Integrating digital topology in image-processing libraries

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Abstract

This paper describes a method to integrate digital topology informations in image-processing libraries. This additional information allows a library user to write algorithms respecting topological constraints, for example, a seed fill or a skeletonization algorithm. As digital topology is absent from most image-processing libraries, such constraints cannot be fulfilled. We describe and give code samples for all the structures necessary for this integration, and show a use case in the form of a homotopic thinning filter inside ITK. The obtained filter can be up to a hundred times as fast as ITK’s thinning filter and works for any image dimension. This paper mainly deals of integration within ITK, but can be adapted with only minor modifications to other image-processing libraries.

1. Introduction

Digital image processing is by nature a discrete process: though signal processing algorithms can be applied to digital images, they have to be adapted in some way to take into account that the image they process is not a continuous signal anymore but a set of pixels, or of voxels for three-dimensional images.

This discrete nature causes few problems at the geometric level, as most of the geometric operations that can be applied on an image are independent of the underlying grid. At a topological level, this is however different. The notion at the very base of topology, the neighborhood, is radically different from continuous spaces to discrete spaces. This leads to continuous topological algorithms not respecting topological constraints when applied on a digital grid.

Algorithms based on topological information are numerous, from connected component labeling to skeletonization [1] or loop removal, all of which are used in the field of medical image processing [2–4]. In two major image-processing libraries, ITK [5] and Vigra [6], the type of neighborhood used during the algorithm is hard-coded in that algorithm. This causes of course a loss of flexibility, but also a loss of coherence when processing both the foreground and the background of a digital image, as it is a well-known fact that two different connectivities must be used for the background and the foreground [7]. If this condition is not respected, the Jordan theorem [8] will not hold and situations will arise where a closed curve does not partition the space in two regions.

This rigid characteristic of those both major libraries is due to the lack of pertinent data structures to correctly represent the topology of digital images. In this paper, we show how to integrate the digital topology information in an image-processing library in a way that is:

• generic, with respect to both the image dimension and the different types of neighborhood;
• automated, in the sense that as few “special case” code as possible has to be written;
• fast, by pre-computing as many things as possible.

The language used in this paper is C++, as this work was realized within the ITK framework. However, the concepts
explained here could easily be adapted to other languages, and other image-processing libraries.

We will first present the limitations of two major image-processing libraries, ITK and Vegra, with respect to digital topology, and detail the theoretical background. We will then present the necessary structures to integrate digital topology in an image-processing library, and give an example on how to use these structures to implement a homotopic skeletonization algorithm. We conclude by summarizing our work and by giving leads for future improvements.

2. Previous work

In this section, we show how both the ITK and Vegra libraries lack the necessary structures to correctly embed digital topology in the images and algorithms.

In ITK, there is no structure related to digital topology. All algorithms use a hard-coded neighborhood, usually the 18-neighborhood in three-dimensions, and the 4-neighborhood in two-dimensions. As these neighborhoods are hard-coded, it is not possible to use coherent connectivities for the background and the foreground.

In Vegra, there is a basic support for digital topology, using the NeighborhoodCirculator class. This class is however limited to two-dimensional images and treats the four- and eight-connectivity in a non-generic way. In our sense, this is not an easily maintainable solution: each connectivity is treated as a special case. And as the developer has to hard-code every case, this multiplies the possible sources of errors by the number of cases.

The lack of digital topology information in those two major image-processing libraries shows that it will be difficult, or even impossible, to write algorithms respecting topological constraints.

3. Digital topology basics

We will now recall the basics of digital topology, and present the notations used in the rest of the article. To ensure that our framework will be generic with respect both to the dimension of the image and the type of neighborhood, we will use a cell decomposition representation [9].

In this representation, a binary image of any dimension is represented as a set of cells, with well-defined neighboring relations, rather that just a set of pixels (cells of dimension 2) or voxels (cells of dimension 3).

3.1. Cells

Let us consider images of dimension \( n \). A \( k \)-cell of \( \mathbb{R}^n \) [9] is defined as a subset of \( \mathbb{R}^n \) of the form \( c = I_1 \times \cdots \times I_n \), such that:

- \( I_i \) is either of the form \( [z_i, z_i + 1] \) or the form \( \{z_i\} \) (\( z_i \in \mathbb{Z} \));
- \( k \) of the \( n \) sets \( I_i \) are of the form \([z_i, z_i + 1]\) and the other \( n - k \) are of the form \( \{z_i\} \).

The dimension of a \( k \)-cell is \( k \). A \( n \)-cell has the form \([z_1, z_1 + 1] \times [z_2, z_2 + 1] \times \cdots \times [z_n, z_n + 1] \), and is thus a pixel/voxel of the image, occupying a unit area/volume.
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