A FAST AND EFFICIENT GEOMETRICAL METHOD TO OPTIMIZE LRI PROCESSES

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Abstract

This paper presents a fast and efficient geometrical method to optimize LRI processes based on Level set methods. Previous work presents, until now, the first method to find the optimal inlet and outlet location in LRI processes [1],[2],[3]. These papers aims to design the distribution channel of resin infusion processes where are not use iterative methods. For this purpose, the algorithm commonly used has been replaced for FPCS (Flow Pattern Configuration Space) and Delaunay triangulation.

The FPCS has been developed with the variables to be optimized, in this case distance. In the case of 2.5D geometries, the use of these spaces reduces the size of the search space. This reduction, combined with the Delaunay triangulation for 2D allows us to compute the medial axis, which is the basis of the optimal resin channel distribution.

However, the use of the FPCS and/or Delaunay triangulation has an important limitation. The FPCS cannot be applied to pieces with curving areas or holes where the geodesic distance cannot be computed from a single point. In addition, 3D Delaunay triangulation cannot be applied directly for manifolds (2.5D) because it was developed for 3D objects.

Therefore, the aim of the present paper is to replace the computational tool proposed in our previous work, [1],[2],[3], that allows to compute the optimal resin channel distribution for whatever case. Although there are algorithms to compute the medial axis directly in a complex manifolds with holes, see for instance [4], a level set method is selected as a computational tool. It is due to level sets not only allows to compute the medial axis with holes in a manifold but also allows us to improve the design of the optimal resin channel distribution. Level set enables us to introduce some new parameters as a design parameter not treated in the present paper. At the end of the paper, some numerical examples are shown.

1. Introduction

Liquid Resin Infusion (RI) processes are 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. Figure 1 (left) shows a diagram of this process. Negative pressure allows

designers to introduce resin channel network structures in the areas where the quality of the piece is not relevant, see Figure 1 (left).

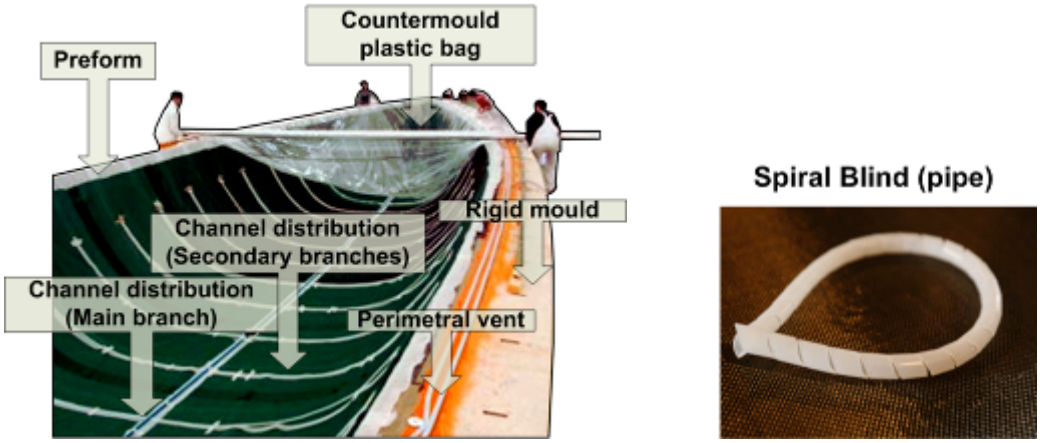


Figure 1. Liquid Resin Infusion Process (left). Spiral blind, pipe, (right)

Resin infusion processes are usually slow due to the low-pressure gradient and the size of the geometries to infuse. For this reason, the channels are necessary to reduce cycle times. Using it as in Figure 1 (left), the filling of a boat hull with 11.8 m length can be completed in 195 min.

Spiral blind (pipes), is commonly used to build these channels, Figure 1(right). These components are hollow tubes made with a plastic strip rolled in a spiral shape. The resin flows much faster inside the pipe than inside the preform. When the resin fills the channel, it begins to permeate the preform through the holes left by the spirals.

There are many contributions in the literature on how to place the injection nozzles and vents in rigid countermould processes, as RTM (Resin Transfer Moulding). In these cases, inlets and outlets are points. However, there are few contributions regarding semi-rigid countermould processes, [5],[6]. This is due to it is possible to introduce resin channel distributions, that they can take complex shapes.

1.1. Previous works. Optimal resin channel distribution computation

The aim of the optimization algorithms in LRI processes is the same than RTM; the flow front must be achieve the vent (in LRI the contour) at the same time and the filling time must be reduced as more as possible. The literature does not offer tools to compute it. However, the industry, and in particular, expert teams has the ability to design the resin channel distribution and getting amazing results. This expert teams use trial and error and the optimal Resin channel distribution obtained is like the depicted in Figure 1 (left). Then, the aim of our previous works, was to obtain a tool to compute the same than expert teams [1],[2],[3] in an automated way. These works divide the optimal channel distribution in two parts, called "*main branch*" and "*secondary branches*", see figure 1 (left). Main branch was obtained by applying the Delaunay triangulation to the vent, the entire contour in LRI process. This algorithm provides the circles and the vertex that are tangent with at least three contour points, see Figure 2.

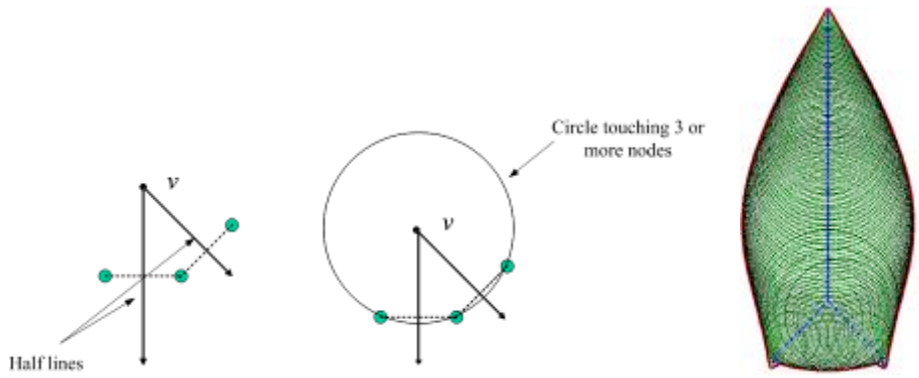


Figure 2. Main branch computation (Left). Example of a Boat (Right)

Main branch was improved in [1],[2],[3], by means of the same concept, the *secondary branches*. Therefore, each *secondary branch* is equidistant to at least two contour nodes. Then, the bisector between these two nodes, passing through the center, intersects in a point of the main branch. Thus, the secondary branch was defined from the point of intersection with the main branch and the center that ensures the tangency, see figure 3.

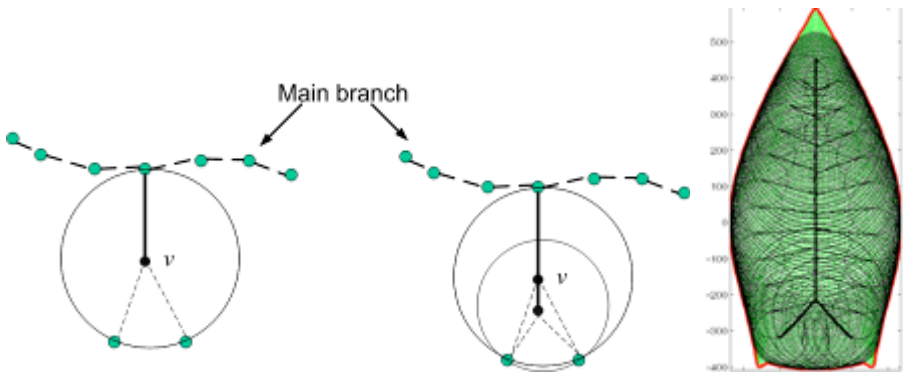
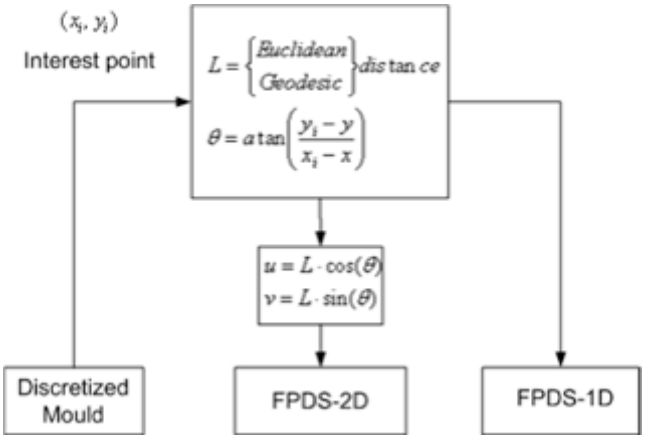


Figure 3. Secondary branch computation (Left). Example of a Boat (Right)

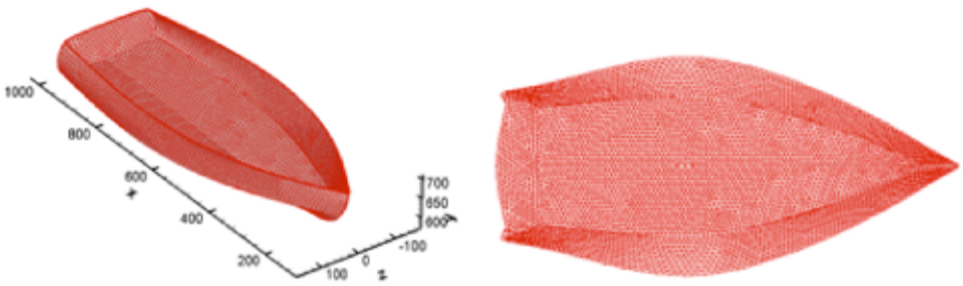
The secondary branch has a degree of freedom. The center and the radius of each secondary branch can be modified without losing the tangency, see Figure 3 (middle). Thus, the radius of all secondary branches can be homogenized in order to have the same effect on the contour. Hence, when a radius value of the main branch is selected, all the secondary branches shall have the same value. For a given secondary branch, the nearest secondary branches located into the circle are deleted because has similar effect to the contour. Therefore, the lower the value of the radius selected is, the greater the number of secondary branches. This fact provides a degree of freedom in the design process that it was solved in [2]. For the one hand, once the filling of the mould has been completed, the resin located in the pipes is trapped provoking a waste of resin and increasing the cost of the final piece. This added cost is proportional to the length channel. The labour cost in terms of the assembling time of the injection channel network also increases as length raises. For the other hand, a high channel resolution allows us to reduce filling times and the flow front shape is more similar to the shape of the mould contour. In [2] was proposed an index that takes into account the channel efficiency. It is defined as a relationship between the energy inverted, in this case the quantity or pipe length and the total filling time reduction.

The use of Delaunay triangulation is the most efficient tool to compute the main and secondary branches because the circle and its radius defines itself the equidistance between the contour and the computed vertex. Unfortunately, this fact do not occurs in 2.5D

geometries. In this case, the alternative is to use the Delaunay triangulation for 3D geometries. However, the equidistance is computed with a sphere and it does not guarantee equidistance in 2.5D geometries. In order to solve this problem, in [1] was introduced a configuration space concept. The idea is very simple; replace the Cartesian space for another space developed using the variables of interest. For our case, a Flow Pattern Distance Space (FPDS) is developed as a distance map for a selected point, see Figure 4.



a) Flow Pattern distance Space (FPDS)



b) Boat example. Mould (left), FPDS-2D (right)

Figure 4. a) Flow Pattern Distance Space. b) Boat example.

To develop the FPDS, the geodesic distance between a selected point and all the mould nodes is computed. With this distance and the angle projection, a 2D map is calculated, Figure 4 (b). In this 2D map, a Delaunay triangulation is computed as 2D geometries. The results are translated to the real world because both spaces are node to node connected. However, the literature does not offer algorithms to compute geodesic distance with the ability to avoid holes or take into account curved parts. In order to solve this problem, the literature offers a few solutions; see [4], to compute the medial axis in 2.5D geometries. Medial axis is the research topic in computational geometry that can be equivalent to the main branch. However, the present paper explores the use of level sets because apart to solve the 2.5D problem, allows to introduce a new design parameters.

2. Level set methods to compute optimal resin channel distribution

Following [8], we will describe the resin advancing front as the zero set of an implicit function φ. The evolution of this implicit function under an external velocity field will be given by

$$\phi_t + v \cdot \nabla\phi = 0 \qquad (1)$$

Here, sub-index indicate a partial derivative with respect to that variable. The gradient of the implicit function is defined as:

$$\nabla\phi = \left(\frac{\partial\phi}{\partial x}, \frac{\partial\phi}{\partial y}, \frac{\partial\phi}{\partial z}\right) \quad (2)$$

Here, sub-index indicate a partial derivative with respect to that variable. If, under the simplifying assumptions mentioned in the introduction, we assume that the velocity field at the resin flow front is normal to the implicit function φ itself, $v = an$, we will have

$$\phi_t + a|\nabla\phi| = 0 \qquad (3)$$

and, since our ultimate goal is to compute an approximation to the medial axis, we are interested in computing a signed distance function, i.e., $|\nabla\varphi| = 1$. For this it is sufficient to take $a = cte$. For simplicity we will take $a = 1$, so as to give

$$\phi_t = -a = -1 \qquad (4)$$

See Section 6.2 of [7] for details on the discretization of this equation. In general, any method for the construction of a signed distance function could be useful to us. See [7], sections 7.3 to 7.5 on the basis of the Fast Marching Method. In Figure 4 a representation of the evolution of the level set curves giving rise to the approximate location of injection nozzles is made.

Figure 4. Level set of a rectangle

Figure 5 represents the medial axis obtained through level set representation

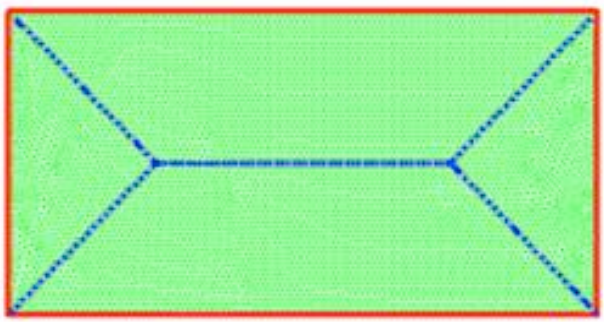


Figure 5. Medial axis of the rectangle

2.1. Secondary branches computation by means of level set

As can be mentioned in the introduction, the secondary branches are defined by means of the bisector between two neighborhood nodes and the intersection with the medial axis. This fact guarantees that secondary branches are perpendicular to the contour. It is the same than the level set method hereinbefore explained. The gradient $\nabla\phi$ is perpendicular to the contour and then, the velocity field too. Thus, the secondary branch using level sets is defined as the path followed for each velocity vector (that is perpendicular to the contour) and the intersection with the medial axis, see Figure 6.

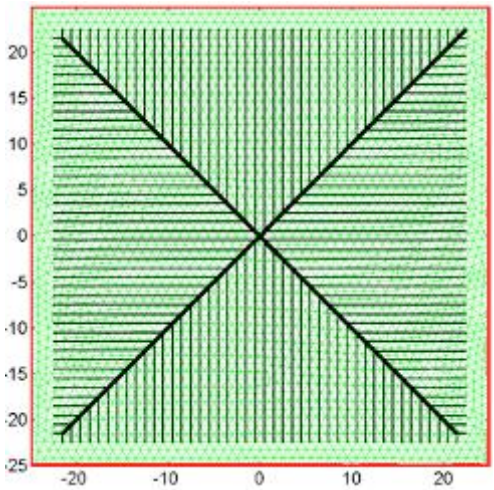


Figure 6. Secondary branches

This path gives itself the distance to the contour. It is the same than the radius computed by Delaunay triangulation in [1], [2], [3], Figure 7.

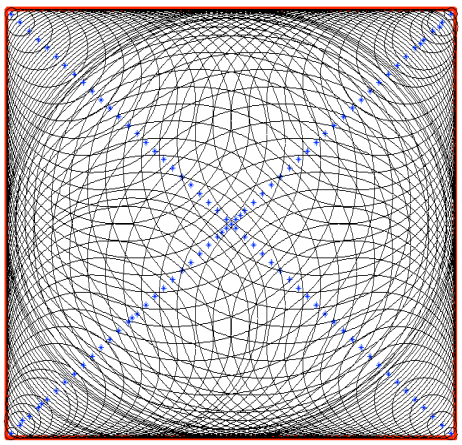


Figure 7. Main branch

As it can be observed, there is a high number of secondary branches, see Figure 5. However, many of them have almost the same effect as they are very close to each other. In our previous works, [1], [2], [3], a filtering criterion was proposed. It imposed that, within the tangent circle of a secondary branch, there cannot be another center, that is, another secondary branch. The same criterion can be constructed by level sets, but in this case, outward level set, see Figure 8

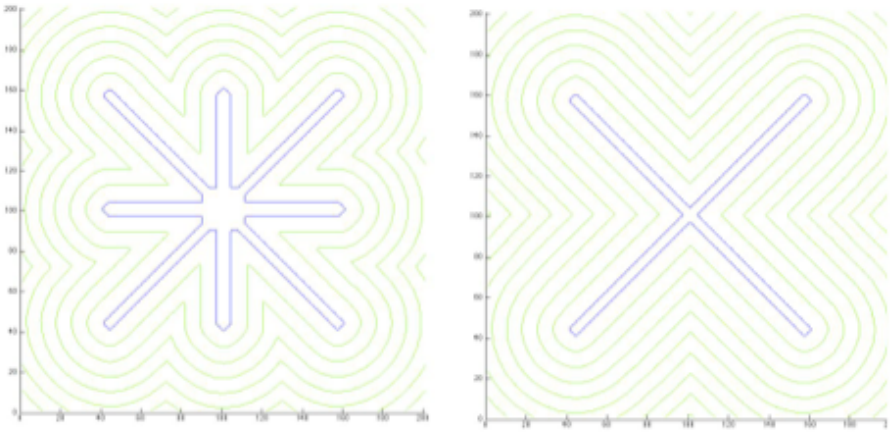


Figure 8. Outward level set.

The methodology is like follows. First, a radius is selected. Second, outward level set is computed for an arbitrary secondary branch until the predefined distance is achieved. Third, the secondary branches located inside to the zone are deleted. Fourth, the nearest non-deleted secondary branch is selected and outward level set is computed again. The process concludes when all redundant secondary branches are filtered. Figure 9 shows an example of a rectangle mould.

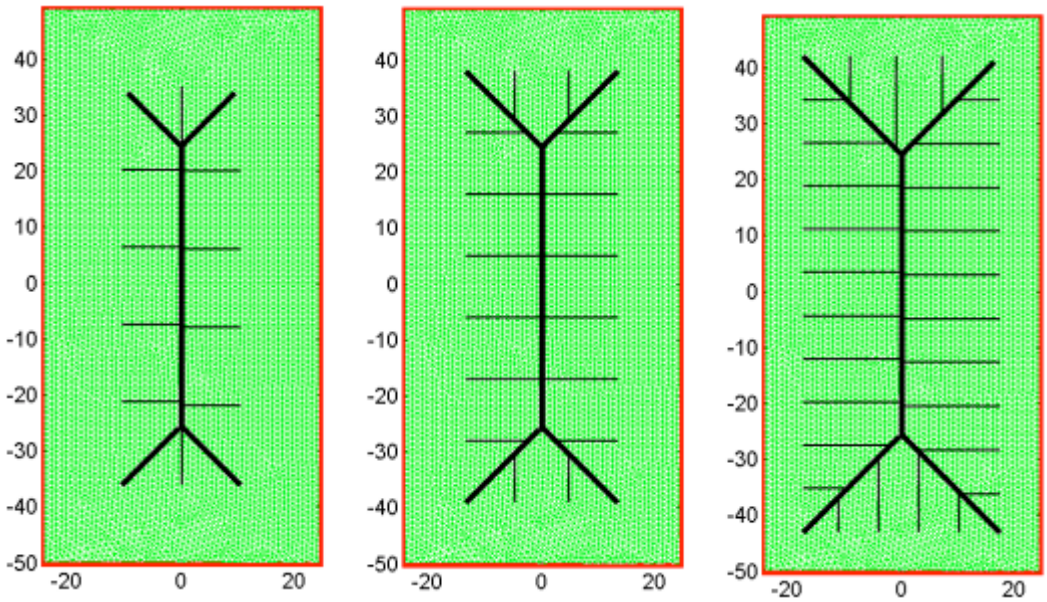


Figure 9. Secondary branches filtered by outward level set

3. Conclusions and future works

This paper presents a fast and efficient geometrical method to optimize LRI processes based on Level set methods. Previous work presents, until now, the first method to find the optimal inlet and outlet location in LRI processes [1],[2],[3]. These papers aims to design the distribution channel of resin infusion processes where are not use iterative methods. For this purpose, the algorithm commonly used has been replaced for FPCS (Flow Pattern

Configuration Space) and Delaunay triangulation. However, the FPCS cannot be applied to pieces with curved areas or holes where the geodesic distance cannot be computed from a single point.
Therefore, in the present paper proposes a level set method to replace FPCS+Delaunay triangulation. As it is demonstrated, Level sets allow us to obtain the same results than [1],[2],[3] but without the limitations of FPCS+Delaunay.

There are another alternatives to solve the restriction, see for instance [4]. However, we select level sets because not only allow us to compute the main and secondary branch with holes in a manifold but also allow us to improve the design of the optimal resin channel distribution. Level sets enable us to introduce some new parameters not treated in the present paper to improve the process design. In particular, it can be possible to obtain with level sets an accurate approximation for the flow front shapes. It can be useful to define accurately the optimal size of the injection channel.

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