Finding regional extrema - methods and performance

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January 4, 2006

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Abstract

Finding regional extrema of images is an important step in a number of morphological algorithms, such as some versions of the watershed transform[1]. Regional extrema may also be important cues of other tasks, such as splitting objects based on distance transform information. This report provides an overview of the methods available in ITK and compares the performance with a new filter.

Keywords: regional minima, flooding, performance, mathematical morphology

1 Introduction

There are two classes of regional extrema - regional maxima and regional minima. Regional maxima are flat zones that are connected to pixels of lower value while regional minima are flat zones that are connected to pixels of higher value. The notion of higher and lower is obviously critical to the definition of regional maxima and minima, which means that it doesn't make sense to apply the definitions directly to vector images. The notion of connectivity is also important to define which pixels are connected to others.

2 Filters currently available in ITK

Regional extrema are already used inside the ITK watershed implementation and may be computed using *HConvexImageFilter* and *HConcaveImageFilter*.

The regional extrema computed in the watershed are not available externally (which could obviously be changed). The technique used in the watershed filters is based on a labelling approach, very similar to that used in the *ConnectedComponentImageFilter*, where each region of uniform intensity is labelled and checked to determine whether it is an extrema or plateau.

The convex and concave filters are based on the principles of morhpological reconstruction. Regional minima are located as follows: create a marker image by adding h to the original, carry out a reconstruction by

[1]This work started because we were trying to compare different watershed algorithms

erosion of the marker image using the original as the control surface, and then, finally, take the difference between them. If h=1 then any non-zero pixels are regional minima, if h is greater than one then the non zero pixels are minima that are at least h below the lowest surrounding ridge point. The value h is often referred to as the *dynamic* of the minima, and is often used to give an indication of the importance of the regional minima.

The concave and convex filters are therefore capable of providing more information than just the location and value of the regional minima - they also provide some clues about the local topology. However this additional information comes at a computational cost as well as a restriction on the type of images to which the technique can be applied. The need to add or subtract h, rather than relying on equality, means that it is only possible to find extrema when the smallest step in image intensity is known. This is difficult to do sensibly on floating point image types.

3 *ValuedRegionalMaximaImageFilter* and *ValuedRegionalMinimaImageFilter*

The new filters use a simple flooding approach to find regional extrema. They produce an output image with the non minima (maxima) set to the maximum (minimum) of the pixel type. The minima or maxima retain their original value. The flooding approach is very simple, and proceeds, for minima detection, as follows:

- Copy the input to the output.
- Visit each pixel of the input image.
  - If the the corresponding output value is not maximal (meaning this pixel hasn't already been visited) then check all the neighbors.
    - If any of the neighboring grey levels are less than the current pixel value, then this pixel cannot be a regional minima.
      - Flood fill the region, in the output image, with the same grey level as the current pixel that contains the current pixel, with the maximal value for the pixel type.
- Go to next input pixel.

This algorithm requires that the image border is preset to the maximum value for the pixel type, which is done using a constant boundary condition.

It is generally quite difficult to produce efficient parallel parallel implementations of flooding algorithms, and no attempt has been made to make a threaded version of the new filter.

The pixel neighborhood is controlled by the *FullyConnected* attribute. All adjacent pixels are included in the neighborhood when FullyConnected=True and the diagonally adjacent pixels are not included when FullyConnected=False. Different terminology is often used to describe neighborhoods – one common example is the "connectivity" notation, which refers to the number of pixels in the neighborhood. FullyConnected=False corresponds to a connectivty of 4 in 2D and 6 in 3D, while FullyConnected=True corresponds to a connectivity of 8 in 2D and 26 in 3D. FullyConnected=False is also commonly referred to as "face connected".

The core implementation is done in *ValuedRegionalExtremaImageFilter*. *ValuedRegionalMaximaImageFilter* and *ValuedRegionalMinimaImageFilter* are instantiations of *ValuedRegionalExtremaImageFilter* using the standard library comparison functor to select between the two types of behavior.

4 *RegionalMaximaImageFilter* and *RegionalMinimaImageFilter*

A constant, or flat, image will be marked as a regional extrema by this filter due to the border condition mentioned earlier. The *ValuedRegionalExtremaImageFilter* will set a flag if this situation arises, so the user can decide to consider the entire image as an extrema or not. The flag can be retrieved with `GetFlat()` method.

To make this situation easier to manage, *RegionalMaximaImageFilter* and *RegionalMinimaImageFilter* have been created. They return the regional extrema in a binary image. Because the situation is not properly defined, the `SetFlatIsMinima()` and `SetFlatIsMaxima()` method let the user choose what to do in constant image case.

RegionalMaximaImageFilter and *RegionalMinimaImageFilter* are implemented as a sequence of filters and introduce some overhead compared to valued filters.

5 Performance

A timing test comparing performance on a $371 \times 371 \times 34$ image showed that the flooding approach was significantly faster than the reconstruction approach. The results[2] achieved on an Athlon 64 Processor 2800+ (1802 MHz) with 512Kb cache, 512 Mb of RAM and gcc 4.0.2 are shown in Table 1.

FullyConnected	h-concave	valued regional minima	non-valued regional minima
false	22.7868 s	1.92568 s	2.02878 s
true	25.7276 s	3.04492 s	3.13012 s

Table 1: Execution time.

The same test can be run with the command `./perf3D ../ESCells.img`.

This is an approximately 10 fold reduction in computation time. Note that the left-most column indicates whether the filters were run in fully connected or face connected mode.

There are a few approaches that might be taken to improve performance further. For example, that standard face calculator might be used to reduce the boundary condition check. Alternatively, if a copy of the input image is made, and the border of that is set to the maximum value, then there is no need for a boundary check at all. The cost of this is a missing border region and probably an extra copy of the image.

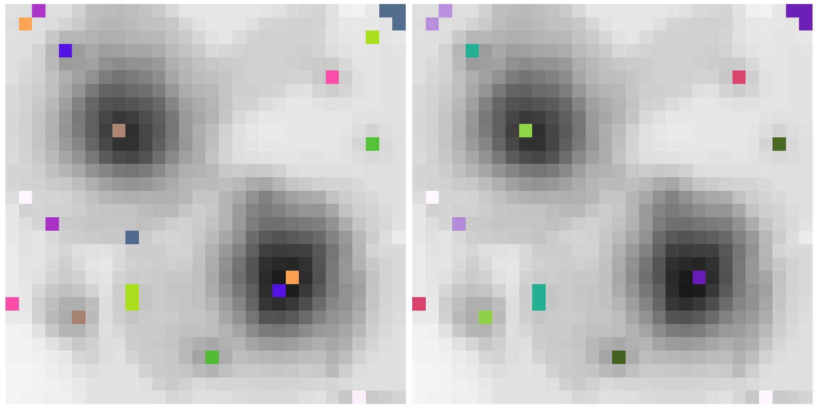
It should be noted that the overhead of the *RegionalMinimaImageFilter* is quite small and should not be a problem in most of cases.

6 Results - just to prove that it runs

Figure 1 shows the labelled (colored) minima on top of a synthetic image while Figure 2 shows the labelled maxima of the *cthead1* image.

[2] We had some problems to reproduce the results shown here. On some systems, running HConcaveImageFilter have an important impact on the execution time of the other filters. It might be necessary to separate the execution of the HConcaveImageFilter and the other filters to reproduce the execution times.

See `http://public.kitware.com/pipermail/insight-users/2005-December/015916.html` for details.



(a) FullyConnected=False (b) FullyConnected=True

Figure 1: Regional minima found using the flooding method with connectivity of 4 and 8.

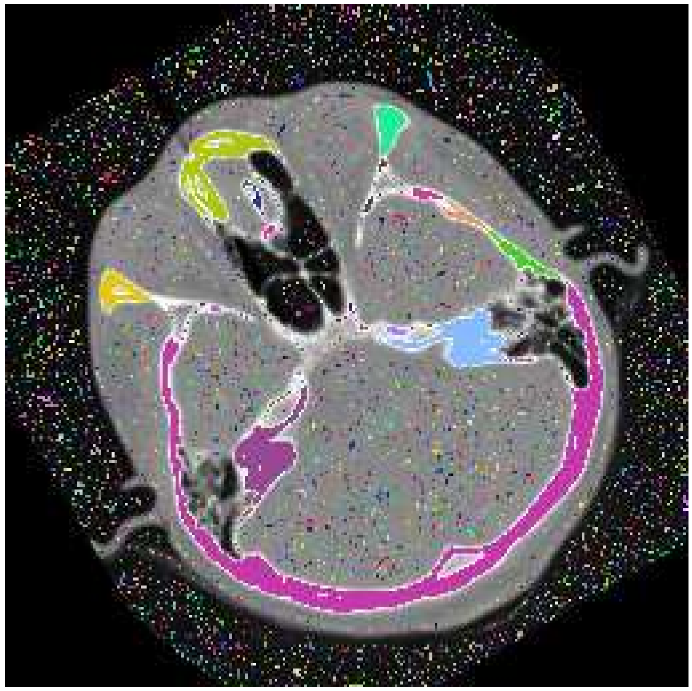
7 Comparison of operations

So which method is “best”? Well, they are all a bit different, so the choice will be application dependent. The labelling approach isn’t currently available as standalone filter, so it is difficult to judge performance. The algorithm requires several steps, which may slow it down, but some of the steps are certain to visit the pixels in raster order, which can be a big advantage. If the regional extrema are going to be labelled anyway then the performance may be competitive. The reconstruction based approach is considerably slower, but is able to do a lot more. If you are interested in image dynamics rather than regional extrema then this is the only way to go. If you definitely want extrema then the new filter is currently the fastest option.

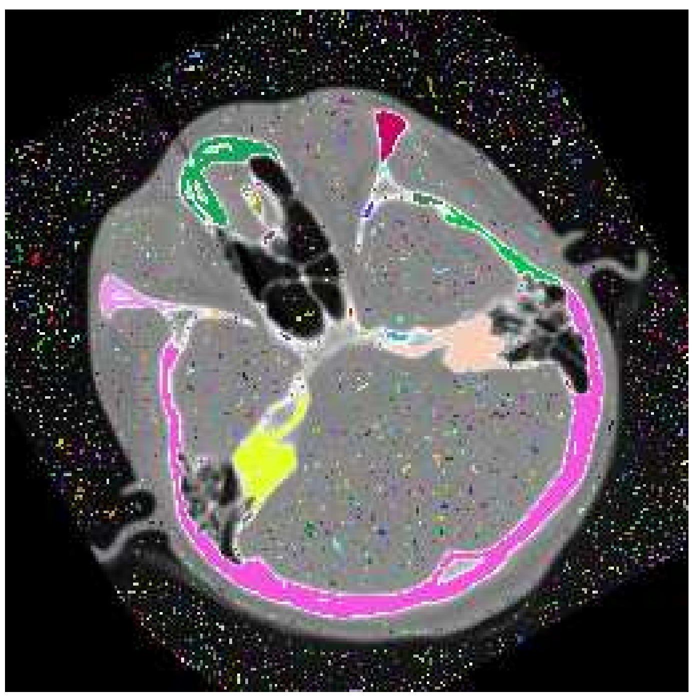
8 Sample code

The following code is from `vrmin.cxx`, and compares the operation of *ValuedRegionalMinimaImageFilter* and *HConcaveImageFilter*.

```
// a test routine for regional extrema using flooding
#include "itkValuedRegionalMinimaImageFilter.h"
#include "itkHConcaveImageFilter.h"
#include "itkMaximumImageFilter.h"
#include "itkInvertIntensityImageFilter.h"
#include "itkImageFileReader.h"
#include "itkImageFileWriter.h"
#include "itkCommand.h"
#include "itkRescaleIntensityImageFilter.h"
#include "itkAndImageFilter.h"
#include "itkCommand.h"
#include "itkSimpleFilterWatcher.h"
```



(a) FullyConnected=False



(b) FullyConnected=True

Figure 2: Regional maxima of *cthead1* found using the flooding method with connectivity of 4 and 8.

```
int main(int, char * argv[])
{
  const int dim = 2;

  typedef unsigned char PType;
  typedef itk::Image< PType, dim > IType;

  typedef itk::ImageFileReader< IType > ReaderType;
  ReaderType::Pointer reader = ReaderType::New();
  reader->SetFileName( argv[2] );

  typedef itk::ValuedRegionalMinimaImageFilter< IType, IType > FilterType;
  FilterType::Pointer filter = FilterType::New();
  filter->SetInput( reader->GetOutput() );
  filter->SetFullyConnected( atoi(argv[1]) );
  itk::SimpleFilterWatcher watcher(filter, "filter");

  typedef itk::ImageFileWriter< IType > WriterType;
  WriterType::Pointer writer = WriterType::New();
  writer->SetInput( filter->GetOutput() );
  writer->SetFileName( argv[3] );
  writer->Update();


  // produce the same output with other filters
  typedef itk::HConcaveImageFilter< IType, IType > ConcaveType;
  ConcaveType::Pointer concave = ConcaveType::New();
  concave->SetInput( reader->GetOutput() );
  concave->SetFullyConnected( atoi(argv[1]) );
  concave->SetHeight( 1 );

  // concave gives minima with value=1 and others with value=0
  // rescale the image so we have minima=255 other=0
  typedef itk::RescaleIntensityImageFilter< IType, IType > RescaleType;
  RescaleType::Pointer rescale = RescaleType::New();
  rescale->SetInput( concave->GetOutput() );
  rescale->SetOutputMaximum( 255 );
  rescale->SetOutputMinimum( 0 );

  // in the input image, select the values of the pixel at the minima
  typedef itk::AndImageFilter< IType, IType, IType > AndType;
  AndType::Pointer a = AndType::New();
  a->SetInput(0, rescale->GetOutput() );
  a->SetInput(1, reader->GetOutput() );

  // all pixel which are not minima must have value=255.
  // get the non minima pixel by inverting the rescaled image
  // we will have minima value=0 and non minima value=255
  typedef itk::InvertIntensityImageFilter< IType, IType > InvertType;
  InvertType::Pointer invert = InvertType::New();
  invert->SetInput( rescale->GetOutput() );

  // get the highest value from "a" and from invert. The minima have
  // value>=0 in "a" image and the non minima have a value=0. In invert,
```

```
  // the non minima have a value=255 and the minima a value=0
  typedef itk::MaximumImageFilter< IType, IType, IType > MaxType;
  MaxType::Pointer max = MaxType::New();
  max->SetInput(0, invert->GetOutput() );
  max->SetInput(1, a->GetOutput() );

  WriterType::Pointer writer2 = WriterType::New();
  writer2->SetInput( max->GetOutput() );
  writer2->SetFileName( argv[4] );
  writer2->Update();

  return 0;
}
```

9 Acknowledgments

We thank Dr Pierre Adenot and MIMA2 confocal facilities (http://mima2.jouy.inra.fr) for providing image samples.

References

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