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The "MEDIP – Platform Independent Software System for Medical Image Processing" Project

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Abstract: In this paper we present the structure and the achieved results of the R&D project IKTA-4, 6/2001 "MEDIP - Platform independent software system for medical image processing" supported by the Hungarian Ministry of Education. The aim of the project was to develop a software background for our basic and applied research in the field of medical imaging that can be used in clinical routine, as well. Realization was based on the experience of information technology and medical imaging research university teams and a company specialized on software and hardware developing for nuclear medicine. The aims also reflect some former research and development activities of the participants. Thus some of them are well experienced in registration, segmentation and image fusion techniques. These experiences were also considered in the determination of the main purposes. The capabilities of the provided software library were demonstrated through test applications from the fields of orthopedics, oncology and nuclear medicine.

Keywords: medical image processing, multimodal image analysis, virtual surgery, surface rendering, volume rendering, visualization
Categories: D.1.5, G.2.3, I.4.0, I.3.7, J.3

1 Introduction

The growth of the corresponding supporting systems shows that better pre-operative visualization leads to better surgical planning and evaluation of medical examinations. Conventional image-guided systems provided the data gathered prior to surgery to the surgeon, and supported tracking the surgical instruments along with the data. General purposed state-of-the-art systems have been planned in consideration to the following requirements: standardization, versatility (platform independence), real-time applicability, improvability, multimodal fusion, 3D visualization, temporal (4D) analyzes, decision making support, physical simulations and realizations (e.g. finite element analysis, rapid prototyping).

Many systems have released aiming similar goals listed above. For some of the most recent and popular systems we refer to [Cosic 1997, Escott and Rubinstein 2004, IDL, Liao 2002, SPL, Yoo 2002]. All these systems have a strong focus on (2D and 3D) visualization though temporal analysis is rarely supported. For example, the open source system 3D Slicer [SPL] provides capabilities for automatic registration, semi-automatic segmentation, surface model generation, 3D visualization, and quantitative analysis of various medical scans. Usually, according to current software development practices in object oriented programming, C++ is selected as the programming language (as e.g. in [Yoo et al. 2002]) as it is strongly supported for visualization (by OpenGL), and also as the standard approach for image processing applications. Moreover, to provide an archival mechanism, C++ is adequate for programming a library. Java perhaps provides better cross-hardware-platform portability, but it can be still considered as a too young language, though we can find corresponding systems, like [Cosic 1997, Liao 2002]. Moreover, as it is clear that currently DICOM has become the standard for the storage and transfer of digital medical images and data, the ability to read and write DICOM files is a natural general consideration, even for rare platforms, like Mcintosh [Escott and Rubinstein 2004].

The systems presented above more or less meet the current requirements even at industrial level [IDL]. According to our corresponding work in this field in terms of an R&D project, we were motivated to create a system according to the general state-of-the-art approaches, but also wanted to provide less usual support for specific medical needs that we expect to be more common in the future. Accordingly, we provide support for temporal 4D (analysis), special geometric descriptions for finite element analysis to check surgical plans and preparations for rapid prototyping. Moreover, we were also motivated to help medical personnel to be able to test novel surgical plans, and consequently we provided some specific tools.

1.1 Project aims and partners

The aim of the project was to develop a software background for our basic and applied research in the field of medical imaging that can be used in clinical routine, as well [Hajdu and Kormos 2002]. These objectives well suit to the requirements of the multimodal tomography where complex software system needs to cover the field of data acquisition, list mode data processing, image reconstruction, study database management and image processing tools necessary to advanced multimodal visualization. A lot of appropriate software is available matching any of the above demands, however, single complete software supporting all the listed tasks does not exist to our best knowledge. In this project we focused only to the medical imaging, while the development of the other part of this complex system is demanded for further projects.

The realization was based on the experience of information technology and medical imaging research university teams and a company specialized on software and hardware developing for nuclear medicine. The aims also reflected some former research and development activities of the participants. Thus some of the participants were well experienced in registration, segmentation and image fusion techniques. These experiences were also considered in the determination of the main purposes. The consortium was constituted by the following partners:

Consortium coordinator:

- Department of Information Technology, University of Debrecen, Hungary

Consortium members:

- PET Center of University of Debrecen, Hungary
- Mediso Medical Imaging Systems Ltd., Budapest, Hungary
- Department of Orthopedic Surgery, University of Debrecen, Hungary

- Chair of Radiotherapy, Semmelweis University, Hungary
- Department of Radiology and Oncotherapy, Semmelweis University, Hungary

1.2 Project objectives

The development of the software parts of the project required the solution of several problems that needed sophisticated theoretical investigations, as well. The tasks to be solved mainly corresponded to digital image processing results, but starting from there, other fields of mathematics and computer science were also investigated. Namely, the solutions of the problems needed the tools of mathematical morphology, computer geometry, linear programming, probability theory and statistics. The main purpose was the integration of the recent image segmentation, image registration, and image fusion tools as well as the applied computer graphics solutions of GI systems. The multilayered software product consisted of three different layers: modules for functional tasks of the software, visualization, and graphical user interface. An important point was the marketability of those programs that were (and will be) based on this software library.

1.3 Work description

During the project, several test programs and three demonstration software were to be created to complete the whole task. The goal of the test programs was to choose the optimal hardware and software environment for the developing phases. Proving the applicability of the complex developing environment, the demonstration programs presented solutions for image processing tasks from the fields of orthopedics, oncology and nuclear medicine. Medical experts were involved into planning and testing the software. Beside developing, the project contained several research tasks, like composing algorithms for segmentation and geometric modeling. Moreover, the implemented algorithms were optimized, as well. Integrating the research results into the software modules was a very important point during the developer process. These results made it possible to create more effective displaying and interactive programs, which indirectly improved the quality of the diagnostic and therapeutic clinical work. Involving Ph.D. and undergraduated students, the development of the system can be continued after the project finished, thus the ability of the software libraries and programs can be improved with respect to the dynamically developing performance of graphic hardware devices. This assures continuous co-operation between a university knowledge base and a technology centre.

2 Realizing the system

The underlying principle of a complex software development environment is the idea that the development of any medical imaging software may be based on the functionality, visualization and graphical user interface (GUI) libraries. In this project the C++ based functional and visualisation libraries were developed and integrated with a GUI library selected in point view of the usage of C++ language and the cross-platform possibility.

The *functional layer* was created by the design models of the standard C++ language, which offers many features useful for scientific computing: inheritance, polymorphism, operator overloading and generic programming. By using templates cleverly, optimizations such as loop fusion, unrolling, tiling, and algorithm specialization can be performed automatically at compile time. The modeling of multidimensional (2D, 3D, or higher dimensional) parameterized type data structures, and the algorithms needed to handle them were given in an abstract way [Opposits et al. 2004]. Thus the image information recorded by different tools (PET, SPECT, MRI, DSA, CT) were handled uniformly by the help of a 3D image matrix. This approach assured that data storage and algorithms relating to elementary image processing tasks (like image algebra, spatial linear and non-linear transformations, spatial filtering, convolution) were covered by this base library.

The second main task was the creation of the *visualization* and 3D interactive computer geometry algorithms. This was solved by using standard OpenGL software libraries after specifying the supporting hardware and software system. The structure of visualization process and view are managed by a hierarchical system containing montage, draw-port and layer abstract components. The montage is a visualization area which is withdrawn from the control of GUI. This is covered by any number of draw-ports that is the rendering unit in this concept. A draw-port contains a number of elementary OpenGL based visualization layer (2D slice, contour, 3D surface, curve, label, cursor, etc.) configured by the user or the application. During this development step, the connection between the OpenGL libraries and the storage classes of the functional layer were needed to be solved. Another sophisticated problem was to create the graphic interface for the interactive selection of the ROI/VOI system.

The creation of medical imaging applications required the designation of a *user interface*. It was recommended to choose such a system, which allows multiplatform development. This problem was handled by the matching of the designated software package and the developed OpenGL based displaying and interactive software libraries.

The development environment takes the existing capabilities of these libraries and extends them in several new services including automatic documentation features, usage of a concurrent version system (CVS) server, distributed image database, and a mailing list for the developers.

3 Research tasks

The creation of the software described in the project required to perform several theoretical investigations. The solution of these problems can be grouped into three main areas, as listed below.

3.1 Composing mathematical (geometric) models

This basic step was needed to compose mathematical (geometric) models for handling different human tissues and simplifying their usability in CAD environment. The resulted pixel/voxel set of segmentation was usually not sufficient for displaying, thus we rendered some geometric objects to them. This way the interesting regions could be nicely displayed, moreover, this geometry also could be imported into CAD systems. Thus geometric parameters were determined, and other investigations (such as finite elements analysis) also performed. When a nice visualization or a natural model was desired, then the elements of continuous geometry were used (e.g. B-splines, Coons patches, etc.). On the other hand, if a rough geometric model was sufficient, then discrete geometric objects were applied. We gave both surface and volumetric description for the same object to support fast visualization, and direct data load into robust finite element systems (like [ANSYS]), respectively. In this way, a surgical intervention can be performed on the volumetric model. For visualization purposes, the surface model is adequate with all the standard possibilities for smoothing or decimation.

3.2 Image segmentation procedures based on mathematical morphology

This step was considered basically for CT and MRI inspections to extract ROIs and VOIs of several human tissues. The demonstration programs showed example for bone (mainly the hip joint and femur), brain, and heart/lung extractions. The difficulty of the segmentation task highly depended on the observed human tissue, thus automatic techniques were seldom usable instead of manual ones. To make the segmentation step more reliable, it was recommended to execute some pre-processing. Similarly, to refine the segmentation results some post-processing steps were also useful. As a typical post-procession, morphological operations were performed to obtain more precise and "natural" final results.

3.3 Optimizing the algorithms and geometric objects

In this step the models and algorithms created in the project were optimized to improve efficiency. The models extracted from the images were often extensively detailed, which caused hardware and also software capacity problems. (For example, the number of nodes of a geometry was often limited by CAD systems.) The reduction of nodes and other geometric elements were performed in such a way that the usable information was not ruined. The selection of ROIs and VOIs had primary importance in medical image processing applications, thus sometimes it was recommended to apply more segmentation methods, parallel. E.g. automatic techniques were completed with manual ones, or region growing algorithms by gradient based methods. Moreover, the smoothing of the resulted contour was also recommended in many cases.

4 Demonstration software

After realizing and testing the developer's environment of our library, we analyzed its performance and usability through three independent demonstration applications: 3D radiation planning based on image fusion; planning orthopedic interventions using finite element evaluation; visualizing 4D isotope diagnostic analyzes.

4.1 3D radiation planning based on image fusion

A radiation planning problem is solved in a reliable way, if the PTV (planning target volume) receives its prescribed dose, while the healthy neighboring tissues (especially the essential organs) receive minimal (optimally zero) radiation. The general aim is to make the regions with large dose be conforming to the shape of the PTV, which also decreases the amount of radiation that the neighboring healthy tissues suffer. For this reason, the precise initial definition of the target VOIs (volumes of interest) has high importance, since the mistakes arising from wrong initialization are rarely compensated in the daily clinical routine, as these parameters are usually not checked later on. For accurate VOI selection one can considers the image data extracted from the four medical projection image acquiring methods CT, MRI, SPECT, PET.

For 3D planning, CT data by no means are needed, since they carry the anatomic information based on the weakening of the X-ray, and provide the electro density values of tissues for accurate dose calculation. The CT can provide only approximate information about the position of the viable tumor mass, as we can separate the abnormal parts according to the differences in their position or size with respect to the normal anatomic relations. The same statement is valid also for the classic MR acquiring method. Though by functionality it is a projection image provider method, SPECT can have only a limited role in displaying viable tumor masses because of its low resolution, and the non-physiological behavior of the tracer materials. Thus, currently only the PET technology provides a solution for locating the viable tumor masses accurately for radiation planning, as theoretically it is capable to display any metabolism processes using tracer materials [Valastyán et al. 2004].

Taking advantage of the developed software library, the planning expert can freely select any of the image data sequences acquired by the CT, MRI, SPECT, and PET technologies for a certain patient. They can be displayed in individual or fusioned form. The registration can be executed in both automatic and manual (landmark based) ways, as it is shown in Figure 1.

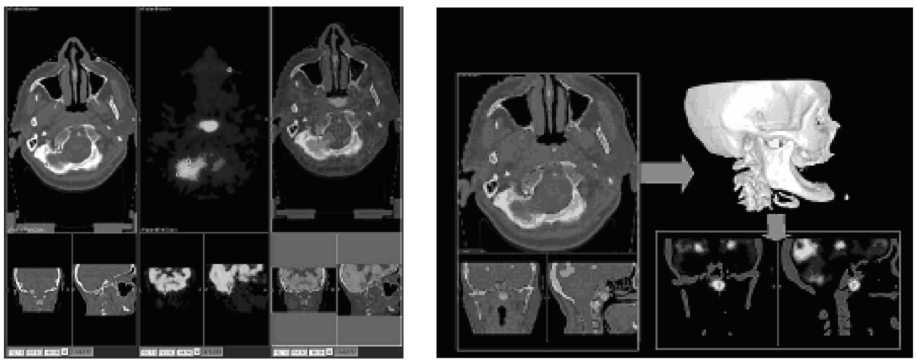

Figure 1: User interface for image registration and fusion, and some results on VOI selection using 2D and 3D multimodal visualization

The target VOIs can be selected for both individual and registered image pairs, using automatic or manual selector algorithms. The selected 3D VOIs can be displayed in a separate window using real-time 3D surface rendering. If an MRI data sequence is also available for spatial standardization, the target volume can be displayed with an additional brain atlas structure or with a subregion of a CT based skeleton surface.

4.2 Planning orthopedic interventions using finite element analyzes

Analyzes, imaging and visualization technologies are being applied increasingly in medical applications, particularly in evaluating different approaches to surgery and determining the best ways to proceed in the operation. In this growing field, one of the primary focuses of our work applies finite element analysis to orthopedic surgery: specifically, the specialized area of osteotomy, where bones are surgically segmented and repositioned to correct various deformities. Medical imaging technologies such as CT, MRI, PET or SPECT deliver slice or projection images of internal areas of the human body. These tools are generally used to visualize configurations of bones, organs and tissue, but they also have the ability to export image data and additional information in commonly known medical file formats like DICOM. These files then can be processed by third-party computer programs for assessing and diagnosing the condition of the patient and planning surgical intervention, that is, how the surgical procedure will be performed. Other very promising fields include telesurgery, virtual environments in medical school education and prototype modeling of artificial joints.

The goal of the corresponding research was to realize a computer application based on the software library in the field of orthopedic surgery, especially osteotomy interventions based on CT images. We used this simulation to examine theories underlying new types of surgeries as well as to aid doctors in treating individual patients undergoing hip joint correction. These two approaches have many common tasks: extracting image data from diverse medical image exchange format files, enhancing images, choosing appropriate segmentation techniques, CAD-oriented volume reconstruction, data exchange with FEM/FEA tools, and geometric description of virtual surgery. For some results, see Figure 2.

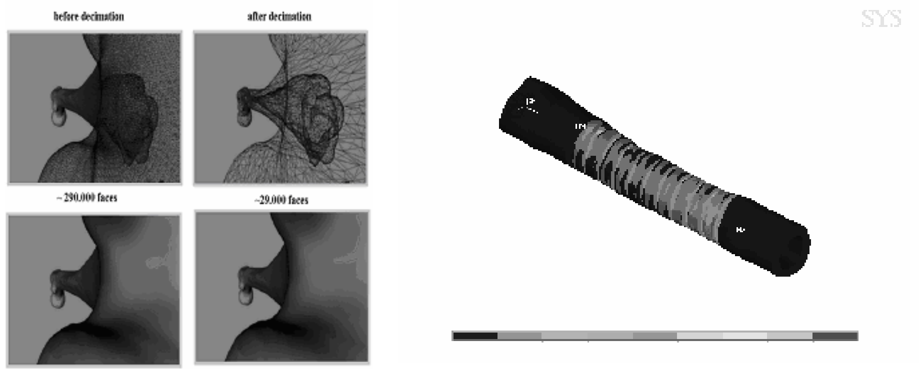

Figure 2: Geometry from user interface for virtual osteotomy and a result of a finite element analyzes

We have already tested some novel surgical ideas on simple topologies (lengthening pipe-like bones, see [Csernátony et al. 2003, Csernátony et al. 2004b, Zörgö et al. 2003]), by taking advantage of the geometric support of scientific finite element modeling software in building up the 3D solid by B-splines and Coons patches, see [Csernátony et al. 2004a, Hajdu and Zörgö 2002, Hajdu and Zörgö 2004].

We also defined some basic geometric tools, by which interventions can be made on the model used for visualization. We also tested several ways to find the optimal channel to import our geometries into finite element systems [Hajdu et al. 2005]. In the future, we will go on with making such tests for other novel surgical ideas, like for the one described in Kiss et al. [Kiss et al. 2004] for placing a spherical object into the ankle joint.

4.3 Visualizing 3D and 4D isotope diagnostic analyzes

This test software belongs to the family of nuclear medicine applications. The aim of this application was to demonstrate the graphics solutions provided by our software library regarding visualizing the results of dynamic tomographic or planar examinations individually or in a fusioned way. In this way we could test the performance of the OpenGL based visualization components, and also the video cards equipped by hardware acceleration capabilities. As it had also high priority in the project, we keep on focusing on those elements of the rapidly growing OpenGL solutions that can be effectively applied for medical image processing purposes.

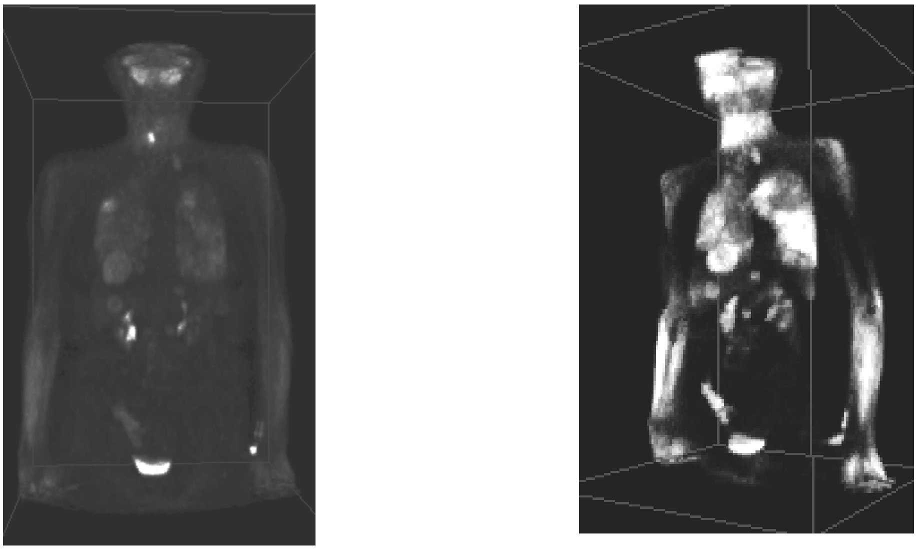

Figure 3 : Interactive visualization of a whole body SPECT scan using real-time Maximum Intensity Projection (left) and Volume Rendering (right) methods based on 3D texture based OpenGL features

This demonstration application was proved to be very useful in testing our surface and volume rendering algorithms in multimodal visualization. After pre-processing (smoothing, interpolating, transforming, segmenting, clustering) the projection image data set, we created surface models to visualize the shape change of different structures in time. The 3D visualization can be adjusted to be stationary or temporal for the selected surfaces. In another mode, the same objects can be displayed using maximum intensity projection or volume rendering methods based on special OpenGL hardware accelerated features (see Figure 3.). As these methods have large computational and storage demands, in this case we could check under what limitations they could be used for medical image processing purposes.

5 Discussion

In this paper we presented the platform independent software system MEDIP for medical image processing. The conceptualization of the system and its realization regarding portability, programming, data exchange, visualization, quantitative measures for decision support, etc. is similar to other state-of-the art systems like [Cosic 1997, Escott and Rubinstein 2004, IDL, Liao 2002, SPL, Yoo 2002]. However, we incorporated some rarely supported features like temporal analysis, and complex geometric description for finite element analysis and rapid prototyping.

Besides creating a system for further development needs, we were motivated to support pure research with letting novel surgical ideas to be tested. Accordingly, some of our demonstration software provided specific tools. For instance, the bone lengthening idea [Csernátony et al. 2003] has been already analyzed [Zörgö et al. 2003], while the investigation of some more novel orthopedics intervention plans is in progress. Among our corresponding future plans, we would like to improve further the rapid prototyping capabilities of our system for an ultimate realization of our results.

In-vivo imaging of small laboratory animals is a valuable tool in the development of new dugs. The PET scanners designed for this purpose should exhibit high and possibly uniform spatial resolution and high sensitivity over a field of view, allowing to image mice or other animals of similar size. A small animal PET camera, the miniPET was developed at our institutes to meet such demands [Kis et al. 2005]. A versatile development framework was worked out containing the components of MEDIP and other specific libraries and special file formats supporting the complex software system of this scanner. This software package contains utilities for data acquisition, control of the cluster of detectors built together with PCs, event sorting and image reconstruction. An integrated graphical image processing and data acquisition program has been also worked out. This program provides tools for advanced multimodal visualization and SQL-database study management based image registration and ROI/VOI analysis.

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