Growing Circles: A Region Growing Algorithm for Unstructured Grids and Non-aligned Boundaries

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Abstract

Detecting the boundaries of an enclosed region is a problem which arises in some applications such as the human upper airway modeling. Using of standard algorithms fails because of the inevitable errors, i.e. gaps and overlaps between the surrounding boundaries. Growing circles is an automatic approach to address this problem. A circle is centered inside the region and starts to grow by increasing its radius. Its growth is limited either by the surrounding boundaries or by reaching its maximum radius. To deal with complex shapes, many circles are used in which each circle partially reconstructs the region, and the whole region is determined by the union of these partial regions. The center of the circles and their maximum radius are calculated adaptively. It is similar to the region growing algorithm which is widely used in image processing applications. However, it works for unstructured grids as well as Cartesian ones. As an application of the method, it is applied to detect the boundaries of the upper airway cross-sections.

CCS Concepts

•***Computing methodologies*** → ***Shape modeling;*** *Reconstruction;* •***Applied computing*** → *Physics;*

1. Introduction

Human upper airway is a cavity which is bounded by several anatomical structures such as maxilla, mandible, tongue, pharynx, larynx, etc. Boundaries of the surrounding structures implicitly define the geometry of this cavity. However, an explicit representation of the cavity is of interest in some modeling applications (see e.g. [AFH*17, DAEG17]). In such an application, the geometries are represented with an unstructured grid, and the boundaries are not aligned (i.e. there are gaps and overlaps) due to inevitable errors during model development. Motivated by this, we seek for a solution to construct the geometry of an enclosed region using the geometry of the surrounding objects. Using of geometrical boolean operations [Vat92] fails when the surrounding boundaries are not perfectly aligned; for example when there is a small gap between boundaries. It may also create slivers, and tail-like corners when there are gaps/overlaps along the boundaries. Alternatively, we may see this problem as a segmentation problem and employ region growing algorithm [AB94]. However, image-based approaches are designed to work with Cartesian grid and they may not work for unstructured grids. We have developed a region growing algorithm, namely growing circles, that works for unstructured grids and non-aligned boundaries.

2. Growing Circles

Figure 1 illustrates the concept of the growing circle by providing an example. In this example, a region is enclosed by two polygons. For the meantime, we assume that the center of the enclosed region p_c is known. A circle with radius r is positioned at the center p_c and starts to grow by increasing the r. This growth is limited by the surrounding boundaries. To implement the algorithm efficiently, a set of rays originating from p_c intersect all boundaries and the closest point to p_c is chosen as the boundary of the region. In some cases, the circle may grow unlimitedly if there is a wide gap between the surrounding boundaries. Figure 2a shows an example. The gap size that leads to this problem depends on the coordination of p_c and the angle between rays in the implementation. To avoid this situation, a maximum radius r_m is defined which also limits the circles growing in addition to the surrounding boundaries. Employing of r_m results in Figure 2b. There is another situation when an existing bulge on the surrounding boundaries (see Figure 2c) prevents the circle from growing properly, and leads to imprecise result. In this case, a minimum of three circles are needed to detect the boundaries of the region precisely as shown in Figure 2d. Each circle identifies part of the region, and the whole region is determined by the union ($\cup$) of the partial regions.

The growing circles algorithm requires three parameters to be determined: number of circles, their centers p_c, and the maximum radius r_m. These parameters are calculated adaptively as depicted by Figure 3. A set of vertical lines scans the region of interest and intersect with all boundaries. The intersection points (x_1, x_2) which are next to the region are identified. p_c is chosen so that it has a equal perpendicular distance to all intersected boundaries. In some

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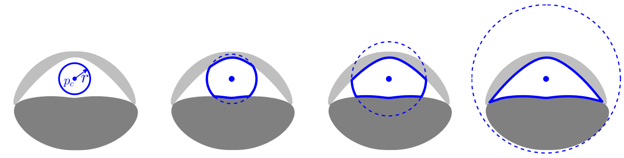
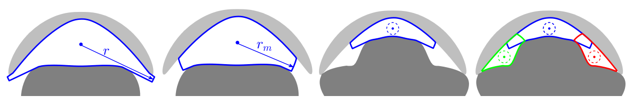
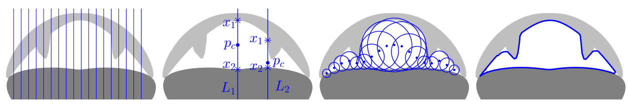


Figure 1: *The concept of the growing circle.*



(a) (b) (c) (d)

Figure 2: *More examples of growing circles when there is a wide gap (a, b) and a bulge (c, d).*



(a) (b) (c) (d)

Figure 3: *Calculation of the circles center and maximum radius.*

cases, such as line L_1, this is equivalent to the midpoint of the segment line $\overline{x_1x_2}$. However, this is not always true (e.g. see line L_2). The maximum radius r_m is calculated using the following equation:

$$d = \min_{i \in (1,2)} \|x_i - p_c\|, \qquad d_l = \frac{\|L_1 - L_2\|}{2}, \qquad r_m = K \times \left(d^2 + d_l^2\right)^{0.5}$$

In this equation, $\|.\|$ is the Euclidean norm, d is the minimum distance between the center p_c and two intersection points x_1 and x_2, d_l is the distance between two consecutive vertical lines, and K is a constant. The distance between the vertical lines affects the accuracy of the results and it becomes even more important to detect the closure areas, which is an area where the surrounding boundaries meet each other. With large d_l, the algorithm may fail to detect a small closure area. If d is less than the threshold, then the line is considered to be in the closure area and hence no circle is determined in this case.

The constant value K should be chosen based on the boundary shapes, as illustrated by examples in Figure 4. Small K (usually less than 1), may result in several disconnected polygons. Large K can guarantee a continuous polygon, but may not accomplish good results when there is a wide gap. Furthermore, small K results in smoother shapes and large K may result in a polygon with small angles.

3. Application to the upper airway

As an application of the method, it was employed to detect the boundaries of the airway cross-sections as shown in Figure 5. The first cross-section (Figure 5a) is positioned in the laryngopharynx. In this cross-section, the airway, is enclosed by the larynx, thyroid bone, and pharynx; the cavity consists of two polygons. The second cross-section (Figure 5b) shows another cross-section of the

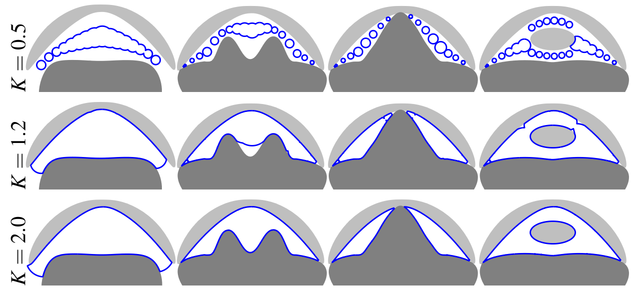
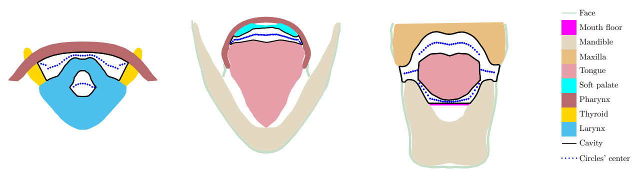


Figure 4: *The influence of K on the resulting geometry.*



(a) (b) (c)

Figure 5: *Examples of detecting boundaries of the upper airway cross-sections.*

airway which is enclosed by pharynx, soft palate and tongue. The third one (Figure 5c) depicts a cross-section in the oral cavity which is enclosed by maxilla, mandible, tongue, and mouth floor. In all examples, the geometry of the enclosed region was constructed accurately.

4. Conclusions

Growing circles is a region growing algorithm which detects the boundaries of an enclosed region and represents its geometry explicitly. It works well for unstructured grids and non-aligned boundaries. To further generalize the method, one may use an estimation of the region's centerline as the circles' center. The vertical lines used for scanning may not be a good choice if the region is expanded in the vertical direction. Nonetheless, it suffices for our application since in most of the cases the region is expanded in the horizontal direction.

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