Research Tracks in Computer Vision Applied to 3D Medical Images

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Abstract

This short paper is mainly the introduction of the available INRIA Research Report No. 2050 (55 pages) published by the author in Sept. 1993 [1].

The automated analysis of 3D medical images can improve significantly both diagnosis and therapy. This automation raises a number of new fascinating research problems in the fields of computer vision and robotics.

In this paper, I propose a list of such problems after a review of the current major 3D imaging modalities, and a description of the related medical needs.

I then present some of past and current work done in the research group EPIDAURE[1] at INRIA, on the following topics: segmentation of 3D images, 3D shape modeling, 3D rigid and nonrigid registration, 3D motion analysis and 3D simulation of therapy. I also try to suggest a number of promising research tracks and future challenges.

Keywords: Volume Image Processing, Medical Images, 3D Vision, Medical Robotics, Research Trends.

Introduction

New Images

Three-dimensional (3D) images are becoming very popular in the medical field [24], [55], [41], [6], [26]. A modern hospital commonly produces every year tens of thousands of volumetric images. They come from different modalities like Magnetic Resonance Imagery (MRI),Computed Tomography Imagery (CTI, also called Scanner Imagery), Nuclear Medicine Imagery (NMI) or Ultrasound Imagery (USI).

These images share the particularity of describing the physical or chimical properties at each point of a studied volume. These informations are stored in a discrete 3D matrix $I(i,j,k)$ of voxels (volume elements), called a 3D image because of the analogy with digital 2D images $I(i,j)$ stored as 2D matrices of pixels (picture elements).

New 3D imagery devices are emerging, like angiographic MRI, which describes the anatomy of the vascular system, magneto-encephalography equipment, which measures magnetic field variations, or functional MRI, which provides metabolism informations (like NMI), but with a non invasive method. These new modalities are still in the research stage, but might lead to major 3D imaging devices in the near future.

New Markets

The market of the production of medical images was evaluated to 8 billion of US dollars in 1991 [45], [17], and shows approximately an increase of 10% per year. Among these figures, MRI represents currently a market of 1 billion dollars, with a strong increase of approximately 20% per year [32]. Also, USI shows a strong increase close to 15%.

Besides the production itself, 3D image processing is the most recent market. Almost inexistent a few years ago, it is evaluated to 350 million dollars in 1992, with a planned evolution between 20 and 40% per year during the next 5 years.

This comes from the new capabilities demonstrated by computer vision applied to 3D imagery. Not only it provides better diagnosis tools, but also new possibilities for therapy. This is true in particular for brain and skull surgery, laparoscopy and radiotherapy, where simulation tools can be tested in advance, sometimes with the help of virtual reality, and used during the intervention as guiding tools [27], [18], [39]. In some cases, even robots can use pre-operative and per-operative 3D imagery to complete precisely some specific medical gestures prepared during a simulation phase [40], [28], [44].

One must notice that 3D imagery is also in expansion in other fields than medical. In biology, confocal microscopy produces voxel images at a microscopic scale.

[1] EPIDAURE is a very nice location in Greece which used to be the sanctuary of ancient medicine. Today, for computer scientists, it is also a recursive acronym (in French): *Epidaure, Projet Image, Diagnostic AUtomatique, et RoboiquE.*

In the **industry**, non destructive inspection of important parts like turbine blades for instance is sometimes made with CTI. Finally, in **geology**, large petroleum companies like Elf-Aquitaine for instance, have bought scanners (CTI) to analyse core samples.

New Medical Needs

Exploiting 3D images in their raw format (a 3D matrix of numbers) is usually a very akward task. For instance, it is now quite easy to acquire MRI images of the head with a resolution of about a millimeter in each of the 3 directions. Such an image can have 256^3 voxels, which represent about 17 Megabytes of data. High resolution 3D images of the heart can also be acquired during a time sequence, which represent spatio-temporal data in 4 dimensions. In both cases, displaying 2D cross-sections one at a time is no longer sufficient to establish a reliable diagnosis or prepare a critical therapy.

Moreover, the complexity of the anatomical structures can make their identification difficult, and the use of multimodal complementary images requires accurate spatial registration. Long term study of a patient evolution also requires accurate spatio-temporal registration.

We identified the automation of the following tasks as being crucial needs for diagnosis and therapy improvement:

1. **Interactive Visualization** must be really 3D, with dynamic animation capabilities. The result could be seen as a flight simulation within the anatomical structures of a human body. A recent review of the state of the art can be found in [46].
2. **Quantification** of **shapes, textures** and **motion** must provide the physician with a reduced set of parameters useful to establish his diagnosis, study temporal evolution, and make inter-patient comparisons. This must be true for the analysis of static and dynamic images.
3. **Registration** of 3D images must be possible for a given patient between single or multi-modality 3D images. This spatial superposition is a necessary condition to study in great details the evolution of a pathology, or to take full advantage of the complementarity information coming from multimodality imagery. Extensions to the multi-patient cases is also useful, because it allows subtle inter-patient comparisons.
4. **Identification** of anatomical structures within 3D images requires the construction of computerized anatomical atlases, and the design of matching procedures between atlases and 3D images. Such a registration would provide a substantial help for a faster interpretation of the most complex regions of the body (e.g. the brain), and it is a prerequisite to solve the previous multi-patient registration problem, and to help planification (see below).
5. **Planification, Simulation and Control** of therapy, especially for delicate and complex surgery (e.g. brain and crano-facial surgery, hip, spine and eye surgery, laparoscopy ...), and also for radiotherapy: this is an ultimate goal. The therapist, with the help of interactive visualization tools applied to quantified, registered and identified 3D images, could planify in advance its intervention, taking advantage of a maximum of planification advices, and then observe and compare predicted results before any operation is done. Once the best solution is chosen, the actual intervention could then be controlled by passive or active mechanical devices, with the help of per-operative images and other sensors like force sensors for instance.

New Image Properties

To fulfill these medical needs, it is necessary to address a number of challenging new computer vision and robotics problems [2], [19]. Most of these problems are quite new, not only because images are in three dimensions, but also because usual approximations like polyhedral models or typical assumptions like rigidity rarely apply to medical objects. This opens a large range of new problems sometimes more complex than their counterparts in 2D image analysis.

On the other hand, specific properties of 3D medical imagery can be exploited very fruitfully. For instance, contrary to video images of a 3D scene, geometric measurements are not projective but **euclidean measurements**. Three dimensional coordinates of structures are readily available!

Moreover, one can usually exploit the **intrinsic value of intensity**, which is generally related in a simple way to the physical or physiological properties of the considered region; this is almost never the case with video images where intensity varies with illumination, point of view, surface orientation etc...

Also, **a priori knowledge** is high, in the sense that physicians usually have protocols (unfortunately depending on the image modality) to acquire images of a given part of the body, and different patients tend to have similar structures at similar locations!

Finally, having a dense set of **3D data** provides a better local regularization when computing local differential properties, as we shall see later.

New Computer Vision and Robotics Issues

Having listed the medical needs and the new image properties, I now set a list of computer vision and robotics issues which we believe are central problems :

1. **3D Segmentation** of images: the goal is to partition the raw 3D image into regions corresponding to meaningful anatomic structures. It is a prerequisite to most of the medical needs listed before. Efficient segmentation requires the modeling and extraction of 3D static or dynamic edges and of 3D texture, as well as the generalization of 2D digital topology and mathematical morphology in 3D.

2. **3D Shape Modeling**: this is mainly a prerequisite to solve the registration and identification needs, but also for efficient visualization. It is necessary to describe non-polyhedral 3D shapes with a reduced number of intrinsic features. This involves mainly computational and differential geometry.

3. **3D Matching** of 3D shapes: once segmented and modeled, new algorithms must be designed to reliably and accurately match such representations together, both in rigid and nonrigid cases. This is necessary to solve the registration and identification needs.

4. **3D Motion Analysis**: this requires the development of new tools to process sequences of 3D images, (i.e. 4D images!), in order to track and describe rigid and nonrigid motion of 3D anatomical structures. This is necessary for the quantification of motion needs.

5. **Dynamic Physical Models** of anatomical structures should be developped to provide realistic simulation of interaction with 3D images. This is required for the planification and simulation of therapy. Physical models can also help solving the previous 3D motion analysis problems.

6. **Geometric Reasoning** is required to help therapeutic planification, in particular to determine trajectories of beam sources in radiotherapy, and succession of accurate medical gestures in surgery.

7. **Virtual Reality** environment should be developped to provide realistic interactive visualization and to help planification and simulation.

8. **Dedicated Medical Robots**, possibly passive or semi-active, equiped with specific sensors (force sensing, optical or ultrasound positioning, ...), must be developped for the automatic control of therapy.

As one should notice, these problems are mainly computer vision and robotics problems, involving also graphics. In the oral presentation, I address most of them by presenting a part of the research conducted during the past 5 years in the research group EPIDAURE at INRIA. (this is detailed in [1] where principal references can be found).

Conclusion

I tried to show in this paper that automating the analysis of 3D medical images was an abundant field of new research topics in computer vision and robotics. I presented the past and current work of the research group EPIDAURE at INRIA, and tried to define current trends and future challenges for research.

One of these challenges will be the capability of transferring the knowledge from the research centers to the hospitals. This will require the creation of a number of companies starting selling dedicated software and hardware.

Acknowledments

Of course, aknowledments go primarily to the researchers of the EPIDAURE group who actively contributed during the past 5 years to the research work presented in this paper. They are, by alphabetical order, **I. Cohen, L. Cohen, A. Guéziec, I. Herlin, J. Lévy-Véhel, G. Malandain, O. Monga, J.M. Rocchisani, and J.P. Thirion.** More recently, important contributions also came from **E. Bardinet, S. Benayoun, J.P. Berroir, H. Delingette, J. Feldmar, A. Gourdon, P. Mignot, C. Nastar, X. Pennec and G. Subsol.** This work benefited from close interactions with **R. Hummel** during a one year sabbatical he spent in our group, and also with **J.D. Boissonnat, P. Cinquin, C. Cutting, R. Kikinis, O. Kubler, B. Geiger, D. Geiger and J. Travere.** Thanks also to our system engineer, **J.P. Chièze** who made everything work!

Digital Equipement supported a significant part of this research and **GE-CGR** in Buc, France, supported part of the rigid matching research work. **Matra-MS2I** and **Philips** supported part of the research on ultrasound images. **Aleph-Med** and **Focus-Med** in Grenoble contribute to the transfer of software towards industry. The European project **AIM-Murim** supported collaborations with several European imaging and robotics. Finally the Esprit European project called **BRA-VIVA** supported part of the work on the extraction and use of euclidean invariants for matching.

please note that because of the lack of place, I essentially reported here references to the Epidaure work. Additional references can be found in [1].

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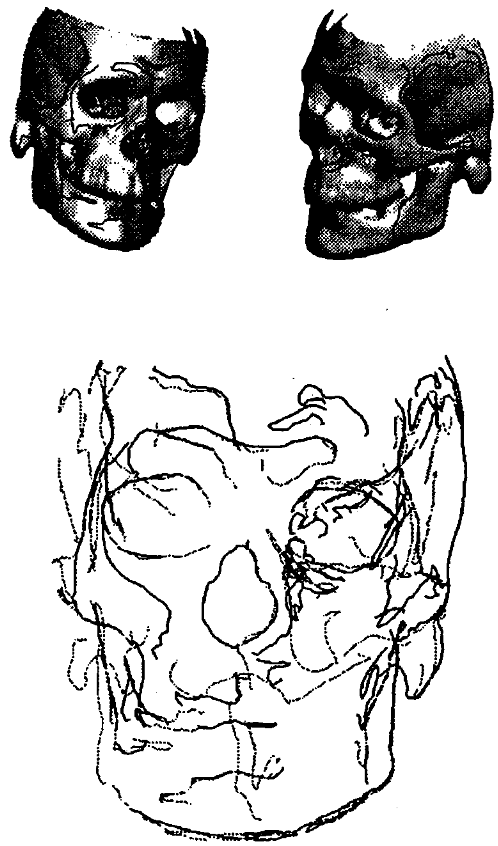

Figure 1: Top: Ridges (in black) extracted on the surface of a skull scanned in 2 different positions (left and right). Bottom: Automatic registration of the two sets of ridge lines (respectively solid and dotted lines), allowing a sub-voxel comparison of the 2 original 3D images. Original 3D images are produced by a GE-CGR CT-Scan. (Courtesy of A. Gueziec, J.P. Thirion and A. Gourdon)

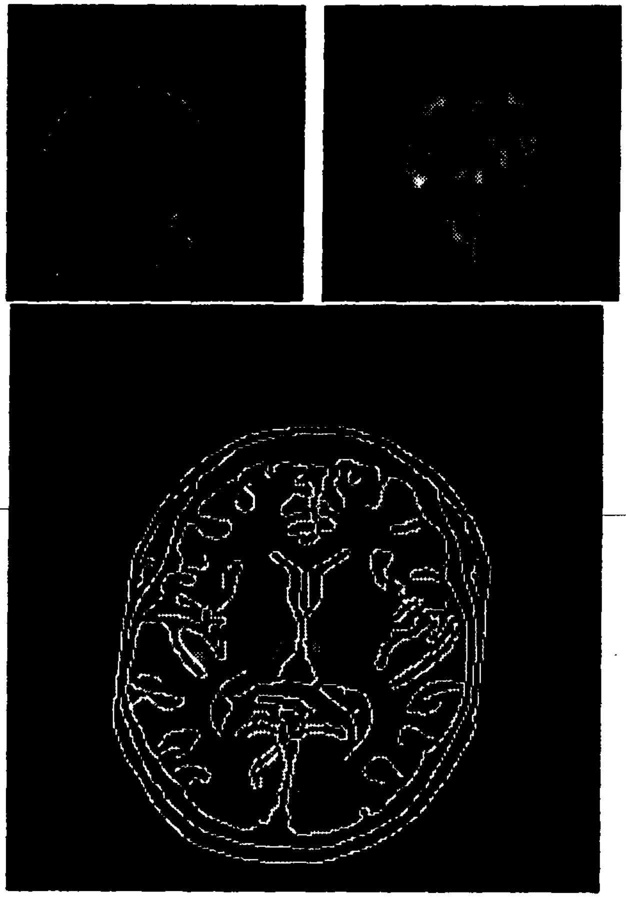

Figure 2: A potential based method allows the registration of an MRI image (top left) with a NMI image of the head (top right). Interpolated cross section of the registered 3D MRI is computed, and its edges are shown superimposed on the NMI images (bottom). Images are courtesy of Jael Travere, from the Cyceron Center in Caen, France. (Courtesy of G. Malandain and J.M. Rocchisani).

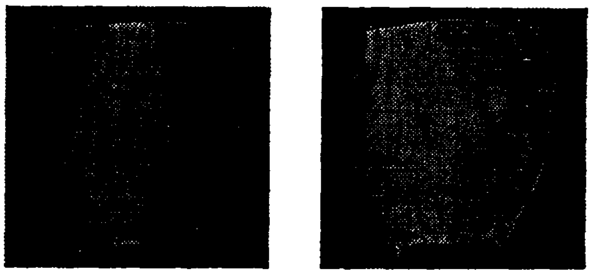

Figure 3: Left : segmented diastole (mesh), tracked to the systole (plain). Right : modal approximation of the motion ; the factor of compression is 40, using 300 modes. (Courtesy of C. Nastar.)

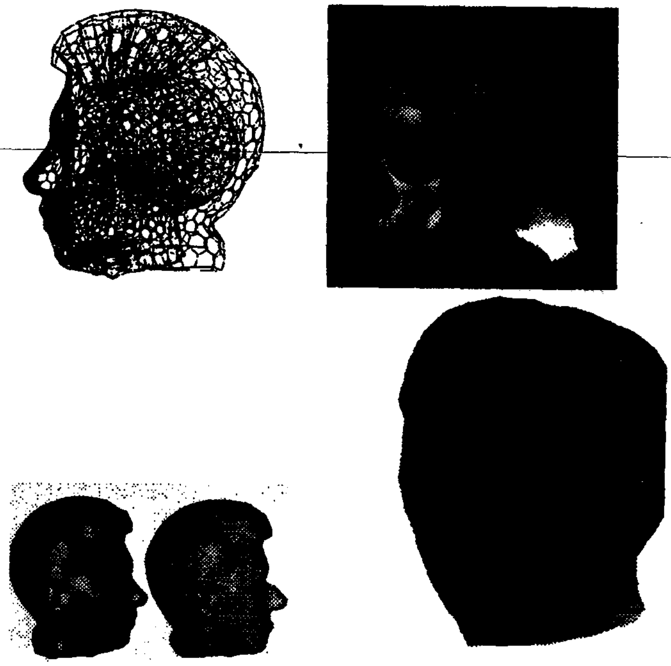

Figure 4: Top Left: an elastic model of the head is designed from the 3D image of the head. Top Right: the skull is cut and its shape is modified with a virtual 3D hand. Bottom: the elastic model of head of the patient deforms itself accordingly to the modified shape of the skull, and the expected result (a deformed Herve Delingette!) can be observed (possibly with texture) before any real surgery is done. (Courtesy of H. Delingette, G. Subsol, S. Cotin and J. Pignon).