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Michał CHLEBIEJ[*], Zdzisław KRÓL[**],
Paweł MIKOŁAJCZAK[**]

REGISTRATION APPROACHES FOR THE OPTIMISATION OF MEDICAL DIAGNOSTICS AND TREATMENT

Many medical diagnostics and treatment procedures in the oncology, cranio-maxillofacial surgery, radiotherapy and neurosurgery deal with volumetric as well as surface data. Tumor detection or generation of the virtual treatment scene involves using complementary data sets that are obtained from different sensors, for example MR and CT data, or by the same sensor at different epochs. The very need for registration arises from the fact that the complementary data sets are acquired by imaging devices using different spatial coordinate systems or/and the anatomically correct superposition of two data instances cannot be performed without locally applied elastic transformation. The volume or surface matching is therefore an essential task in these applications. From the mathematical point of view the data aligning problem is an optimization task, which can be solved by using deterministic or non-deterministic optimization algorithms. Depending on the data size and the complexity of required matching transformation the runtime behaviour of the registration methods can stretch out between real-time and many hours' computations. In this paper various applications of the same registration paradigm are presented and discussed. The wide spectrum of the medical applications shows the importance of the registration approach for the optimization of medical diagnostics and treatment.

1. INTRODUCTION

Nowadays medicine more and more often makes use of modern medical imaging devices and high-end computer hardware to offer particular medical services. Quite often, the diagnostic investigation or treatment planning requires that a number of imaging modalities is applied to the same patient, such as computed tomography, magnetic resonance imaging, positron mission tomography, ultrasonography, digital subtraction angiography, etc. Each of these methods has specific advantages and disadvantages. The combination of different studies allows maximizing the degree of overall informativity and minimizing the disadvantages of single methods. Alterations of the soft tissue can be discerned in MRI images, whereas sometimes they remain totally invisible in CT. Bone, on the other hand, is optimally displayed in CT. Only the combination of all methods allows making exact statements on pathological processes that concern different tissue structures. Also, the planning of surgical treatment can be done more exactly if the virtual patient model consists of crucial anatomical and pathological structures in the region of interest. Right now, the physician performs the fusion of these images purely mentally. Much information remains unrecognized or unused. The superposition of the multimodality data lead to new possibilities for

[*] Laboratory of Information Technology, Maria Curie-Sklodowska University, Faculty of Mathematics, Physics and Informatics, pl. Marii-Curie Sklodowskiej 1, 20-030 Lublin, Poland. E-mail: meow@goblin.umcs.lublin.pl
[**] Hightech-Research-Center for Maxillofacial Surgery, University Hospital Basel, Schanzenstrasse 46, CH-4031 Basel, e-mail: zkrol@uhbs.ch

the medical diagnosis and therapy. Tumors, lesions or congenital malformations can be localized more precisely through the combination of morphological and functional data. The alignment of the complementary surface information improves the quality of the face scanning process. Through some sophisticated registration approaches the planning of the maxillofacial graft surgery can be done more successfully than the traditional one. In this work we describe the application of different registration approaches to improve and optimize the diagnostic process, data acquisition and treatment planning. In the following three chapters we will show different medical applications of both standard registration methods based on the surface similarity measure [8] and the voxel similarity measure called mutual information [9]. In the chapter 4 we describe more precisely a novel registration approach for designing the graft shape in the bone graft reconstructive surgery based on the elastic transformation.

2. REGISTRATION IN THE OTOLARYNGOLOGY

In the ear, nose and throat (ENT) diagnostics and surgery planning the multimodal imaging data provides the radiologists and surgeons with an enhanced view of the complex anatomy. In particular, the anatomy of the middle ear is hard to acquire and to delineate even for experienced physicians. For planning of surgical approaches like tympanoplasty, mastoidectomy, ossiculoplasty, cochlear implantation or acoustic neuroma [7] highly detailed 3D image information of the region of interest is required. To help the physician in assessing pathologic conditions of the middle ear region the registration approach has been applied (see Fig. 1).

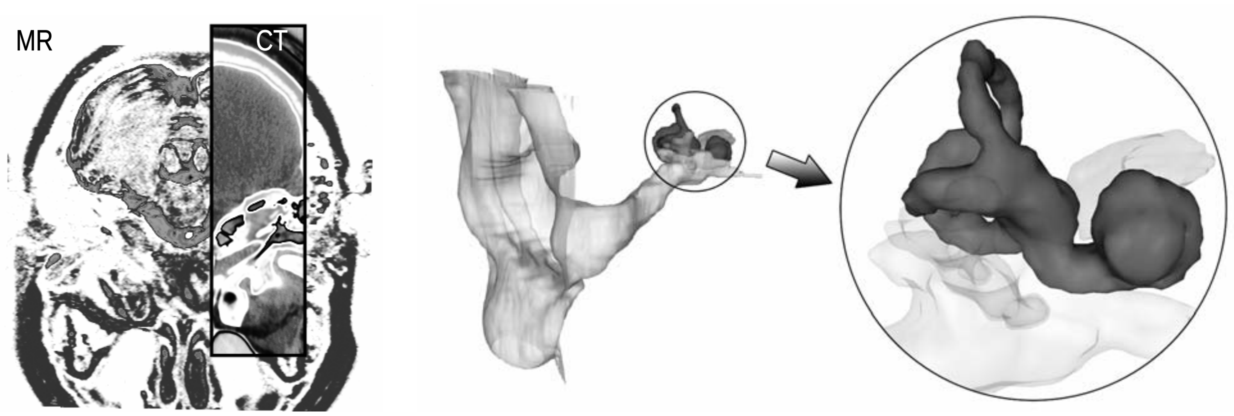

Fig. 1. Superposition of the MR and CT data in the middle ear region. The aligned CT information (showed in the inspection window) has been overlaid on the MR data (*left*). The reconstructed 3D virtual anatomical model of the region of interest (*right*).

The multimodal CT and MR data deliver complementary anatomical information of this spatially small and compact region. It is only when the alignment of the CT and MR data sets is done that the physician can use this enhanced information to make more confident diagnosis and to determine the best therapeutic decision. The registration of the volumetric CT and MR data sets has been done using mutual information approach. The segmented anatomical structures of the middle ear and the surrounding bony tissues have been used to generate 3D patient-specific virtual anatomical model (see Fig. 1 (*right*)). Skeletal structures like the auditory canal and ossicles as well as the auricle were obtained from CT, the cochlea, semi-circular canals and auditory nerve from MR. The auditory nerve were visible only in the MR data set, and the auditory canal was visible only in the CT data set. The surgeon has the ability to interactively interact with the generated 3D model of the surgical site. This novel registration based approach allows faster, easier and more accurate diagnosis as well as greatly aids therapeutic decisions in the treatment of the middle ear disorders.

3. SURFACE SCAN ALIGNMENT

With the advent of cost effective laser scanning devices the planning and the verification of the craniofacial and plastic surgery outcomes can be effectively performed using patient surface data acquired by the optical or laser scanning devices. One of the most important problems influencing strongly the surface mesh quality are the holes in the mesh caused by the highlights, shadows or by the obstructed forward view (see Fig. 2 (*top*)).

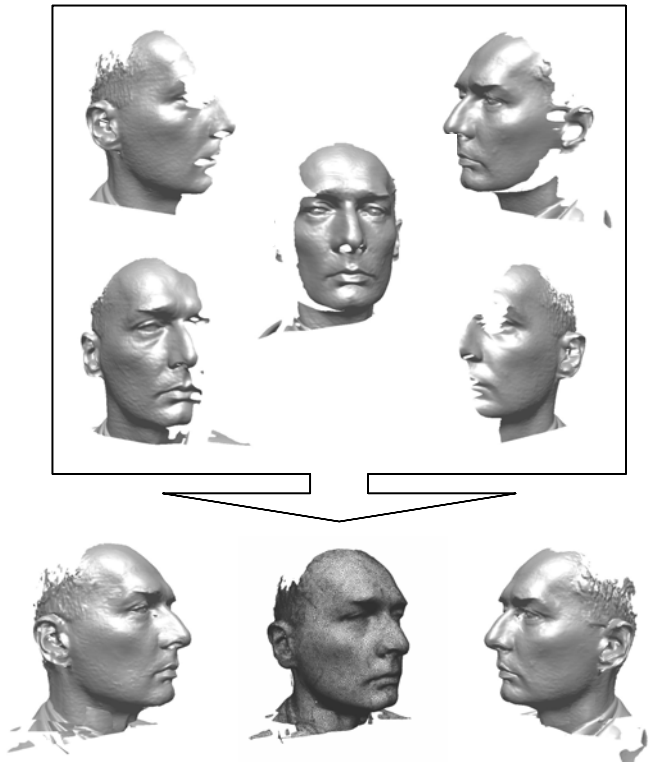

Fig. 2. Single surface scans acquired from different camera positions (*top*). The reconstructed surface of the face derived by registration of partial views into one high-quality surface without holes (*bottom*).

The registration method based on the surface similarity measure [8] let us align the different surface scans of the same patient acquired from different camera positions and generate a new high-quality face surface without holes (see Fig. 2 (*bottom*)). The matching quality can be controlled by choice of the suited surface-to-surface distance measure as well as by reducing the number and quality (removing outliers) of surface points taken into account during the distance computation. The applied rigid-body transformation can cause some discontinuities in the generated final surface because of the patient movement between the single view acquisitions. Therefore the further improvement of the surface quality is possible by applying locally elastic transformation to repair the mismatch caused by the subtle soft tissue deformations.

4. GRAFT SURGERY PLANNING

Craniofacial surgery is a highly complex reconstructive surgery providing comprehensive surgical treatment for facial deformities consequent to trauma, cancer removal and congenital malformations. The mainstay of mandibular reconstruction rests with the replacement of missing mandibular segment by autogenous bone grafts. Autogenous also called autologous grafts are osseous grafts taken from one anatomic site and transplanted to another part of the body in the same individual. Autologous bone transplants can be harvested from various donor sites. Depending on the amount and the shape of the bone required it can be harvested from the ilium, rib, fibula, scapula, cranium, or tibia bone. For mandibular reconstruction the iliac bone is the most often material of choice because of the anatomical similarity with the recipient region. The natural curve of the iliac crest lends itself to reconstruction of mandibular defects. The important fact that the iliac crest is so easily accessible makes the removal of the graft relatively simple, and the secondary defect is usually concealed. The process of graft transplantation consists of two main parts. The goal of the first part is to obtain the graft by harvesting it from a donor site. The second part involves removing the damaged bone and replacing it with the designed transplant. The goal of the planning process is to define the shape of the desired transplant and to select an optimal donor site in the donor region. This process can be carried out in many ways: it can be done according to the surgeons experience and intuition, but it can be also assisted by computers and specialized equipment. Because of the complexity of transplantation surgery, high-tech planning approaches are in high demand and the planning process alone has become an important part of the whole surgical treatment. The conventional graft surgery planning methods (i.e. stereolithography models, manual matching of surface rendered objects) have main common drawback – the lack of a quantitative quality estimation of the selected donor site for a given template. To overcome this drawback a novel computer-aided method for semi-automatic selection of the optimal donor site has been developed [1]. The main idea of the proposed method is based on the registration paradigm. The optimal donor site in the donor region for a given graft's template can be seen as an optimal alignment of two objects according to some mathematically formulated optimality (see Fig. 3). In our work we have focused on the mathematical criterion which utilizes a distance notion [2] defined for two surfaces extracted from the preoperative CT data sets as well as on the deterministic optimization Levenberg-Marquardt method [3][4]. As we can see in Fig. 3 computer-aided surgery consists of several stages. At the beginning planning procedures on the virtual patient are being performed. After the acquisition of CT data sets corresponding to both regions of interest segmentation and triangulation step is performed. The graft's template is defined based on the generated virtual patient-specific anatomical model of the defected site. In the second virtual model the donor region is defined where the surgeon is looking for the optimally aligned bone segment. The non-automatic step of graft design and constraint setting is followed by a fully automatic procedure to find the best-fitting position. We consider two 3D objects: template and donor region that are extracted from the two pre-operative CT data sets. The problem of optimality is considered as a registration task - we define a geometrical transformation relating those two data sets and than we set forth a criterion for the goodness of given transformation. In this way we are able to state the donor site selection problem as an optimization problem under certain geometric constraints. A very important issue in the optimization process is an optimality assessment of the selected donor site. In our developed system during the estimation of the optimal donor site, the user has the possibility to examine simultaneously the maximal and average distances, and the standard deviation characteristics for the points of the given template and the donor region as well as the bone volume difference between the designed graft and the virtually harvested one. The optimal donor site selection process can be performed interactively. The user has possibility to repeat the optimization process for different sub-optimal donor sites. The obtained results can be compared (through statistical features or using virtual reconstruction tools) and the best solution can be selected. After the planning process is complete the surgeon can perform real operation on the patient leaning on simulation results. All described features of the presented surgical planning method provide arguments for its superiority over the standard planning procedures.

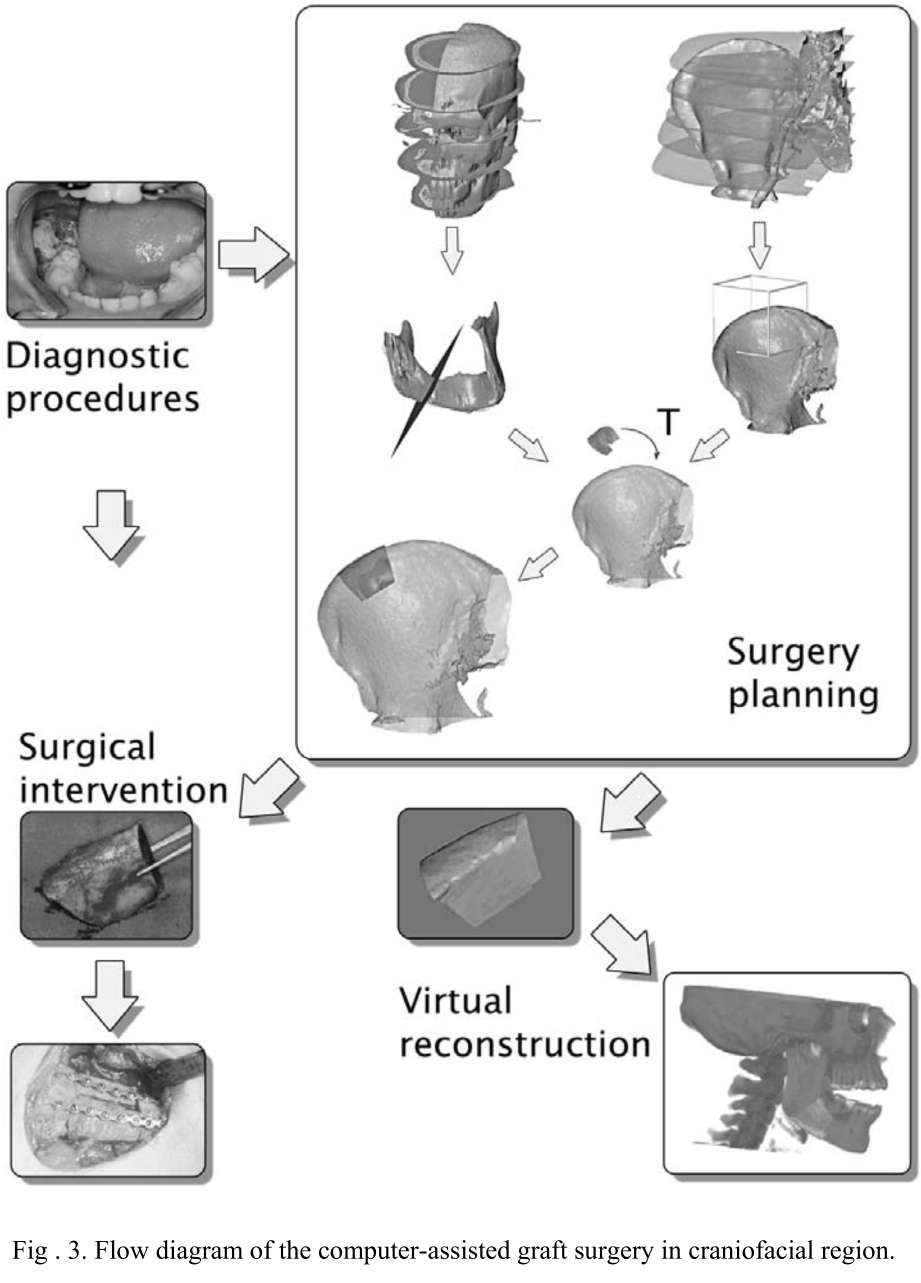

Fig . 3. Flow diagram of the computer-assisted graft surgery in craniofacial region.

5. OPTIMIZATION OF GRAFT DESIGN

As it was mentioned in the previous section in the surgical planning process in craniofacial region the graft's template is defined based on the generated virtual patient-specific anatomical model of the defected site. Because the segmented anatomical structures are represented as triangle meshes, we have to perform mesh cutting procedures to design the shape of the transplant (see Fig. 3). As our main cutting tool we have chosen the standard cutting planes. The result of cutting virtual objects using cutting planes may be considered as the simulation of cutting with a real surgical saw. But it should be mentioned, that it is very simplified approach to simulate real bone osteotomy. In the case of large bone defects the graft design step has to be done using a more sophisticated method. The method of choice in such cases is the mirror technique (see Fig. 4). In this method the healthy side is duplicated, mirrored and aligned with the pathological side. The required grafts shape is then defined in the symmetrically formed template. All stages of this method for some craniofacial defect case which has to be managed using graft surgery have been previously presented in details in [2]. The most crucial parts of this process have been illustrated in Fig. 4.

In our previous work we have extensively used rigid surface registration approaches in the mirror technique to align the healthy mirrored side together with the pathological one. But there exist many cases when rigid registration is highly insufficient. As it can be seen in the right part in Fig. 4 rigidly registered mandible parts are not matching properly because of significant shape differences. Especially the region with the defected bone part that needs to be resected is highly mismatched. Because of that reason an additional transformation is required, which models the local deformation. Therefore, it is difficult to describe the local deformation via parameterized transformations. The method of choice in such cases is usually FFD (free-form-deformation) [5] method which is commonly used as a powerful modelling tool for 3D deformable objects. The basic idea of FFD is to deform an object by manipulating an underlying mesh of control points. The manipulated lattice determines the deformation function that specifies a new position for each point in the deformed surface. Final and complete combined deformation consists of global transformation (rigid or affine) and local deformation [6].

$$T(p) = T_{global}(p) + T_{local}(p) \quad where \quad p = (x, y, z)$$

In our work we decided to use FFD model based on B-splines which have good localization properties. To define such deformation, the domain of the object volume (bounding box of the deformed surface where X , Y and Z denote its resolution) is defined as

$$\Omega = \{(x, y, z) \mid 0 \le x \le X, 0 \le y \le Y, 0 \le z \le Z\}$$

Let Φ denote a $n_x \times n_y \times n_z$ mesh of control points $\phi_{i,j,k}$ with the uniform spacing. The FFD can be written as the 3D tensor product of the familiar 1-D cubic B-splines:

$$T_{local}(p) = \sum_{i=0}^{3} \sum_{j=0}^{3} \sum_{k=0}^{3} B_i(u) B_j(v) B_k(w) \phi_{i+l, j+m, k+n}$$

where $l = \left\lfloor \frac{x}{n_x} \right\rfloor - 1$, $m = \left\lfloor \frac{y}{n_y} \right\rfloor - 1$, $n = \left\lfloor \frac{z}{n_z} \right\rfloor - 1$, $u = \frac{x}{n_x} - \left\lfloor \frac{x}{n_x} \right\rfloor$, $v = \frac{y}{n_y} - \left\lfloor \frac{y}{n_y} \right\rfloor$, $w = \frac{z}{n_z} - \left\lfloor \frac{z}{n_z} \right\rfloor$

and B_i represents the i -th basis function of the B-spline as follows:

$$B_0(t) = \frac{(1-t)^3}{6}, \; B_1(t) = \frac{3t^3 - 6t^2 + 4}{6}, \; B_2(t) = \frac{-3t^3 + 3t^2 + 3t + 1}{6}, \; B_3(t) = \frac{t^3}{6}$$

where $t \in [0,1]$. Because the B-spline function do not interpolate the first and the last control point of the coordinate curves it is necessary to add so called ghost vertices to the control lattice.

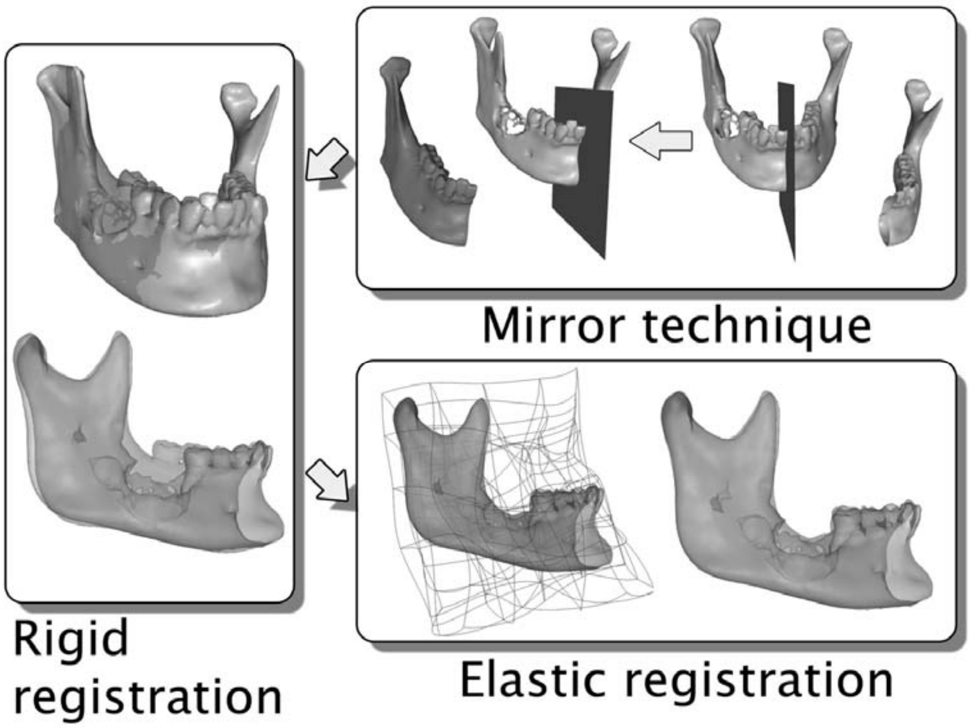

Fig. 4. Optimization of graft design process – through elastic registration of mirrored and rigidly registered surfaces it is possible to design the shape of the desired transplant in the optimal way.

The number of parameters to be optimized is equal 3 times number of control points in the lattice. Because of good localization property of B-spline functions optimization procedures can be applied locally which allows for acceptable running times even for very dense lattices.

The final deformed surface of the healthy-mirrored mandible part is presented in Figure 4. Such deformation from the anatomical point of view is not acceptable but for the described purposes it is indeed extremely useful. Using this method the shape of the desired transplant can be designed much more precisely and effectively.

6. DISCUSSION AND CONCLUSIONS

More and more medical diagnostics and treatment procedures in the different medical disciplines, deal with volumetric as well as surface data. Lesion detection or generation of the virtual treatment scene involves using complementary 3D data sets that are obtained from different sensors, for example MR and CT data, or by the same sensor in a retrospective way. The very need for registration arises from the fact that the complementary data sets are acquired by imaging devices using different spatial coordinate systems or/and the anatomically correct superposition of two data instances cannot be performed without locally applied elastic transformation. Giving different examples of diagnostic and treatment planning procedures it has been shown that volume or surface matching is an essential task in many medical applications. From the mathematical point of view the data aligning problem is based on the same paradigm. Different solution approaches, like the described above surface and voxel based methods, let us adapt the registration method according to the specific problem statement as well as to control its runtime behaviour depending on the required matching quality. In this paper various applications of the same registration paradigm were presented and discussed. The wide spectrum of the medical applications using effectively registration approach shows the importance of this data processing tool for the optimization of medical diagnostics and treatment.

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