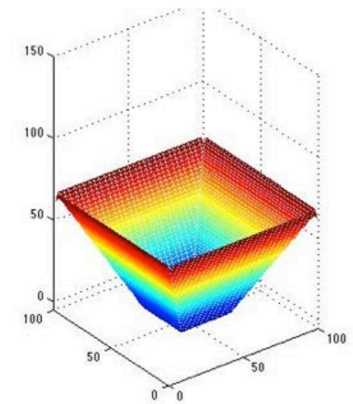
2. To **develop fast (not necessarily physically-based) tools** at the **pre-design stage** that could help designers with a suitable arrangement of injection nozzles and vents. This **should be applicable with industrial LRI processing.**

3. To define **a computational and technological framework for robust processing based on artificial vision techniques**.

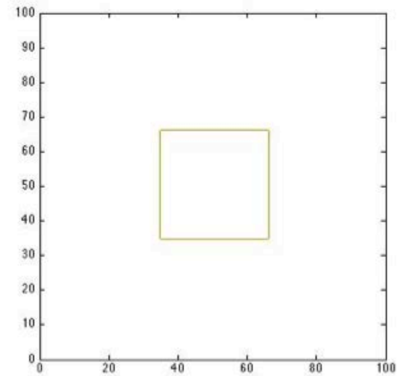
   - Analyse the mechanics of impregnation/saturation and the **resin flow front shapes and velocity measurements during filling.**
   - Put forward improvements for evaluating a **Mixed Numerical Experimental Technique based on CV-FEM** and Artificial Vision. As a result, we may propose **new techniques based on LEVEL SETS for characterization of the dynamic process behaviour** during filling and its application in robust processing.

Implicit Methods. Level Set

- Implicit representation. Embed the curve into a 2-D function $z = \phi(x,y)$

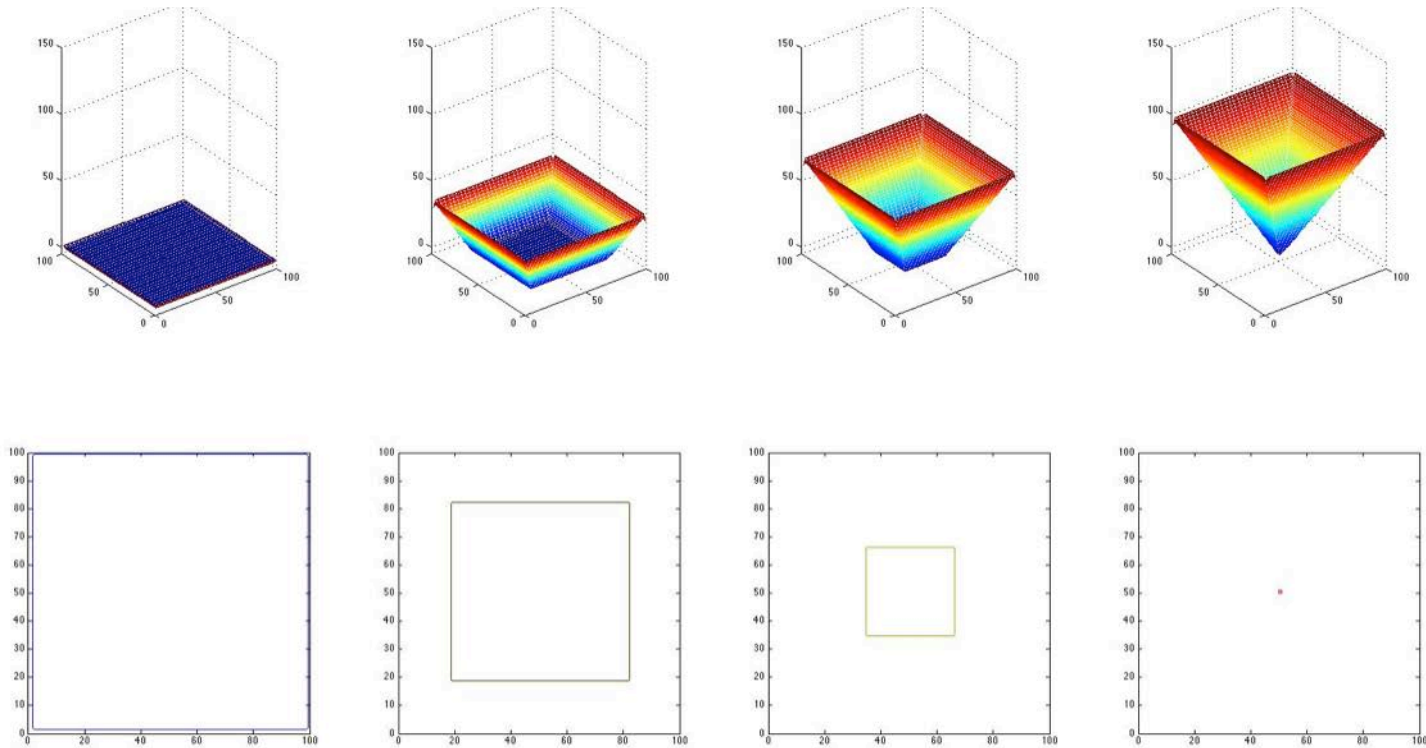


- Curve is embedded as the zero Level Set.
  $\Phi = \{(x,y) \mid \phi(x,y) = 0\}$



Implicit Methods. Level Set

- Main concept:
  - Evolve the embedding function $\phi(x,y)$
  - Keep track of its zero level set



The **evolution of this implicit function** under an external velocity field can be written as

$$\phi_t + v \cdot \nabla\phi = 0$$

If we assume that the **velocity field at the interface front is normal** to the implicit function ϕ itself, with $\mathbf{V_n}$ **is constant**

$$v = V_n n$$

and ϕ is defined as **a signed distance function** i.e.,

$$\left|\nabla\phi\right| = 1$$

All level sets of ϕ are evolving and can be solved with

$$\phi_t + V_n\left|\nabla\phi\right| = 0$$

We only track zero level set. The **front interface** is defined **computing the implicit function $\phi^n=0$ for a given instant *n***

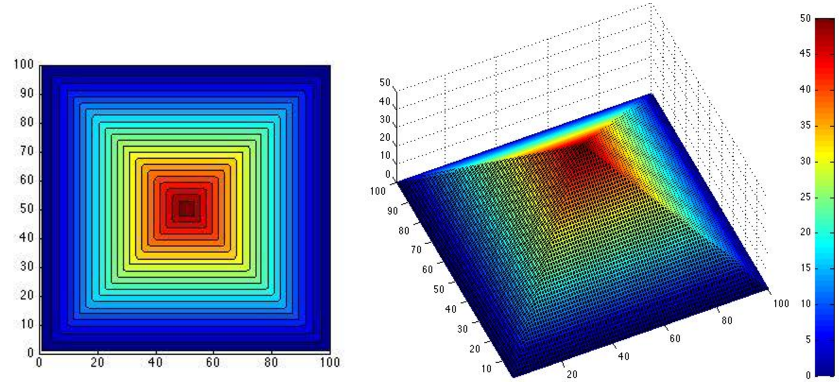
(*) S. Osher and R. Fedkiw. Level set methods and dynamic implicit surfaces. *Springer* Verlag New York, 2003
(**) E.Cueto, C.Ghnatios, F.Chinesta, N.Montes, F.Sanchez, A.Falco, Improving computational efficiency in LCM by using computational geometry and model reduction techniques, In: ESAFORM 2014, Espoo, Finland, 7-9 May 2014

Level Sets in RI geometric modelling

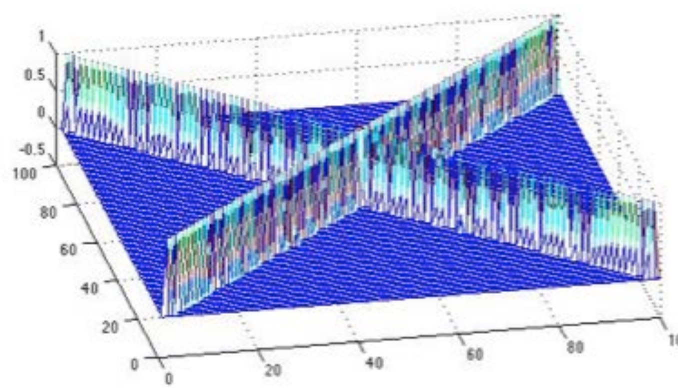
One can now define **different geometric operators for the whole domain** (instead of just a contour front) such are

Distance Pattern function Θ, Computed inwards from the vent contour

Fig. The zero-level set of the function is assumed to be located at the vents position, i.e., the boundary of the square. It can be readily noticed that the just computed level set function possesses a maximum value at the center of gravity of the square, with a value of 50 units.



Its ***Laplacian Λ,*** $\Lambda = \phi_{xx} + \phi_{yy}$, used here as

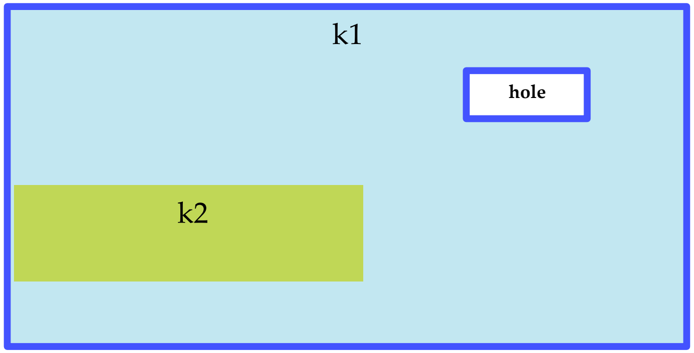


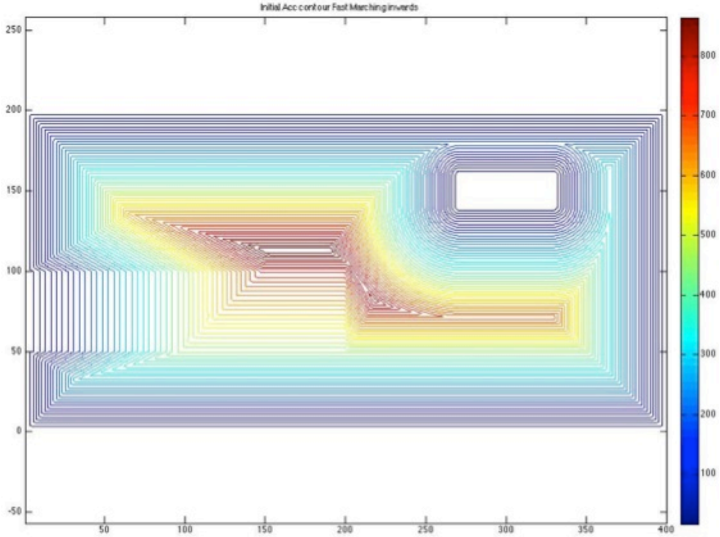
geometric definition of the **medial axis** of the boundary of the square, defined as the locus of the points having more than one closest point on the object's boundary, provides a more convenient means to define a set of injection nozzles.

A **RI flow pattern** modeling approach based on considering a **distance field computation**

Example:

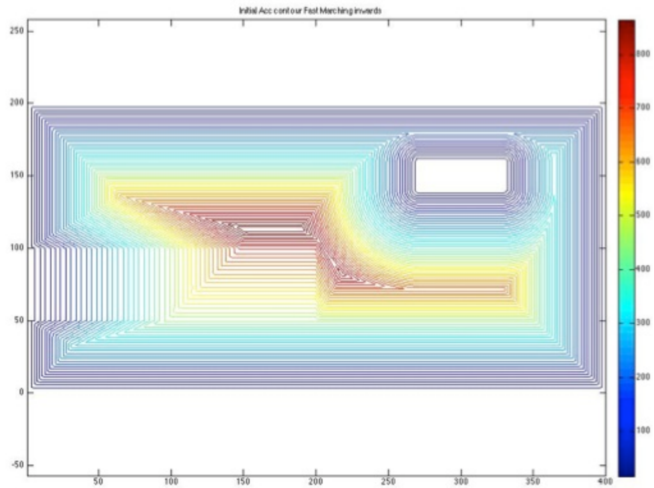
- We can compute the **distance field to an interest location** as the vent vacuum line which is on the contour of a simple 2D-rectangular part taking $\mathbf{V_n=-1}$ and defining ϕ as a signed distance function in the whole domain.
- An interior **obstacle** (upper right) defines a hole. We assume in that region that **Vn=0**
- Moreover, the part **has two discontinuous regions of different permeability** (middle left band permeability is double) that yields complex distance computation. We assume in that region that **Vn=-2**

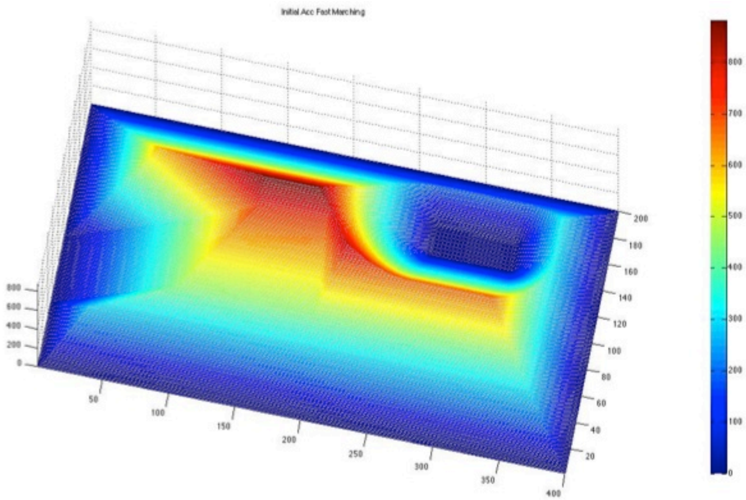




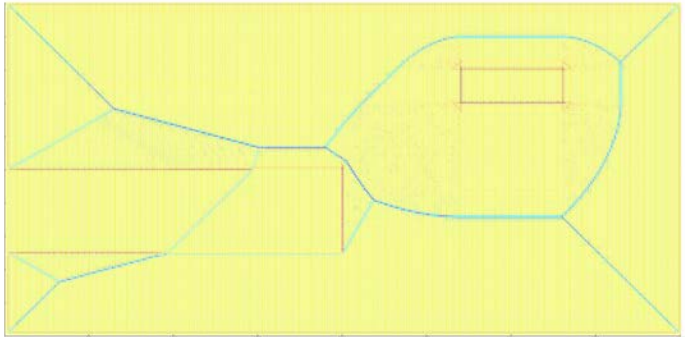
Level Sets in RI geometric modelling

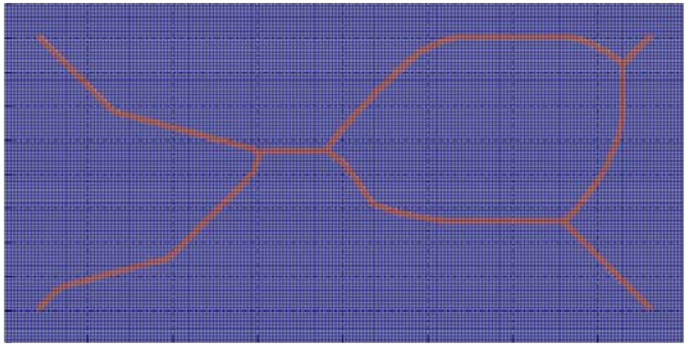
Distance Pattern function Θ, defined as the **distance field of the whole domain** to vent line





Its ***Laplacian Λ***, defines **equidistance location** to the vent line. It defines the arrangement of a channel distribution in a preliminar design stage

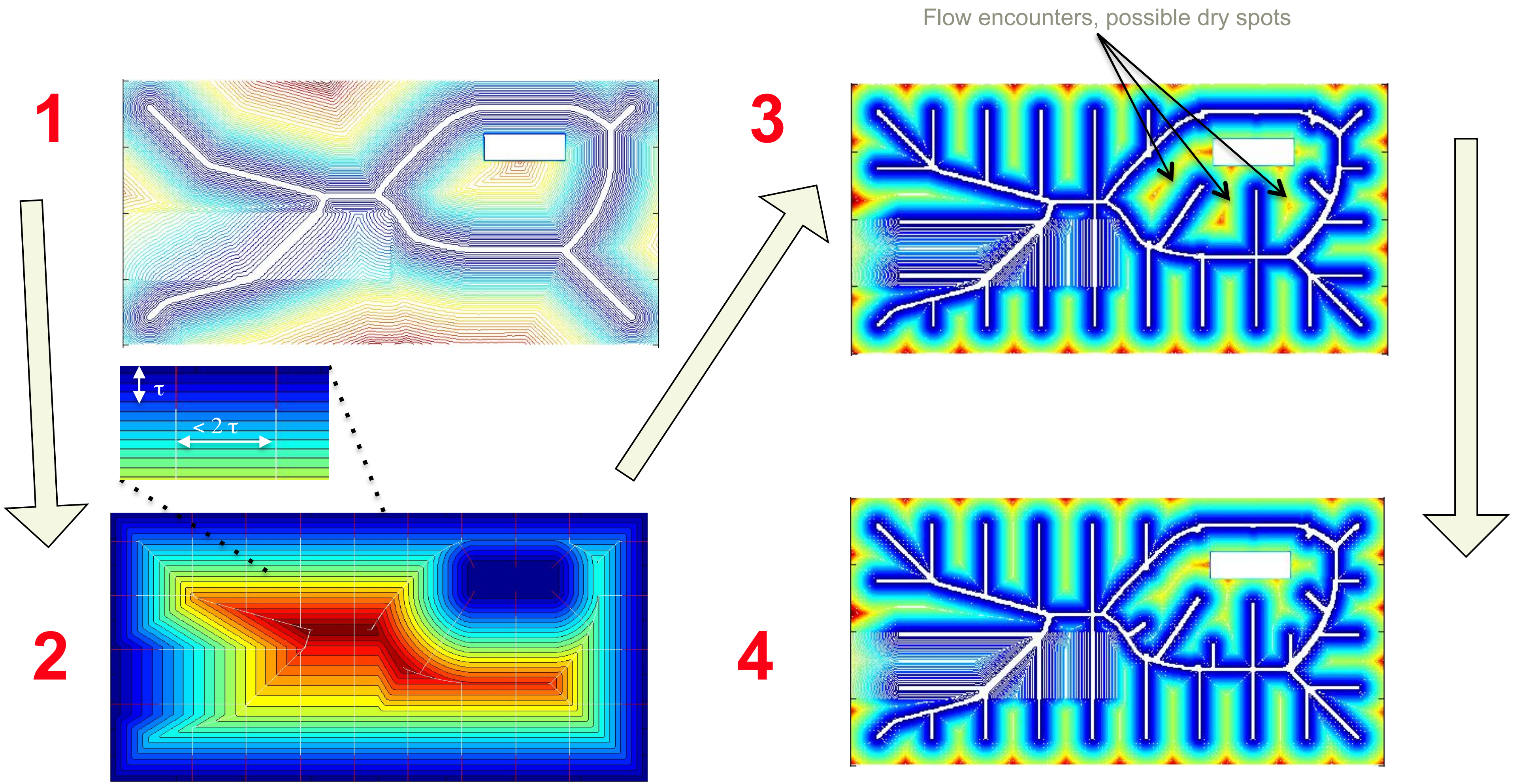




Edge Pattern function Λ as gate arrangement in RI

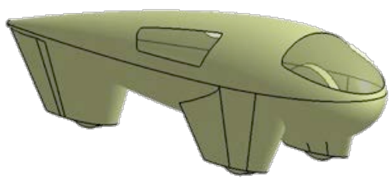
Application of Level Sets. Process pre-Design.

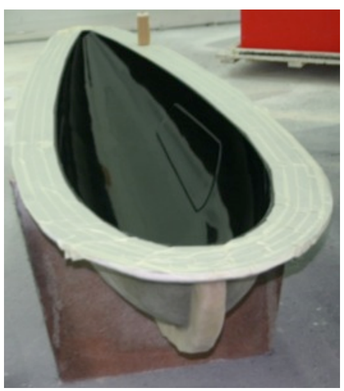
Distance Pattern function ***Θ*****,** defined as the **distance field of the whole domain** to a preliminar **injection line (Fast Marching Outwards, V_n=+1)**



Edge Pattern function Λ as gate arrangement in RI

Application of Level Sets. Process pre-Design.





Mold and filling strategy for car body upper part with no windows as stated in previous computations.

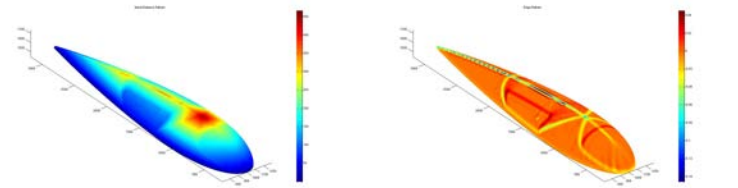


Figure 1. Distance Pattern (left) and Edge Pattern (right) with window areas as thin laminates with isotropic permeability variation. Perimetral vent

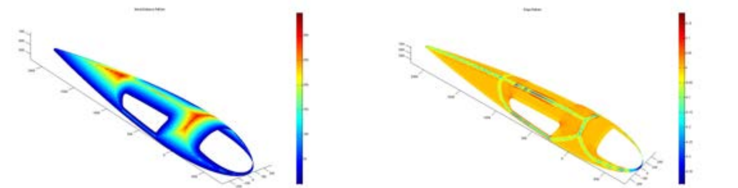


Figure 2. Distance Pattern (left) and Edge Pattern (right) with window areas as holes treated as vent lines and perimetral vent.

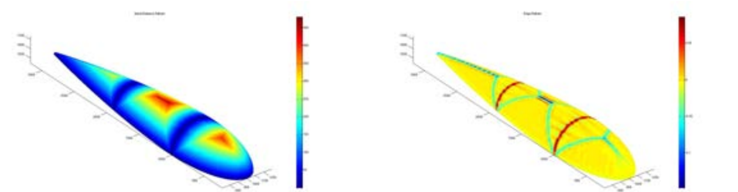


Figure 3. Distance Pattern (left) and Edge Pattern (right) with no window areas but rib as vent lines and perimetral vent.

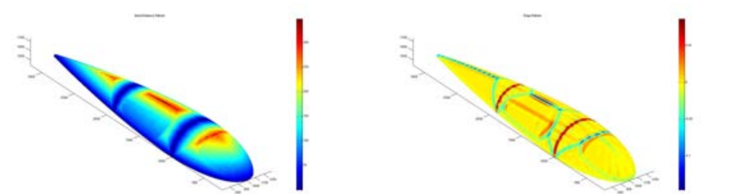
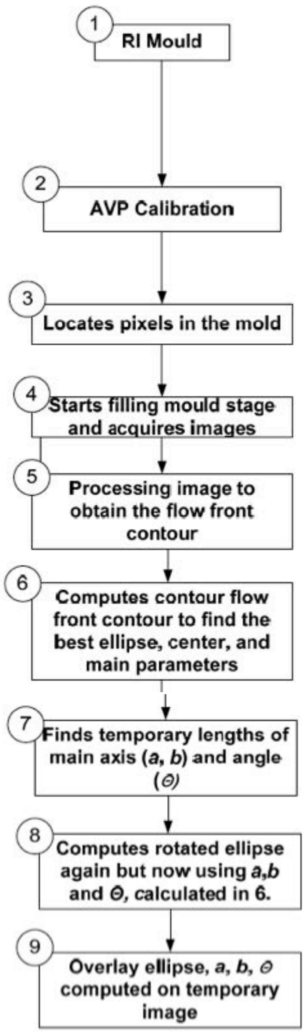


Figure 4. Distance Pattern (left) and Edge Pattern (right) with window areas as thin laminates with isotropic permeability variation and rib as vent lines and perimetral vent.

A Fast Marching-Level Sets approach for the distance field computation

Geometric modelling with anisotropic materials

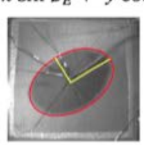


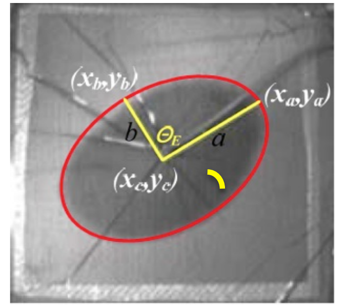
$$a = \sqrt{(y_a + y_c)^2 + (y_a + x_c)^2} \qquad Ø_E = atan\left[\frac{y_a - y_c}{x_a - x_c}\right]$$

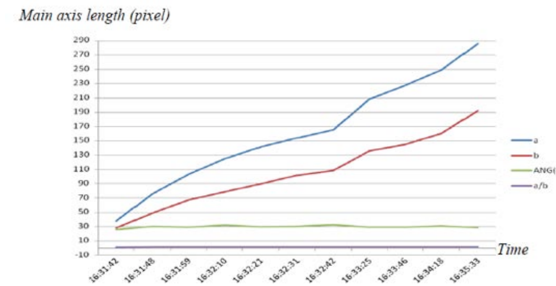
$$b = \sqrt{(y_b + y_c)^2 + (x_b + x_c)^2}$$

$$x^* = x \cos Ø_E + y \sin Ø_E + x_c$$

$$y^* = -x \sin Ø_E + y \cos Ø_E + y_c$$



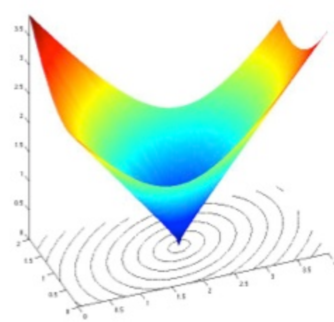


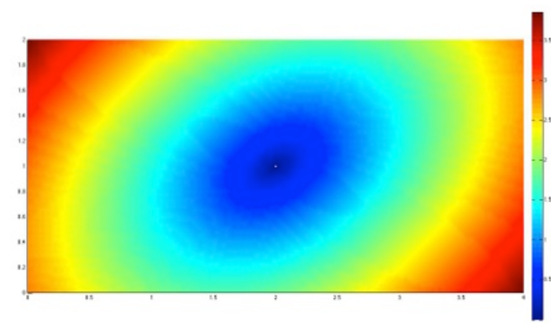


$$\vec{V} = -\frac{\overline{K}}{\mu\,\phi}\nabla P \quad ; \quad \overline{K} = \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix}$$

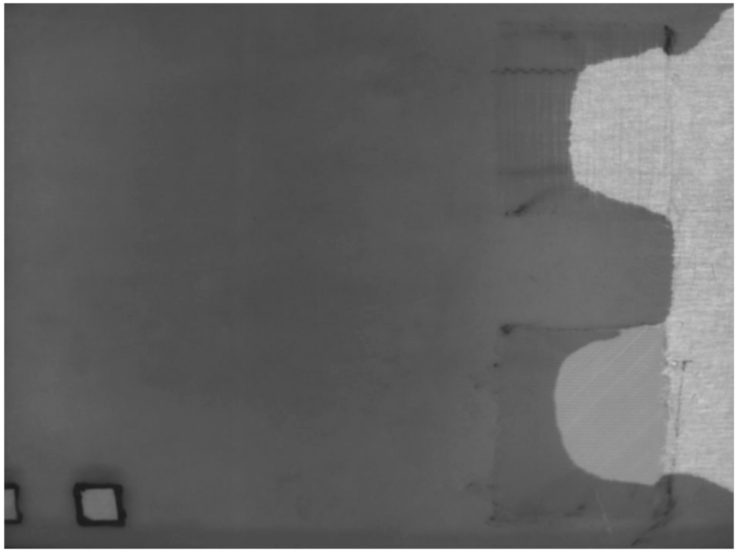
$$\phi_t + \vec{v}\cdot(\overline{M}\cdot\nabla\vec{\phi}) = 0$$

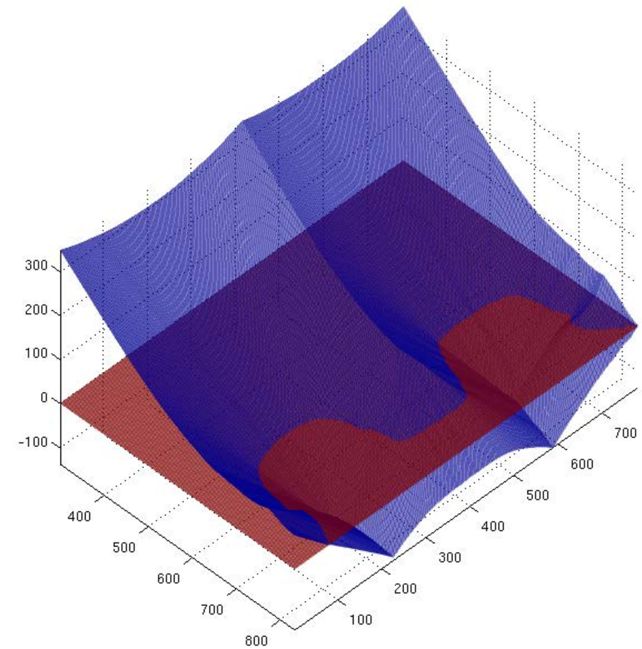
$$\overline{M} = \begin{bmatrix} \cos\theta_E & -\sin\theta_E \\ \sin\theta_E & \cos\theta_E \end{bmatrix} \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}$$





Application of Level Sets. Inverse method





Artificial Vision Image

Real time monitoring during filling

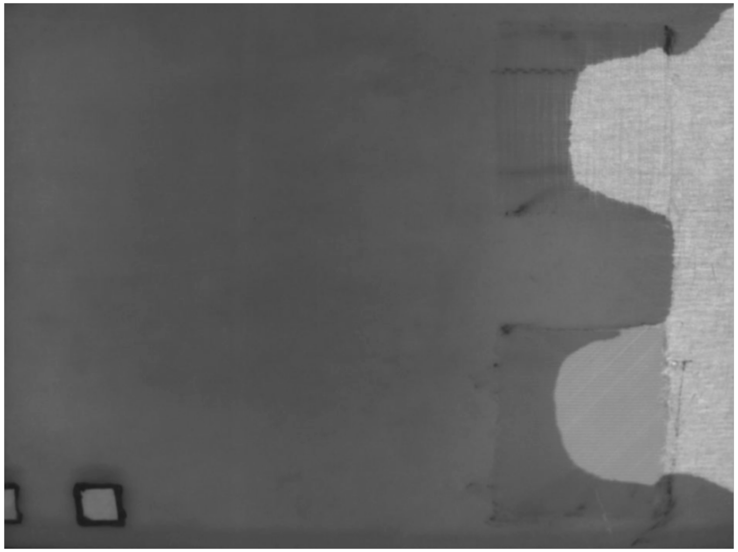
Flow front shape definition

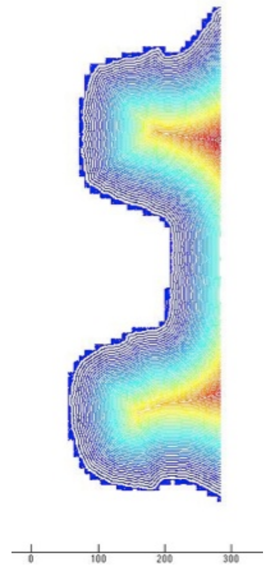
Related implicit Level Set ϕ

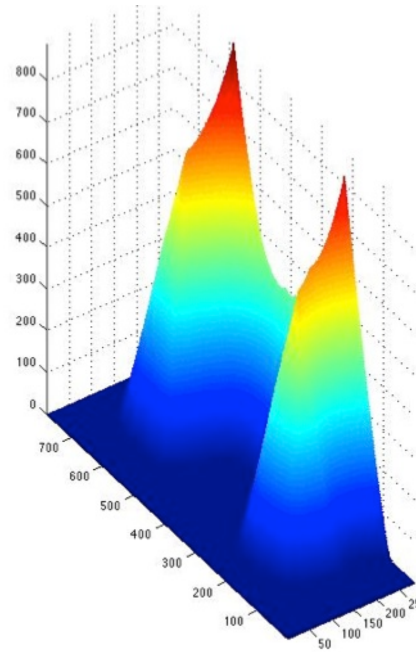
Level set ϕ as a Signed distance function

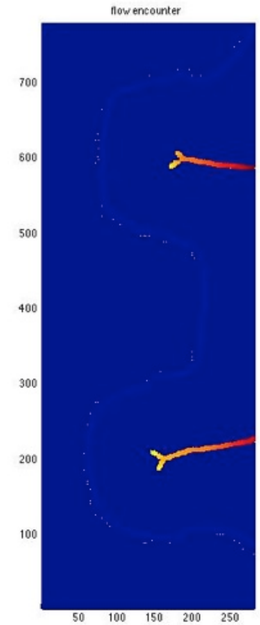
Level set ϕ imposed for every front during filling

Level Sets as computational framework









Artificial Vision Image

Real time monitoring during filling

Flow front shape definition

Related implicit Level Set ϕ

Outwards Fast Marching computation

Distance Pattern function Θ

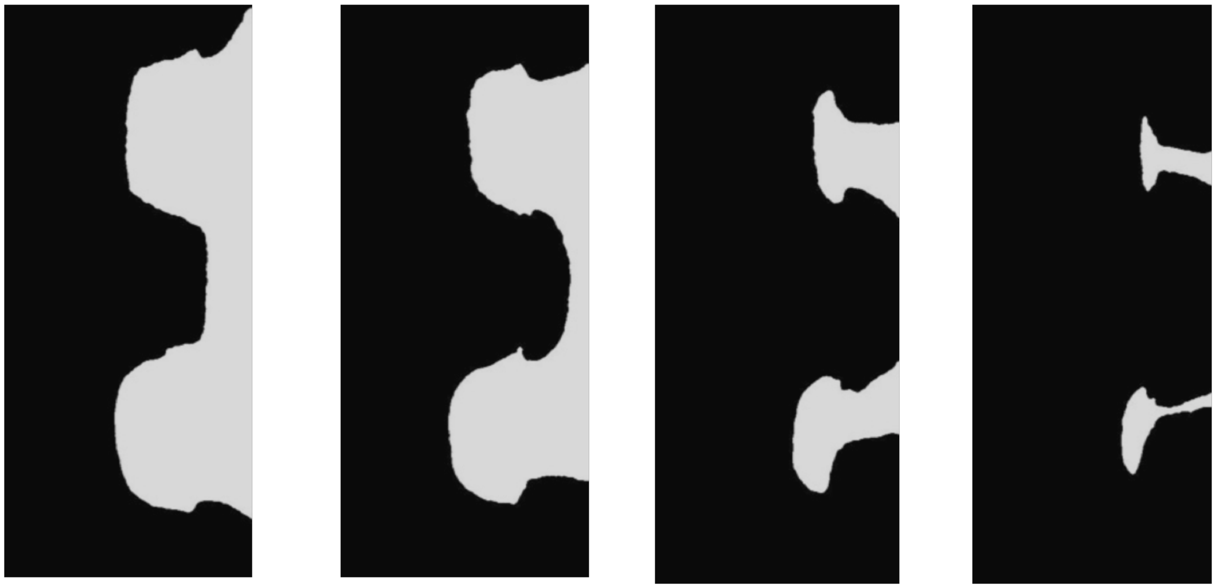
Distance as a filling time indicator

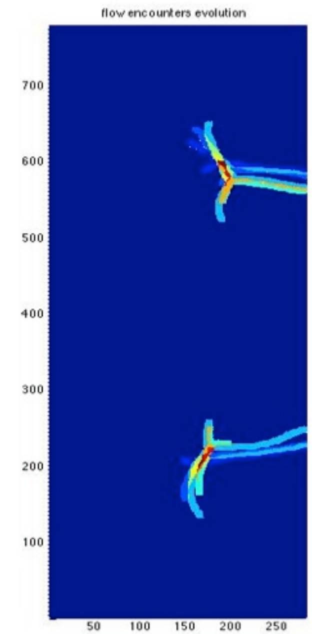
Laplacian Λ

Flow encounters location indicator

Flow Encounters Monitoring During Filling

Level Sets as computational framework



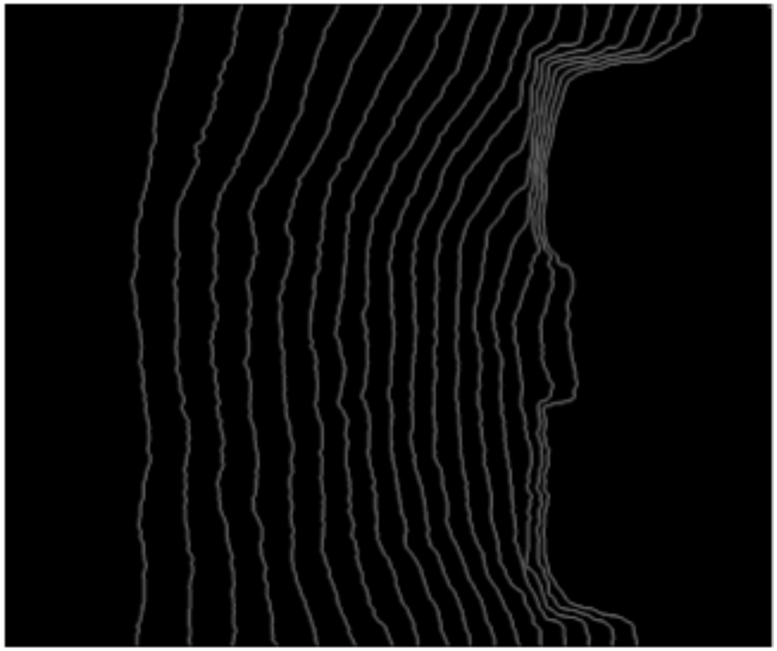


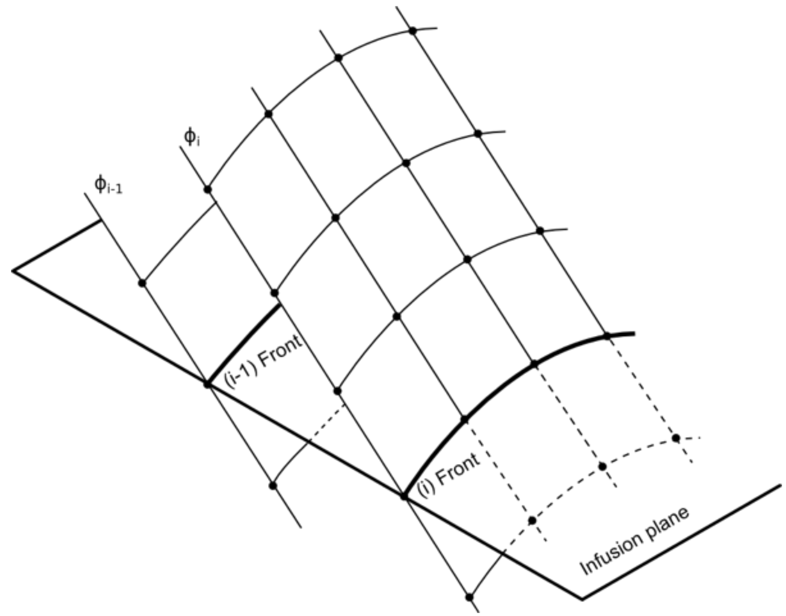
***Laplacian* Λ**

Flow encounters location indicator during filling

Last filled area estimation

Application of Level Sets. Inverse method





Flow front shape definition

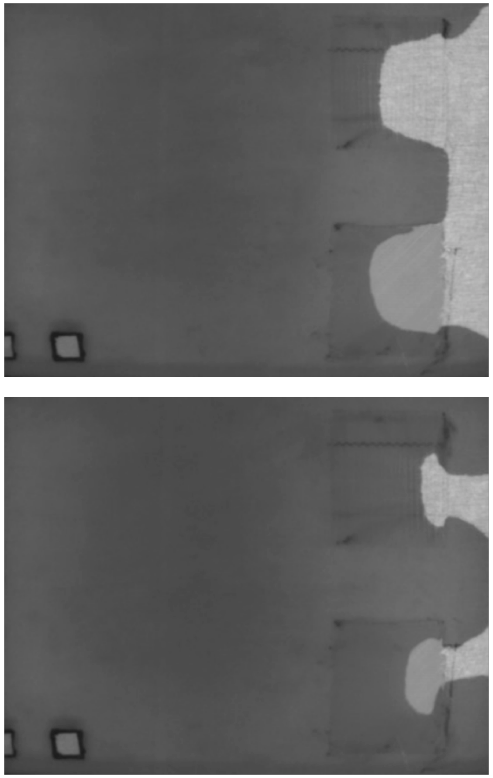
Related implicit Level Set ϕ
For every front during filling

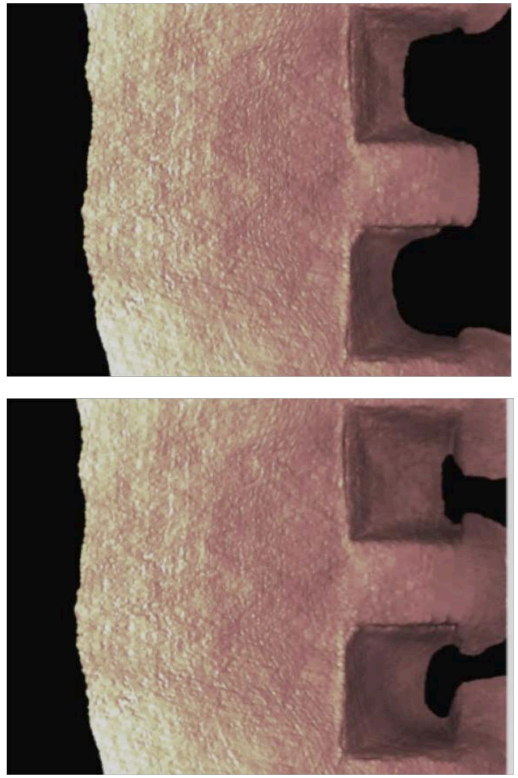
Local Velocities computation

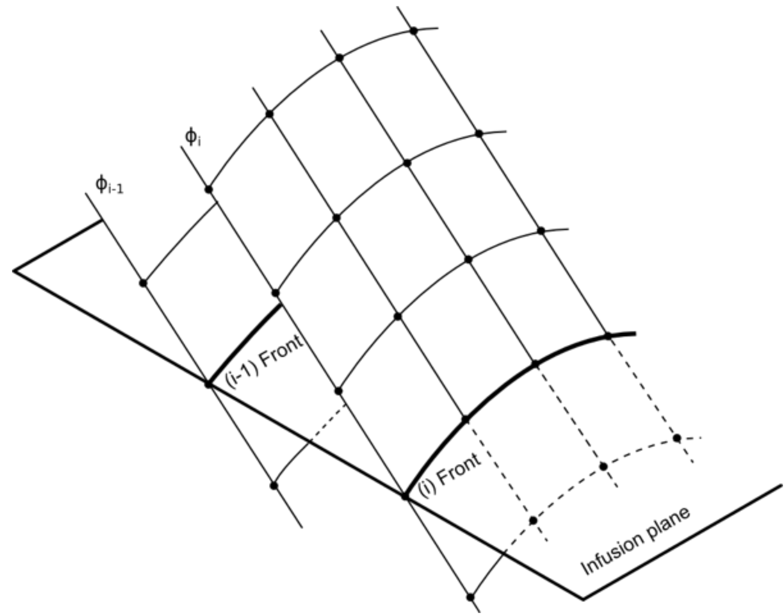
Inverse method applied to the Level Set equation

$$V_{n,i} = \frac{\phi_i - \phi_{i-1}}{\left|\nabla \phi\right|}$$

Application of Level Sets. Inverse method







Local Velocities computation

$$V_{n,i} = \frac{\phi_i - \phi_{i-1}}{\left|\nabla \phi\right|}$$

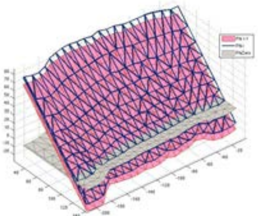
Flow front dynamical behaviour characterization during filling

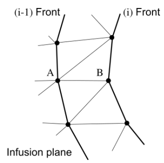
Permeability variations related with velocities

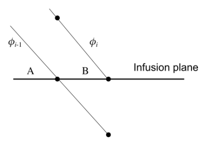
Application of Level Sets. MNET method

A novel **mixed numerical/experimental technique** based on artificial vision for estimating the **induced effect of the textile permeability** in the laminate impregnation and front advance during filling

Darcy's Law: $\underline{v} = -\dfrac{\underline{\underline{K}}}{\varphi \cdot \mu} \nabla P \quad \Rightarrow \quad \underline{v} = -\underline{\underline{M}} \cdot \nabla P$





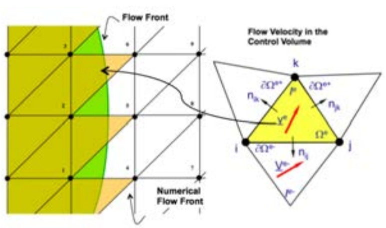


Artificial Vision+LevelSet Velocity computation

Assuming Isotropy

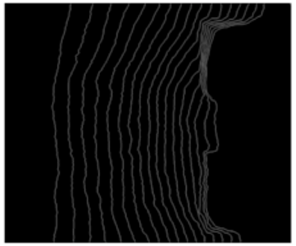
$$M = \frac{\|v\|}{\|\nabla P\|}$$

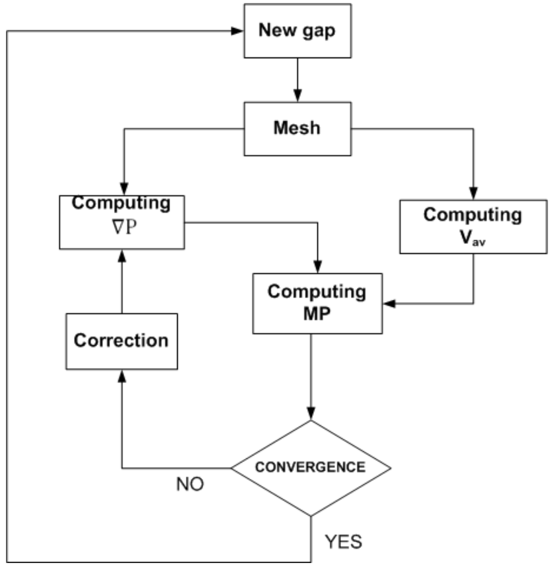
FEM Simulation of Velocity field



$$M^{est} = \frac{\|V_{AV}\|}{\|\nabla P(M^{est})\|}$$

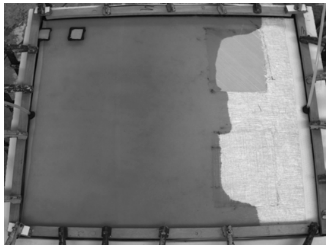
$$M^{est}_{K+1} = \frac{\|V_{AV}\|}{\|\nabla P(M^{est}_{K})\|}$$





Test 3. Areas with textile variation during filling.

Local material Isotropic permeability estimation with flow front evolution



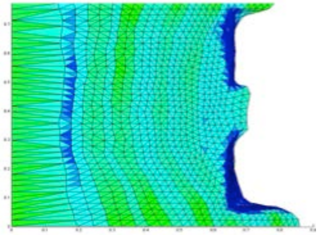
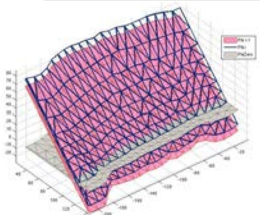


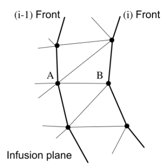
Figure Unidirection flow AV test ((left) , Material Estimation (right)

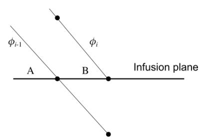
Application of Level Sets. MNET method

A novel **mixed numerical/experimental technique** based on artificial vision for estimating the **induced effect of the surface coating curing** in the laminate impregnation and front advance during filling

Darcy's Law: $\underline{v} = -\dfrac{\underline{\underline{K}}}{\varphi \cdot \mu} \nabla P \quad \Rightarrow \quad \underline{v} = -\underline{\underline{M}} \cdot \nabla P$





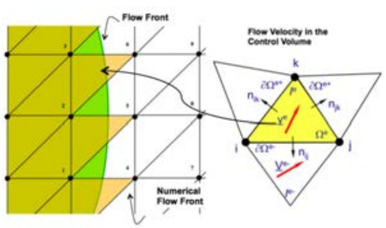


Artificial Vision+LevelSet Velocity computation

Assuming Isotropy

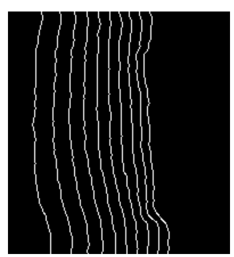
$$M = \frac{\|v\|}{\|\nabla P\|}$$

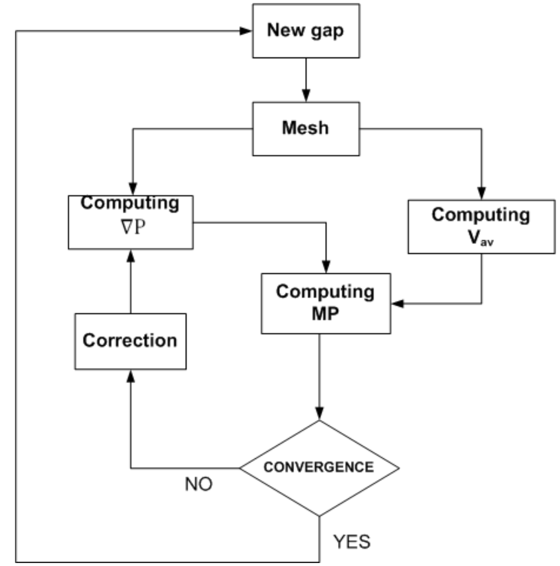
FEM Simulation of Velocity field



$$M^{est} = \frac{\|V_{AV}\|}{\|\nabla P(M^{est})\|}$$

$$M^{est}_{K+1} = \frac{\|V_{AV}\|}{\|\nabla P(M^{est}_{K})\|}$$





Test 2: Bidirectional flow with an abrupt discontinuity in the curing degree of the gel coat

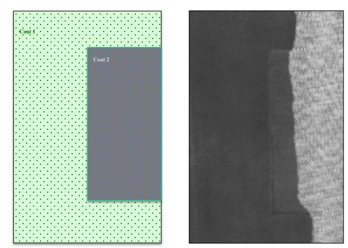


Figure 6 Experimental setup with two different coat areas (left) and intermediate AV image flow front (right)

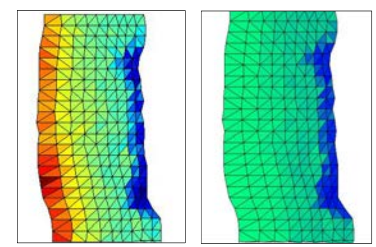


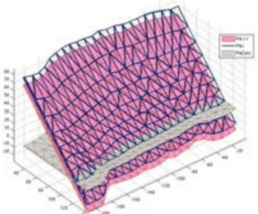
Figure 7 Estimation of Velocity field in elements (left) and Material Properties (right)

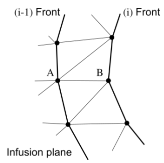
Material Characterization estimation during filling

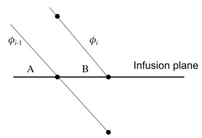
Application of Level Sets. MNET method

A novel **mixed numerical/experimental technique** based on artificial vision for estimating the **induced effect of the surface coating curing** in the laminate impregnation and front advance during filling

Darcy's Law: $\underline{v} = -\frac{\underline{\underline{K}}}{\varphi \cdot \mu} \nabla P \quad \Rightarrow \quad \underline{v} = -\underline{\underline{M}} \cdot \nabla P$







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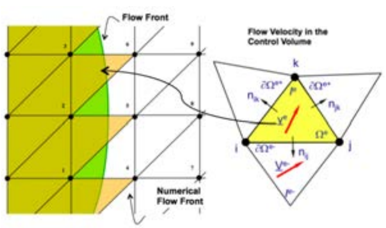
FEM Simulation of Velocity field



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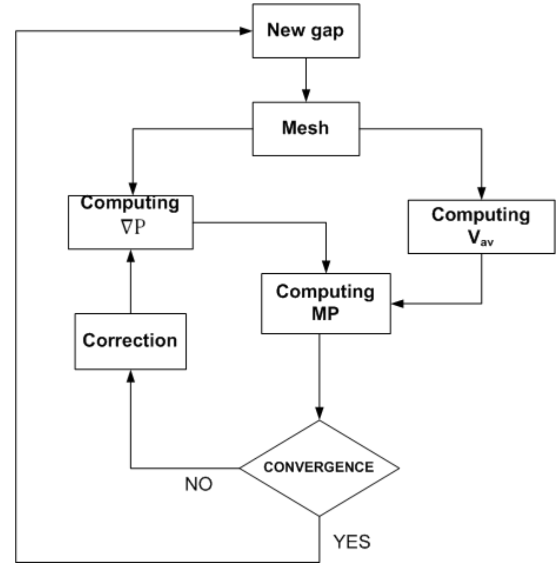
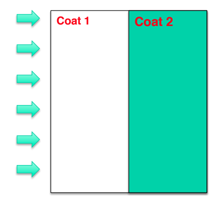
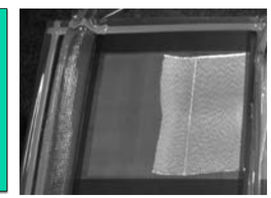


Test 1: Unidirectional flow with an abrupt discontinuity in the curing degree of the gel coat: the coatings have been applied on the mold surface in 2 consecutive areas as outlined





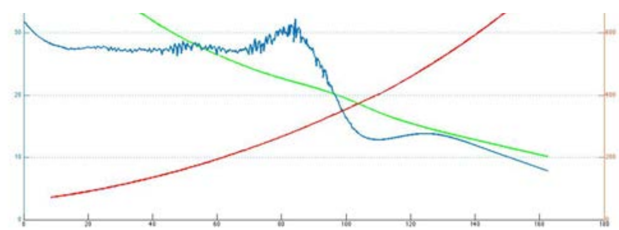


Figure 5 Material Properties Estimation during filling (blue), 1D Flow front position (red) and Flow front Velocity (green)

Conclusions. Questions

In this work it has been presented a **computational and technological framework** for developing tools based on **artificial vision techniques**.

The computation **based on LEVEL SETS allows one to monitor the flow motion under dynamic behavior during filling** and establish **geometric reference benchmarks**.

The main objective regarding to establish the capabilities of using **geometric indicators for the advancing front shapes monitoring** for the **whole domain,** has been accomplished and future works are onwards.

Thank you for your attention