Developments in Biomedical Image Analysis

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In this short paper a number of recent developments in medical imaging is outlined, with an emphasis on image analysis. Medical imaging is an essential part of the diagnostic decision process. The developments are spectacular, both in the acquisition technology and the subsequent automated analysis and visualization of the data. Images are a very rich source of information and the need for automated, fast and correct extraction of information from the images is huge. The goal of the contribution is to give some concise examples of the state of the art in this rapidly developing field.

Introduction

The chain of the lifetime of an image starts with the acquisition. It is here that spectacular developments have taken place the last decade. Tomographic scanning (the imaging of *slices*) with computer tomography (CT) or magnetic resonance (MR, see Figure 1) scanners is now common in most of the hospitals. It has been shown that the effectiveness of this type of imaging far outweighs the relatively high costs of the equipment. The degree of digitization, as well as the number of modalities, i.e., types of imaging, is still increasing. A short list of current routinely applied modalities includes:

- high speed spiral CT
- MR imaging
- MR angiography (vessel imaging)
- Ultrasound
- Digital fluoroscopy and radiography
- Digital Subtraction Angiography (DSA)
- Single Photon Emission CT (SPECT)

Upcoming are:

- MR spectroscopy
- Positron Emission Tomography (PET)
- Rotational Angiography
- MR perfusion and diffusion imaging
- 3D Ultrasound

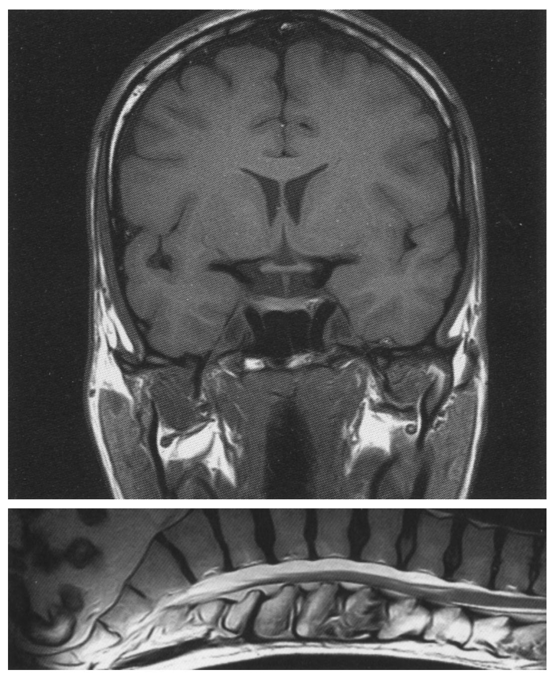

Figure 1: Two examples of high resolution MR imaging. Top: coronal slice from the brain, bottom: spinal cord. Source: Philips Medical Systems.

Electronic workstations start to become common sights in the radiological reading rooms, and recently also in the surgical operation theater (see Gerritsen, page 31 of this XOOTIC MAGAZINE).

They replace the static light-box, and rapidly become the super-assistants of the radiologists. It is here where the results from computer vision and visualization research find their clinical application. Figure 2 shows a typical routine digital workstation (Easy Vision, Philips Medical Systems).

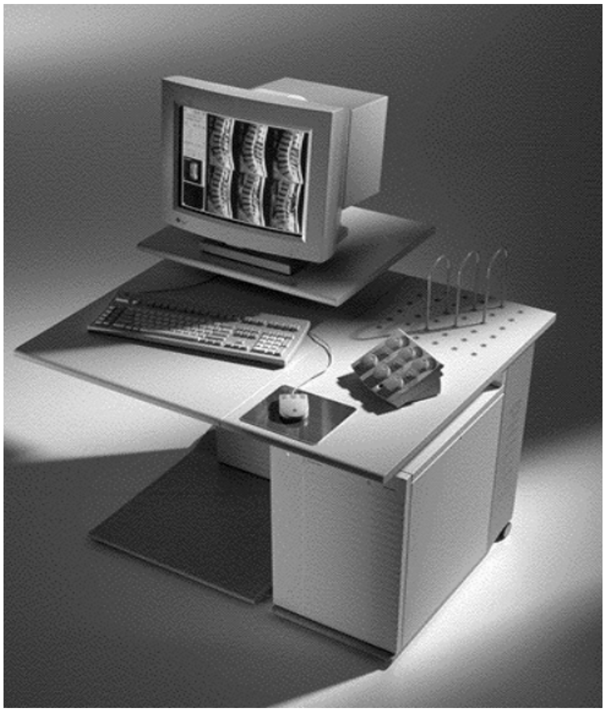

Figure 2: EasyVision electronic light-box (Philips MS).

Data presentation

Historically, one of the first advanced applications of digital imaging was the rendering in 3D. This is in fact a form of data compression for the radiologist, showing in one glimpse the 3D context which is often hard to extract from the literally hundreds of consecutive slices in a study. Examples of 3D surface rendering from a CT dataset and maximum intensity projection from an MR dataset are shown in Figure 3.

Today, 3D visualization is common routine. However, the automatic delineation of the structures of interest (especially soft tissues) is often partially possible, and may require much user assistance. The technique is mainly applied to assist the preparation of highly complex surgery.

Electronic Atlasses

The resolution of a 3D visualization is as good as the resolution of the dataset from which it is constructed. Modern CT and MR scanners have a resolution just below the millimeter. A major step towards the ultimate human anatomy dataset was taken when the National Institute of Health (NIH) in the US started the “Visible Human” project where an executed criminal was scanned with CT and MR, and subsequently sliced on a microtome. The slices were photographed with high resolution. The dataset (300 GB) was made publicly available through Internet and has triggered many interactive atlas designs. A woman dataset is now also available. An extraordinary atlas was developed by prof. Höhne and his team in Hamburg (see Figure 4).

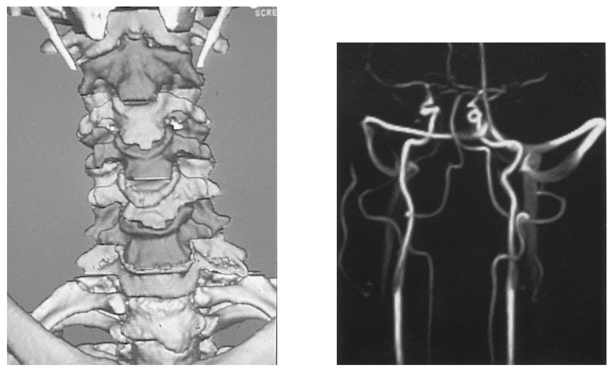

Figure 3: Left: vertebrae in the neck from CT data, segmentation by thresholding. Right: MIP (maximum intensity projection) of the intracranial vessels from MR angiography. Courtesy F. W. Zonneveld (left) and K. J. Zuiderveld (right).

Simulation

With the increased speed of computers and insights in the physical processes, *interactive* modeling and training of medical procedures like laparoscopic surgery is now feasible. One can include the visco-elastic tissue properties for haptic (force) feedback, and many shading models for realistic surface coloring exist. Figure 5 shows an example of simulated suturing.

In order to make a proper 3D view of an object, it has to be *segmented* from the rest of the image. The boundary has to be determined, so the ray-tracing algorithm mimicking the trajectories of the light rays can cast its rays on the proper surfaces. This is not an easy task, and the performance of automatic procedures is often poor. The art of volume rendering however is far developed, with photo-realism, high speed and easy user interactivity, but the art of segmentation is still in its infancy. Segmentation is mostly task-driven and as such hundreds of approaches exist, each having merits for a particular application area. Questions on images include: measurement of sizes and distances (tumors, vessel diameters), extraction of depth information from a stereo pair (range info for robotics, surgery), velocities of objects (deformations, blood flow), to find specific textures, features or objects (pattern recognition) etc. The field that considers the analysis of images is termed *computer vision.*

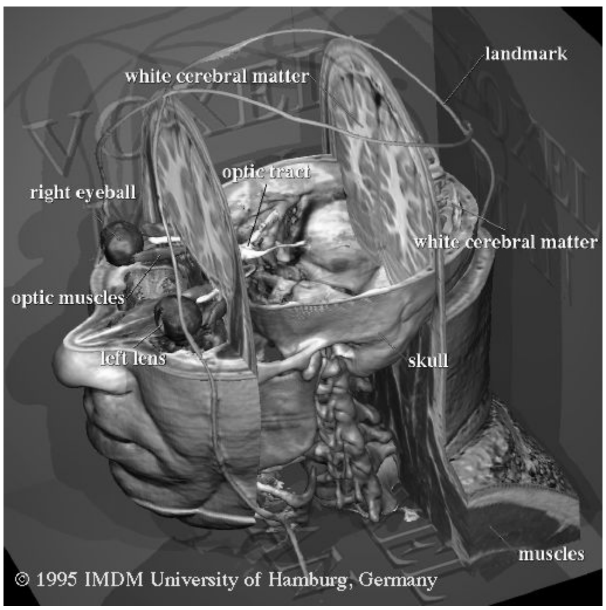

Figure 4: Example of a high-detail electronic atlas from the Visible Human dataset. Source: K.H. Höhne, IMDM, Hamburg. URL: www.uke.uni-hamburg.de/institute/imdm/idv/index.en.html

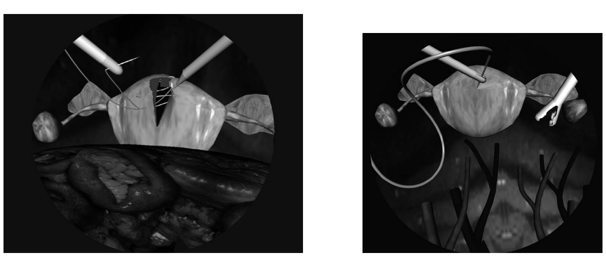

Figure 5: Simulated suturing. Origin: Forschungszentrum Karlsruhe, http://www-kismet.iai.fzk.de/.

Human vision

Actually, there is a lot to learn from human vision. The human retina appears to measure many copies of the image, each on a more blurred level, so it actually measures a *hierarchy* in the image structure. Higher in the brain, in the visual cortex in the back of our head, derivatives are constructed of the incoming images. Figure 6 shows the first order derivative, the gradient of the image L : $\sqrt{\left(\frac{\partial L}{\partial x}\right)^2 + \left(\frac{\partial L}{\partial y}\right)^2}$ for two resolutions. It is clear that the larger edges (contours) denote the more important or prominent edges. The small edges show the details, the larger edges the bigger structures. This is called a multi-scale analysis.

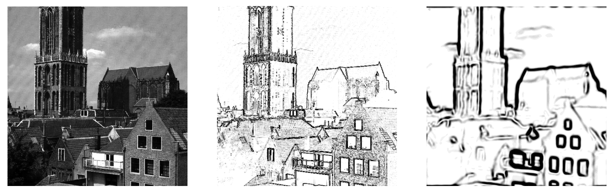

Figure 6: Edge detection at a scale of 1 pixel (middle) and 8 pixels (right) shows the hierarchy emerging with different scales. Resolution 512^2.

The rods and cones in the retina are organized in circular groups, the *receptive fields.* Each receptive field projects to a single output cell in the retina, whose output is transferred to the cortex. For each scale we seem to have a separate hexagonal array with the same number of receptive fields. Stacked together (see Figure 7) they explain why we see only sharp in the middle of our visual field: we don't have small receptive fields at high eccentricity.

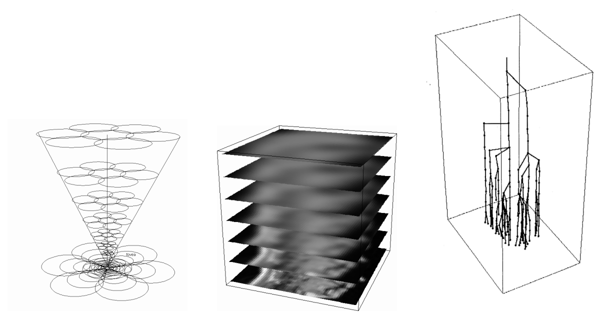

Figure 7: Left: a model for the sampling by the retina of the image with many arrays of different resolutions. Middle: a stack of images sent to the brain. Right: the topological tree structure of image maxima with the presumed image segment structure.

Multi-scale computer vision tries to mimic the mathematics of this structure, and to come up with schemes for segmentation and structure analysis based on this receptive field model from vision. Special points in the image, like minima and maxima, become less in number when we blur the image further. E.g. in a stack of images at a continuous range of resolutions, a topological *tree* structure emerges, the branches of which may be related to specific objects in the image. This field is still very much in development, but proves to be a rather productive area for fundamental imaging science.

The derivatives of images can be taken to high order. We already saw the first order derivatives needed for edge detection. The second order spatial derivatives are involved in extracting to what extent object contours are curved, and many features can be extracted by a proper combination of partial derivatives of the image.

The visual system has an abundance of receptive fields. They also come in pairs, coupled with a small temporal delay to measure velocities, or in pairs in different eyes to measure depth from stereo. When we combine the spatial derivatives with different colors, we get interesting color-specific edge extractors (Figure 8).

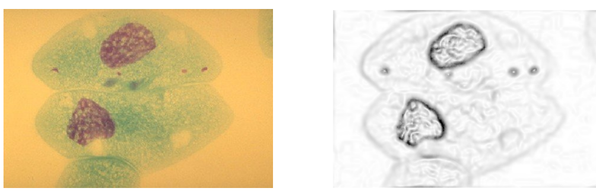

Figure 8: Left: Color labeled nuclei in paramecium caudatum. Right: red-green edge detection. Courtesy J.-M. Geusebroek (UvA) / P. Van Osta (Janssen Pharmaceutical).

The detection of linear structures can be enhanced by cleverly combining the output of neighboring filters with similar orientation. In Figure 9 an example is given of a robust detection of two lines of different width in a fluoroscopy image where the radiation dose had been substantially lowered. This increased the noise substantially, but the goal of catheter and guide wire detection could still be met.

The extraction of depth information from a stereo-pair is a classical computer vision task. Figure 10 shows a (non-medical) example. Medical applications include non-contact surface measurements in e.g., neurosurgery, and in endoscopic navigation.

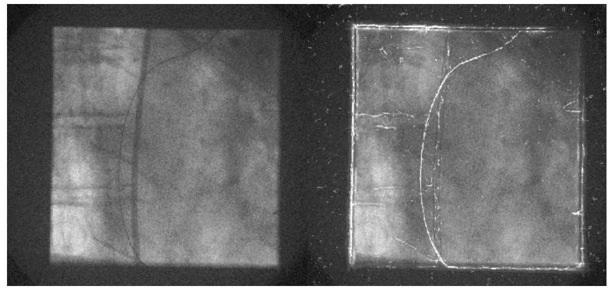

Figure 9: Detection of elongated structured in noisy data. Here a guide wire and catheter is found at two different scales in a very low dose fluoroscopy image of the spine. Courtesy S. Kalitzin.

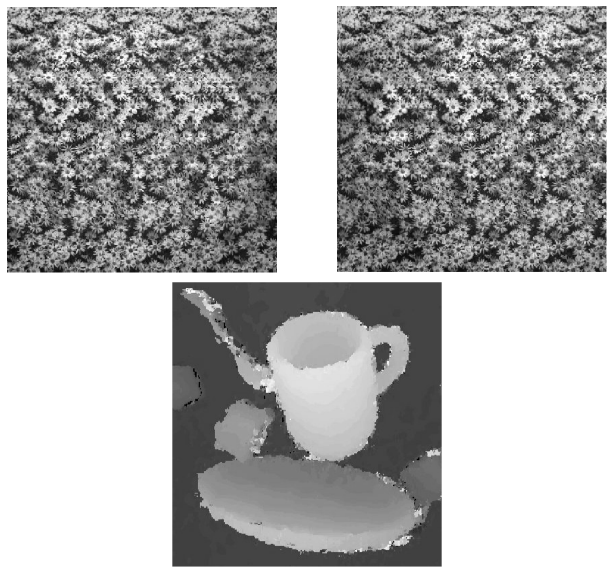

Figure 10: Top: stereo-pair with a hidden depth map. Bottom: extracted depth map with multi-scale adaptive windows. The grey value indicates the depth. Courtesy R. Maas.

It seems counterintuitive not to measure at the highest sharpness. One interesting multi-scale computer vision application is the adaptive use of resolution: small receptive fields when we measure contours and edges, and large receptive fields at homogeneous areas, to get as much as possible rid of the always present noise. This is accomplished with “multi-resolution feedback” schemes, mathematically described with specific types of nonlinear partial differential (i.e. diffusion) equations. An example in 3D is shown in Figure 11, where the noise around a cerebral aneurism is much reduced.

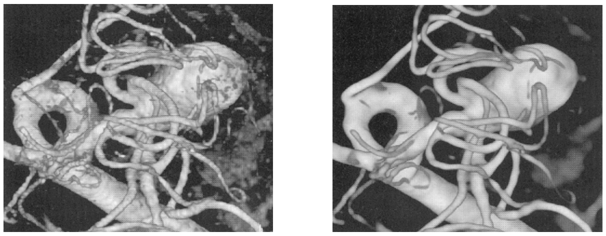

Figure 11: Left: MIP (Maximum intensity projection) image of MR angiography data of a cerebral aneurysm. Right: Denoising with a 3D nonlinear diffusion technique. Courtesy E. Meijering.

Computer Aided Diagnosis

A new and emerging field is the field of computer-aided diagnosis. The shear number of acquisitions made in hospitals, and the increasing size and availability of large archives in hospitals enable the application of statistical techniques for the recognition and classification of specific patterns and textures. The goal here is not the diagnosis, which has to rely on a human decision, but the highlighting of suspected areas, so a second look can be taken. Developments have taken off in digital mammography, and now start to cover other diagnostic areas, as X-thorax radiography (see Figure 12).

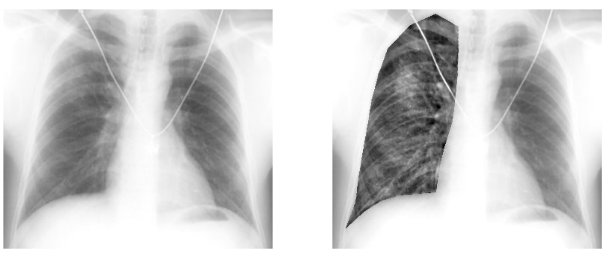

Figure 12: Left: Thorax X-ray. Right: the right lungfield (left on the image) is enhanced by subtracting the statistical mean of many similar images. Courtesy B. van Ginneken.

In conclusion, we only could discuss a few examples, indicating the enormous potential of this field. Medical image analysis has always been in the forefront of the image processing technologies, but in fact, especially when we consider the performance of computer vision with human vision, the field has only just started.

Acknowledgements

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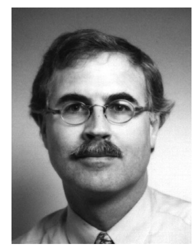
Biography



Bart M. ter Haar Romeny (1952) is associate professor in the Image Sciences Institute (ISI) of Utrecht University since 1989. M.Sc. Applied Physics, Delft University of Technology (1978), military service (Royal Dutch Navy, officer), Ph.D. Utrecht University (1983) in biophysics: non-linearities in human arm muscle control. Principal physicist of the Utrecht University Hospital Radiology Dept. (1983–1989), and clinical project leader of the Dutch PACS (Picture Archiving and Communication System, an electronic Radiology Dept.) project (1986–1989). He teaches a range of courses in medical imaging and heads the multi-scale image analysis research at ISI since 1989. Research interests: medical image analysis, its mathematical foundations and clinical applications, and its relation to the human visual system. He is involved in (resp. initiated) a number of international collaborations on these subjects. He will soon publish a tutorial book on multi-scale medical image analysis. He is president of the Dutch Society for Biophysics and Biomedical Engineering. Homepage, including references: www.isi.uu.nl/ bart.