1 Project Title, Acronym and Principal Researcher

1a) Project Title: Generalized Connected Morphological Operators for Robust Shape Extraction

1b) Project Acronym: GC-MORSE

1c) Principal Researcher: Dr. M.H.F. Wilkinson

2 Summary

The aim of this project is to explore multi-scale and shape-based morphological connected operators, in terms of theory, algorithm development and robustness in a real application, with the main emphasis on the latter two. Connected filters allow image filtering without distorting edges, a feature which is highly desirable in many applications. For this reason they have received much attention in the literature in recent years. Usually, connected filters are defined by classical 4- or 8-connectivity (in 2-D). However, several theoretical developments concerning generalizations of the notion of connectivity have been proposed, which might improve the robustness and increase the versatility of these filters. In this project we will explore the relationships between these various proposals, and aim to develop efficient, unified algorithms for computing connected filters based on a variety of generalized connectivities. After this, algorithms for obtaining shape-scale and orientation-scale spaces using connected filters will be developed. In both cases we will build on a number of algorithms developed here already. These new algorithms will be applied to the problem of enhancing details in 2-D and 3-D medical images, in particular the detection of filamentous details such as blood vessels simultaneously at multiple scales.

3 Classification

Computer Science, computer vision (Subdiscipline: 4.1. Beeld- en Sensorverwerking, NOAG-i 2001-2005 thema’s MSV, i.h.b. 3-D beeld en sensorverwerking, en MM).

4 Composition of the Research Team

<table>
<thead>
<tr>
<th>Staff member</th>
<th>Function</th>
<th>Institute</th>
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<tbody>
<tr>
<td>Dr. M. H. F. Wilkinson</td>
<td>Principal investigator and referent</td>
<td>Institute for Mathematics and Computing Science, University of Groningen.</td>
</tr>
<tr>
<td>Prof. Dr. N. Petkov</td>
<td>Promotor</td>
<td>Institute for Mathematics and Computing Science, University of Groningen.</td>
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<tr>
<td>Prof. Dr. M. Oudkerk</td>
<td>Expert in 3-D medical imaging</td>
<td>Department of Radiology, University Hospital, Groningen</td>
</tr>
<tr>
<td>Dr. M.C.J.M. de Jong</td>
<td>Expert in dermatological imaging</td>
<td>Department of Dermatology, University Hospital, Groningen</td>
</tr>
<tr>
<td>vacancy</td>
<td>PhD student</td>
<td>Institute for Mathematics and Computing Science, University of Groningen.</td>
</tr>
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</table>

The day-to-day supervision of the project will be by Dr. Wilkinson. Dr. Wilkinson has experience in image analysis, both applied [30, 31, 32], and in the development of algorithms of connected morphology [17, 18, 29].
Professor Petkov has a long experience in multi-scale filters used as models for the visual cortex [13, 14].

Dr De Jong is an expert in epidermal imaging, especially fluorescence microscopy, and has collaborated with Dr Wilkinson previously [6, 7, 8].

Professor Oudkerk has a long experience in clinical and scientific research within the field of radiology [19] and is author and co-author of some 100 publications in peer-reviewed articles.

The PhD student will have to have an MSc in computer science or equivalent degree, with good knowledge of image processing, in particular mathematical morphology.

5 Research School

The research is part of the Advanced School for Computing and Imaging (ASCI).

6 Description of Proposed Research

Connectivity is essential to the way we perceive the world about us. Both objects and textures are defined by the way they “hang together”. The human mind apparently uses different forms of connectivity: the way we perceive one bird to be “one” is very from the way one flock of birds is perceived as “one”, which is different again from the notion of connectivity used to perceive a stack of (obviously touching) plates as “more than one.” It is likely that this flexible view of connectivity, or perceptual grouping, adds robustness to visual perception [10]. Clearly, the human brain can deal with notions of connectivity which are distinct from the classical notion of connectivity used in image analysis, e.g., in connected component labelling. The classical connectivity is “bird type”, whereas “flock type” and “stack type” connectivities have been formalized in various generalizations [11]. The importance of connectivity is well recognized in image analysis, and finds an expression in so-called connected filters [11, 22] and certain related segmentation methods [10].

Connected filters form a versatile class of morphological filters, the application of which has been hampered by the lack of fast algorithms, until recently. A morphological filter operates by merging flat zones in the image, and assigning new grey levels to them [11, 22]. The flat zones of an image are simply region of constant grey level, no neighbouring pixels of which have the same grey level (i.e., they have maximal extent). It is easily seen that the flat zones of an image form a partition of the image domain, i.e. they are disjoint, and the union of all flat zones equals the image domain. Connected filters always result in an image in which the flat zones form a coarser partition than those of the original. One reason connected filters are important is that they preserve causality (do not introduce new edges) in morphological scale-spaces, whereas (in 2-D and higher) classical morphological filters do not [3, 4]. Connected filtering for image sequence processing and analysis has also been done [21].

The first connected filter was the opening by reconstruction, for which efficient algorithms are available [27]. Later, area openings and closings were proposed [9], which allows removal of bright or dark image details below a given area size, without distorting other features. The straightforward approach for computing them in the grey-scale case is through threshold decomposition [1, 16]. The first improvement on this naive approach for grey scale was made by Vincent [26], who used a priority-queue algorithm for the area opening. This was subsequently extended to grey-scale attribute openings, thinnings and granulometries by Breen and Jones [5]. Attribute openings allow filtering based on other size criteria besides area, such as moment of inertia, convex-hull area, etc. The thinnings they propose allow filtering using non-increasing attributes, such as perimeter, or circularity for retaining or rejecting image features.
Though fast on many images, it has been shown that the priority-queue approach has a time complexity of $O(N^2 \log N)$ in the worst case [18, 29]. In recent years, two alternatives for the priority-queue algorithm have been developed: (i) the Max-tree algorithm by Salembier and co-workers [21], which is linear in time complexity but cannot be parallelized, and (ii) a method based on Tarjan’s Union-Find algorithm developed in Groningen [17, 18, 29], which is $O(N \log N)$, but faster than the Max-tree method in practise, requires only one third of the memory, and may be parallelized. However, the Max-tree developed by Salembier et al. allows more flexibility in filtering, especially in the case of attribute thinnings [18, 21]. This is because it elegantly separates flat-zone analysis and filtering stages. In the first stage a graph, called a Max-tree, determining the relationships between the flat zones is built. During the filtering stage, each node of the tree is visited to determine if it should be retained, and if not, with which node it should be merged. Because the Max-tree is a compact, multi-scale representation of the image, efficient multi-scale analysis of the image is possible in just a single pass through the Max-tree [25, 32].

All these algorithms use classical 4- or 8-connectivity, and the flat zones are defined accordingly. Recently, Sofou et al. proposed an algorithm for using generalized connectivities in openings by reconstruction and area openings [24]. This algorithm is based on iterative dilations, and therefore slow. We propose to extend the existing, fast algorithms for grey scale connected filters to these new connectivities, and to determine whether the resulting image operators are more robust. In this project we will investigate how the partition of the image into its flat zones is altered by changing the connectivity, and in particular, how it affects the Max-tree structure. If consistent definitions of flat zones and the corresponding Max-trees are possible, a vast range of connected filters using generalized connectivities will become available, simply by constructing the appropriate Max-tree, and filtering it using the existing algorithms.

Many image processing applications require multi-scale analysis. Common examples are wavelets, linear and nonlinear scale-spaces [4, 12], alternating sequential filters [2, 3], and granulometries [15, 28]. In our group multi-scale mathematical morphology has been used, e.g., in diatom analysis [30] and computation of connected filter based pattern spectra [17]. Other research on multi-scale techniques in this group include modelling of the visual cortex by non-linear operators [13, 14, 20]. Many of these techniques are computationally intensive, due to the need for filtering the image at multiple scales. This high computational burden increases further if different orientations are required, e.g. in orientation-scale spaces, which have found applications in enhancement of filamentous details in images, such as blood vessels in angiograms [23], or in analysis of oriented textures [13].

Recently, a new type of multi-scale image operator, called shape filter, was developed at this department, which avoids this computational burden [25, 32]. Shape filters are idempotent, scale invariant image operators, which select or remove image features based solely on shape, not on either scale or orientation. To date, the only available shape filters fall into the class of morphological connected filters, in particular attribute thinnings [5]. These shape filters use the Max-tree algorithm, so if the extension of Max-tree to generalized connectivities is possible, they too can be extended easily. The efficacy of shape filters was demonstrated in a pilot study, in which vessels were extracted from a $256^3$ volume in 42 s on a personal computer [32], compared to 10 min wall-clock time on an 8 CPU Ultrasparc-based machine for the orientation-scale space approach of Sato et al. [23] for a volume of $256 \times 256 \times 103$. An added bonus is the absence of distortion due to the connected nature of the filters used. Apart from medical applications, shape filters may be of use in any field were image details of a given shape are sought, regardless of size. For example, when searching an image database for images of given objects, it may not be known a priori at which scale these objects occur. In this case, shape filters may be used, provided an efficient method is available to parameterize the shape sought for. Though we will not explore these possibilities in this project, we will explore
efficient methods to compute certain popular methods to parameterize shape within the context of shape filters. Finally, it should be straightforward to compute orientation attributes, e.g. from the principal components of the distribution of pixels coordinates. This will allow implementation of an orientation-scale space within the Max-tree framework.

In summary, the current proposal aims to build on the earlier work in our group by:

- Developing algorithms for connected filters in the case of generalized connectivities, in particular based on the Max-tree approach.
- Development of shape, orientation and scale sensitive attribute sets, suitable for use in attribute openings and thinnings, and especially the development of shape filters for medical applications.
- Analysis of the robustness of various connectivity measures.
- Testing the utility of connected shape filters as filament extraction methods for various medical applications.

**Computer Science Challenges**

The computer science challenges of this project can be split into three categories:

1. Theoretical challenges.
2. Algorithmic challenges.
3. Filter design challenges.

The first set of challenges are posed by the development of a generalized connectivity framework for connected filters. The main algorithmic challenge concerns the incorporation of the generalized connectivities into the connected filter algorithms. Further algorithmic challenges are found in the efficient computation of various attributes. The third set of challenges concerns the choice of attributes, either shape, size, or orientation sensitive, for different filtering tasks. In particular, the vessel extraction method used previously is based on an attribute which was convenient to compute, but was in no way designed to be optimal for this purpose [32]. A more rigorous test of this and other attribute in this application is called for. Furthermore, it has been claimed that certain generalized connectivities increase the robustness of segmentation and filtering [24]. This claim also needs to be investigated.

**Deliverables**

The main deliverables are:

- A generalized framework for connected filters based on Max-trees
- New connected filters
- New algorithms for computation of these filters

The results will be submitted for publication to appropriate journals in the field of computer vision and image processing. Results will also be presented at appropriate international conferences.
7 Work Programme

Work packages

The work programme can be subdivided into the following work packages:

1. Exploration of literature on generalizations of connectivity, especially in the context of connected filters, along with theoretical work on a unified framework for incorporating these generalizations in the connected filter algorithms developed previously.

2. Development of a generalized connected filter algorithm based on the previous work package. Of course, there is no guarantee that a single, unified algorithm will be possible. If no unified framework for all generalizations is possible, one or more algorithms will be developed. We will aim at developing Max-tree like data structures for these connectivities, which are highly flexible, and form a multi-scale representation.

3. Extension of the multi-scale representation to orientation-scale space and shape-scale space representations. The work will focus on developing several efficiently computable attributes for shape, scale and orientation measurement of the image features.

4. Testing the different combinations of connectivity measure and attribute sets in a real application: filament enhancement and detection. Angiography data sets will be obtained from the Department of Radiology, University Hospital Groningen (AZG). Various dermatological images will be obtained from the Department of Dermatology, also AZG.

Though the later work packages build on the results obtained by the previous packages, there is some “play” in the schedule in that a number of shape attributes can be computed efficiently already. If the first two work packages fall behind schedule, work package 3 can be reduced to allow testing of the existing shape attributes combined with different connectivity measures in package 4.

Time path and milestones

The following time path is based on a project start in October 2002. If the project starts later, the time path will be adjusted accordingly. Though the time path has already been filled in for the latter two years of the project, the schedule is of course still tentative, and depends on the results obtained in the first two years.

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<th>Date</th>
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<tr>
<td>1 October 2002</td>
<td>Start of project</td>
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<tr>
<td>1 April 2003</td>
<td>Literature research including review of existing generalizations of connectivity completed (work package 1).</td>
</tr>
<tr>
<td>1 April 2004</td>
<td>Unified framework for connected filtering with different connectivities developed (wp 1); development of grey-scale algorithms for generalized connected filters started (wp 2).</td>
</tr>
<tr>
<td>1 October 2004</td>
<td>Multi-scale and shape filter versions of generalized connected filters available (wp 2 and start of wp 3).</td>
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<tr>
<td>1 April 2005</td>
<td>Orientation-scale space, and shape-scale space representations developed (wp 3).</td>
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Date   Milestone
1 April 2006   Robustness of various filters and connectivities tested on medical image data sets, provided by the Departments of Radiology and Dermatology, University of Groningen (wp 4).
1 October 2006   Thesis on research ready

Note that 6 months have been reserved at the end of the project to complete the thesis on time.

8 Expected Use of Instrumentation

a.) The project will make use of the high performance computing and visualization facilities of the Centre for High Performance Computing of the University of Groningen. These are currently being updated extensively and the new super-computing facilities will come on-line during the first phase of the project.

9 Literature

Most important papers by the research team


References


10 Requested funding

The requested funding concerns the appointment of a PhD student (OiO) for the period of 4 years.

(1) OiO:

a) Aanstelling 1.0 fte × €129.879 = €129,879
b) persoonsgebonden benchfee 1.0 fte × €4,538 = €4,538

Totaal €134,417