Review

Advances in three-dimensional diagnostic radiology

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ABSTRACT

The maturity of current 3D rendering software in combination with recent developments in computer vision techniques enable an exciting range of applications for the visualisation, measurement and interactive manipulation of volumetric data, relevant both for diagnostic imaging and for anatomy. This paper reviews recent work in this area from the Image Sciences Institute at Utrecht University. The processes that yield a useful visual presentation are sequential. After acquisition and before any visualisation, an essential step is to prepare the data properly: this field is known as ‘image processing’ or ‘computer vision’ in analogy with the processing in human vision. Examples will be discussed of modern image enhancement and denoising techniques, and the complex process of automatically finding the objects or regions of interest, i.e. segmentation. One of the newer and promising methodologies for image analysis is based on a mathematical analysis of the human (cortical) visual processing: multiscale image analysis. After preprocessing the 3D rendering can be acquired by simulating the ‘ray casting’ in the computer. New possibilities are presented, such as the integrated visualisation in one image of (accurately registered) datasets of the same patient acquired in different modality scanners. Other examples include colour coding of functional data such as SPECT brain perfusion or functional magnetic resonance (MR) data and even metric data such as skull thickness on the rendered 3D anatomy from MR or computed tomography (CT). Optimal use and perception of 3D visualisation in radiology requires fast display and truly interactive manipulation facilities. Modern and increasingly cheaper workstations ( < $10000) allow this to be a reality. It is now possible to manipulate 3D images of 256$ \times \text{at } 15 \text{ frames per second interactively, placing virtual reality within reach. The possibilities of modern workstations become increasingly more sophisticated and versatile. Examples presented include the automatic detection of the optimal viewing angle of the neck of aneurysms and the simulation of the design and placement procedure of intra-abdominal aortic stents. Such developments, together with the availability of high-resolution datasets of modern scanners and data such as from the NIH Visible Human project, have a dramatic impact on interactive 3D anatomical atlases.

Key words: Volume visualisation; computer assisted radiology; image processing.

INTRODUCTION

The impact of computer technology on medical imaging is increasing exponentially. Not only at the level of high-resolution acquisition but, notably, at the level of sophisticated processing, storage and communication. This is true both for diagnostic imaging and modern anatomy. The appearance of terms such as ‘the digital anatomist’ and ‘virtual anatomy browsers’ on the World Wide Web (WWW) are surely indicative of these developments. There is much to gain by an exchange of views and experience between these related fields.

This paper highlights some recent developments in 3-dimensional (3D) diagnostic radiology, emphasising the preprocessing and 3D display of images. It
is not possible (or desirable) for it to be complete. Instead, the paper aims to give representative examples of directions in modern computer assisted radiology. The examples are all computer vision applications from our institute, the Image Sciences Institute of Utrecht University.

COMPUTER ASSISTED RADIOLOGY

In order to discuss the impact of computers in diagnostic radiology it is necessary to examine the basic tasks. Radiology is in essence the ‘editing’ of massive data volume stacks in order to provide patient management information, navigation, minimally invasive therapy and to assess effectiveness. Patient management information requires optimal probability regarding the presence and stage of disease and solid confidence in the appropriateness of the therapy chosen. Navigation for any invasive procedure including radiotherapy requires optimal insight into the volume, size, location and orientation of the lesion. Computer assisted surgery (CAS) is becoming a major tool in trauma and scoliosis surgery, maxillofacial reconstruction, and neurosurgery. Minimal invasive therapy (MIT) needs in addition an adequate and fast display of the access to the lesion. Assessment of effectiveness will be achieved with the help of epidemiologists to satisfy the claim for value for money by the public at large, i.e. evidence based medicine. In modern radiology establishing a firm diagnosis is a rare event and often a serendipitous finding.

Success in radiology results from reliable pattern recognition, optimal reporting and effective clinical conferencing. These core processes in radiology can be improved by exploiting the substantial processing power (the ‘intelligence’) of modern workstations (Zonneveld & Fukuta, 1994; Zonneveld, 1995). Workstations are used in the reporting rooms for viewing, in clinical conference rooms for demonstrations, in radiotherapy for planning and in operating rooms for guidance and even robotic assistance. 3D display has proven to be notably effective in the interaction with surgeons and is increasingly used in sophisticated interactive anatomy atlases (e.g. Fig. 1; van Wolferen et al. 1997).

3D volume visualisation

3D volume rendering techniques were among the first techniques to mature rapidly. The mathematics of the generation of the images are now well understood. In essence, the process works as follows. In the computer a geometric model is set up, consisting of the spatial positions of a 3D cube with the scanned data, one or more light sources and the eye of an observer. The datacube consists of so-called voxels (voxel = volume element; cf pixel = picture element), typically say 256 × 256 × 150 voxels for a 3D medical dataset. The dataset has been segmented, i.e. by some process the voxels of the specific object to be visualised have been earmarked to discriminate it from the surrounding area or background. The casting of rays from the virtual light source(s) is then simulated. Several hundred thousands of rays are calculated. The physics of the reflection process, where the ray hits and reflects on the surface are carefully modelled to give the object its specific appearance. The reflected rays pass a virtual ‘screen’ between the dataset and the observer, and the intensity and colour of the reflected ray determines the intensity and colour of the new pixel on this screen. This is done for all pixels, which together subsequently form a 3D view (on a flat screen: $2D$) of the object. A view from another direction is calculated by placing the observer at another point in the ‘virtual’ space around the dataset. In this way sequential frames of a movie can be generated. When the rays only reflect on the surface of the segmented object the process is termed ‘surface rendering’. When the rays are allowed to partially enter the segmented object, e.g. to calculate transparency, the process is termed ‘volume rendering’. A major challenge for computer vision scientists in 3D

![Fig. 1. High resolution CT anatomical atlas example, showing the tendons in relation to the hand.](image)
volume visualisation (and only partially solved) is the process of automatic segmentation.

During the presentations at major radiological congresses, the audience is always mesmerised by topics such as ‘virtual endoscopy’ and ‘multimodality matching’ of datasets. But computer assisted radiology techniques already have had a definite impact in the daily clinical practice. Examples are (1) cine display (sequential viewing of the slices of a 3D dataset, mouse driven, provides markedly reduced time requirements to examine large stacks of slices); (2) multiplanar reformatting (MPR, viewing the slices in any direction in orthogonal as well as in curvilinear planes); (3) maximum intensity projection (MIP) of computer tomography angiography (CTA) and magnetic resonance angiography (MRA) (casting rays through the dataset, projecting the maximum value along each ray highlighting in particular the structures; and (4) comparison and matching the results of perfusion and diffusion studies and other modes of functional analysis such as MR spectroscopy, PET and SPECT images.

The field of image processing and computer vision is large: application areas are not limited to the medical sphere, but include robotics, remote sensing (satellites), industrial inspection, astronomy and many more. Inspiration also comes from computational models of human vision, modelling the detection of features, motion, stereo, segmentation, etc.

**IMAGE ENHANCEMENT AND DEIONISING**

A well-known problem with computer assisted image analysis is the sensitivity of the methods to noise in the image data. Before computer analysis can be performed, it is often necessary to ‘clean up’ images; a wide range of techniques exists for noise reduction in images, but these techniques are often somewhat ad hoc, not universally applicable or yield disappointing results. It is remarkable how well the human visual system performs, despite the presence of noise, distortion and even missing data. At the Utrecht ISI, one of the cornerstones of the basic research is therefore to study, model and simulate the physics and mathematics of human visual perception (computer vision) (ter Haar Romeny & Florack, 1993; ter Haar Romeny, 1996). This field, known as multiscale image analysis, is rapidly gaining importance due to its solid mathematical foundation and good performance.

Interesting results are acquired when we make the filters adaptive to the local image structure. Figure 2 shows the effect of denoising as a preprocessing step for 3D visualisation of a 3D ultrasound dataset (Medison–Kretz, Austria). The characteristic speckle patterns are reduced by blurring (smoothing), but the amount of blurring applied depends on the local contents of the image. At image edges no blurring is done, which preserves important boundary infor-
mation. When applied to clinical datasets, this so-called nonlinear diffusion filtering (ter Haar Romeny, 1994) proves successful in removing noise while preserving essential diagnostic information; this technique is therefore very promising for intrinsically noisy images such as low-dose x-ray and CT, fast MR sequences, and ultrasound. We have recently developed advanced numerical schemes that allow fast implementation of nonlinear diffusion filtering (Weickert, 1997; Weickert et al. 1997); a typical filtering step requires only a few seconds, which is considered fast enough for many clinical applications.

Very recent is the development of multiscale orientation filters, to extract in particular elongated structures from noisy images (Kalitzin et al. 1997). Figure 3 shows an example of the detection of a catheter and guidewire in very low dose fluoroscopy. There is a striking similarity between the assumed processing by orientation filters in the human visual cortex. Note that the detection of elongated structures is selective: tuning the ‘scale’ of the filters will give detection of narrow or wide lines. This method enables the rather robust detection of even low contrast line structures. The technique can prove very useful for catheter tracking in intervention applications using low-dose x-ray or MR.

**3D MULTIMODALITY REGISTRATION AND VISUALISATION**

Sometimes different measurements are necessary to obtain a complete picture, e.g. an MR scan augmented with functional information from a PET scanner. Accurate registration (or matching) is then a crucial step for the effective integration of patient data from such different image sources. The registration is accomplished by translating, rotating and scaling the 3D datasets relative to each other, such that some criterion for ‘minimal distance’ is reached. External markers can be used for registration, but the matching using the actual image data is becoming the prevalent method because of its greater accuracy, which today is subpixel, and the possibility of retrospective registration (van den Elsen et al. 1995; Maintz et al. 1996). The registered datasets can be presented by a variety of methods, of which integrated 3D display is the most popular (see Fig. 4).
Fig. 5. Colour coding of local brain perfusion (autistic patient). Left-right frontal lobe comparison shows increased perfusion (red) of right hemisphere. Courtesy of Department of Psychiatry, Utrecht University.

3D display using multiple datasets can roughly be divided into 3 categories, namely anatomy ↔ anatomy, anatomy ↔ function, and anatomy ↔ measurement (Zuiderveld et al. 1995). Figure 4 shows the combined 3D visualisation of CT and MR data in a single image, exploiting the complementary character of these modalities (Zuiderveld, 1992). Figure 5 is from a patient with autistic behaviour. It shows differences between the left and right hemispheres with frontal lobe hyperperfusion, slightly greater on the right (rows from top to bottom: depth of perfusion measurement 1, 5 and 10 mm). Although the gyration appeared normal on the 2D MR images, the 3D volume rendering was suggestive of an abnormal gyral pattern of the left temporal lobe (Stokking et al. 1997). Noteworthy is an absence of perfusion in Wernicke’s area. Figure 6 shows a young patient with a high intracranial pressure, where the skull thickness is colour coded on the skull surface to estimate the overall thickness distribution, especially the fragile thin parts (in blue) (Zuiderveld et al. 1995).

The rendering techniques required for these visualisations have been developed in our Institute using VROOM (Volume Rendering by Object-Oriented Methods). This software package accepts data from an arbitrary number of image sources, has a vast range of adjustable visualisation parameters, and is very fast (especially on multiprocessor machines) (Zuiderveld & Viergever, 1992; Zuiderveld et al. 1994).

INTERACTIVE VOLUME VISUALISATION ON LOW-COST SYSTEMS

For optimal 3D perception, it is important to be able to manipulate the dataset instead of viewing a precalculated movie. The muscle actions of the observer, for example with his mouse, literally bring about an automatic update in his/her brain about ‘what is where in the space around me: I know, because I moved it myself’. This is the very basis for the many aspects of the very popular ‘virtual reality’, where the muscle actions are head, body, hand and even eye movements. In order to explore the 3D dataset, interactively, speed is needed, at least 10 3D views rendered per second. Until recently, rendering was either too slow, or too costly in terms of computer hardware to be of practical use for interactive manipulation. At ISI this inspired the development of a software package (MIRACLE: Medical Image Renderer ACceLeRator, developed by Dr Karel Zuiderveld) that renders typical clinical 3D datasets near real-time (i.e. at multiple frames per second) on
$10000 workstations. The clinical usefulness of fast rendering is currently being investigated in 2 different areas of application. In the radiological reading room, a dedicated system is installed for clinical evaluation (Zuiderveld, 1996; Zuiderveld et al. 1996), and a system will be placed next to an MR system to evaluate its use in image guided MR intervention, notably to track passive catheters in a nearly real-time fashion.

Next to 3D viewing capabilities of modern workstations, a variety of other image analysis tasks can be performed. In the following sections we give examples of such user-specified demands and their solutions.
Fig. 8. Projecting rays in all directions in an aneurysm: the length discontinuity occurs at the neck of the aneurysm.

**Projection angles for intracranial aneurysms**

Knowledge of the shape and exact orientation of the aneurysm neck is essential when considering endovascular coiling of intracranial aneurysms. To view the neck using DSA in an optimal way, it is necessary to find and apply a projection angle perpendicular to the long axis of the aneurysm neck, in the directions where its largest and smallest diameters are observed. A dedicated application was developed to extract these optimal projection angles automatically from 3D CT angiography (CTA) data of the circle of Willis. The radiologist indicates in the application window on his workstation with a mouse click the approximate centre of the target aneurysm. The computer then starts to find the centre (i.e. the centre of gravity) of the aneurysm and projects rays in any radial direction (Fig. 7). When rays are sent into the neck, they are longer, and point to a point on the neck’s border (Fig. 8). From these border rays the 3 required directions (of the long axis of the neck and the directions of minimal and maximal diameter) can be calculated (Fig. 9), and directly applied in the DSA system for the no search, one shot optimal high-resolution view.

**Abdominal aorta aneurysm stents: surgery planning**

In order to treat a patient with an aneurysm of the abdominal aorta with the placement of an endovascular prosthesis, both lumen and thrombus need to be segmented from a CT volume. To assist the radiologist in this tedious task, ISI uses an automatic segmentation algorithm that is based on so-called ‘snakes’, developed in collaboration with Philips Medical Systems. In one of the slices around the middle of the volume, 6 to 10 points are indicated with the mouse on the contour to be extracted, e.g. the lumen. The computer connects the points by lines, and this rough contour forms the initial segmentation. The contour is then given flexibility: it is allowed to bend freely, can be given a certain stiffness, and is free to move in the ‘landscape’ of the CT slice. The computer denotes negative energy for those points that belong to contours by calculating the edges, so the snake is likely to ‘fall into’ the low energy ‘pits’. The final state is that the contour nicely outlines the lumen. The process is repeated for all slices (see Fig. 10). The shape and size of the segmented lumen is important for individualised endovascular prosthesis manufacture.

Fig. 9. Optimal view of 2 aneurysms as calculated by the automatic analysis.
FROM IDEA TO PRACTICE

The techniques mentioned in the preceding sections are indications of the fast developments in computer assisted image analysis, visualisation and manipulation. It is however not a trivial matter to introduce such techniques from the research phase into the clinical routine with its high workload and time pressure. Obviously, a prerequisite for computer analysis is convenient access to image data; if data transfer is too inconvenient (e.g. copying of optical discs or conversion to other data formats), new techniques will simply not be used. Fast and efficient access to image data, by a PACS (Picture Archiving and Communication System) is essential (ter Haar Romeny, 1989; ter Haar Romeny et al. 1990, 1992). The introduction of the DICOM 3.0 standard for exchange of medical image data considerably improved connectivity between imaging equipment, and usable PACS are now gradually becoming affordable.

We strongly believe that novel computer vision techniques should and can be developed, introduced, and evaluated by relatively small interdisciplinary teams consisting of people from the university, industry and clinic. This holds as much for diagnostic radiology as for other sciences where imaging plays an important role, such as anatomy. There is much room for cross-fertilisation. There is a great need for thorough assessment programs of new methodologies. A prerequisite is the close collaboration between science, development and users, which can be accomplished by operating on the same workfloor. In practice, most money from grants or individual resources is earmarked for developing new techniques in computer vision (‘research’), while considerably fewer financial resources are available making things work in the clinical or research environment (‘development’).

Given time, the revolution in the spreading of powerful workstations will undoubtedly induce the full exploitation of the ‘computer vision intelligence’ in workstations, making them the new super-assistants in the visualisation of complex multidimensional image data.

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REFERENCES

APPENDIX

Some useful WWW links

Interactive 3D anatomy atlases

Voxel Man: http://www.uke.uni-hamburg.de/Institutes/IMDM/IDV/IDV_Homepage.html (Inst. of Mathematics and Computer Science, University Hospital Eppendorf, Hamburg, Germany)

Computer Vision: Computer Vision home page: http://www.cs.cmu.edu/~cil/v-groups.html
Medical imaging conferences: http://www.isi.uu.nl/Conferences/

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Radiology websites: ECR list: http://www.rad.unipi.it/services/newlist.html
Medical: Martindale’s Virtual Medical Center: http://www-sci.lib.nci.edu/~martindale/Medical.html

Conferences

CAR: Computer Assisted Radiology
VBC/MR-CAS/CRYMed: Visualisation in Biomedical Computing
IPMI: Information Processing in Medical Imaging
RSNA: Radiological Society of North America
ECR: European Congress of Radiology