Project IMAGINE: Landmark-Based Elastic Registration and Biomechanical Brain Modelling

K. Rohr, H.S. Stiehl, M. Fornefett, S. Frantz, A. Hagemann

The aim of the project IMAGINE is the development of algorithms and methods for computer-assisted analysis of multimodal medical images. Application areas are diagnosis, planning of neurosurgical interventions, as well as intraoperative navigation. This contribution gives an overview of the work within IMAGINE.

1 Introduction

The central topic within the project IMAGINE (IMage- and Atlas-Guided Interventions in NEurosurgery)[1] is *elastic image registration*, i.e., the computation of locally adaptive transformations for the purpose of integrating multimodal medical images (image fusion). Elastic registration schemes can cope with local geometric differences between images and improve the accuracy in comparison to previously applied rigid or affine procedures (for a survey see [12] in this issue). Examples of clinically relevant tasks are the registration of CT (X-ray Computed Tomography) with MR (Magnetic Resonance) images, the registration of images with digital atlases, and the registration of preoperatively acquired images with the current anatomical situation based on intraoperative data. Image registration is important for improving diagnosis, surgery planning, and intraoperative navigation. This contribution gives a brief overview of the work within IMAGINE on elastic registration of 2D and 3D human brain images based on anatomical landmarks.

2 Extraction of 3D Anatomical Landmarks

Landmark-based registration schemes require that corresponding landmarks are extracted from images. *Anatomical point landmarks*, in comparison to fiducial markers, have the advantage that they can be located within inner brain parts to increase the registration accuracy. Our work is based on an anatomical study concerning the definition and characterization of 3D point landmarks of the human head [13]. Prominent anatomical points such as curvature extrema can be defined, e.g., at the skull or the ventricular system. To extract such landmarks we have developed new computationally efficient *3D differential operators* [10, 3, 5, 8], which are applied within a semi-automatic procedure. Key features of our approach are (a) its applicability to different types of landmarks (e.g., tips or saddle points), (b) the use of only low order image derivatives which increases the robustness w.r.t. noise, (c) automatic selection of an optimal region-of-interest size to diminish interaction effects of neighboring structures, and (d) incorporation of additional prior knowledge of curvature properties to reduce the number of false detections. Also, we have introduced *multi-step procedures* for refined localization of 3D landmarks yielding subvoxel positions [3].

Exemplarily, Fig. 1 shows the detection result of applying a 3D differential operator to a 3D MR image of the human head (only one slice is shown). Recently, we have evaluated our approaches within an application study on rigid registration of MR and CT images, comparing the performance of semi-automatic landmark extraction with that of a purely manual procedure [4]. We found that the elapsed time for landmark extraction can be reduced significantly using the semi-automatic procedure, while the registration results of both procedures have similar quality as shown in Fig. 2 for one 3D MR/CT image pair. In this figure the transformed MR image has been fused with automatically detected edges in the CT image.

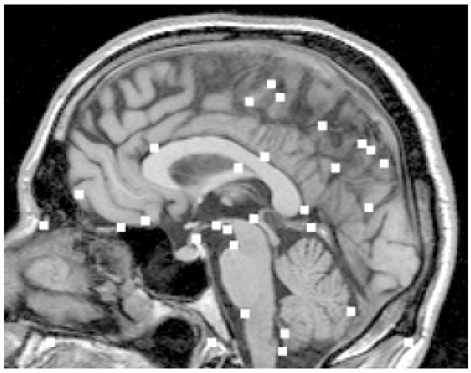

Figure 1: Detected landmarks in a 3D MR image (slice 37).

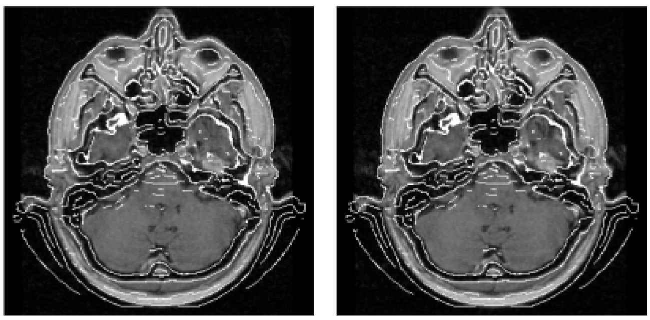

Figure 2: Rigid MR/CT registration result based on semi-automatic (left) and manual landmark extraction (right)

[1] http://kogs-www.informatik.uni-hamburg.de/PROJECTS/imagine/Imagine.html

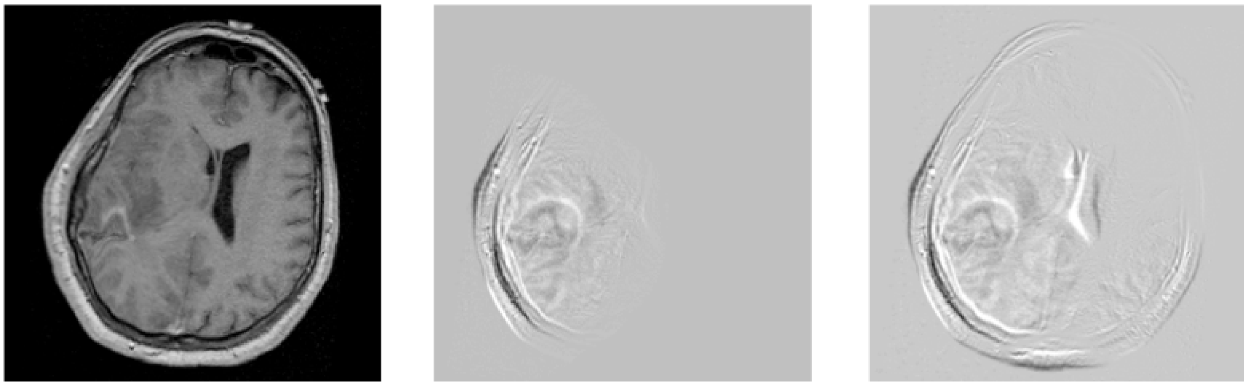

Figure 3: Registration result using radial basis functions with compact support (left) and difference image (middle), as well as difference image when using thin-plate splines (right).

3 Landmark-Based Elastic Image Registration

Given extracted point landmarks, we compute an elastic transformation to map two images as accurate as possible. Our approach is based on *approximating thin-plate splines* and, in comparison to earlier work, allows to integrate landmark localization errors [14, 11], which is important in practical applications. The approach has a physical motivation, is mathematically well-founded, efficient, and robust. The basis is a minimizing functional for which a unique analytic solution exists. For the components of the searched transformation $\mathbf{u}$: $\mathbb{R}^d \rightarrow \mathbb{R}^d$ where d denotes an arbitrary image dimension, this solution consists of polynomials and a superposition of certain radial basis functions R:

$$\mathbf{u}_k(\mathbf{x}) = \sum_{v=1}^{M} a_{k,v}\phi_v(\mathbf{x}) + \sum_{i=1}^{n} w_{k,i} R(|\mathbf{x}\text{-}\mathbf{p}_i|), \quad k=1,...,d. \qquad (1)$$

where $\mathbf{p}_i$ are the landmarks of the first image. It is also possible to integrate orientation attributes at landmarks. This allows to further improve the registration accuracy without selecting additional landmarks. An application is the preservation of the shape of rigid structures under elastic transformations [14].

To increase the local influence in elastic registration, we have also introduced an approach, which is based on radial basis functions with *compact support* [1]. With this scheme, the influence is limited to a circle in 2D or, respectively, to a sphere in 3D. As basis functions R in (1) we use the ψ-functions of Wendland. As with thin-plate splines, it is guaranteed that the resulting system of linear equations is always solvable for general positions of the landmarks. The principal behavior of this approach is demonstrated by Fig. 3. On the left, the result is shown of registering a preoperative MR image of a human brain with a tumor to a postoperative image, where the tumor has been resected and the resection hole is left (cf. Fig. 4). The difference between these two images (middle) demonstrates that the influence of the transformation is limited to an area around the tumor. For comparison, we also show the difference image when applying the standard thin-plate spline approach (right). Although here we have added 12 additional landmarks in other areas to constrain the transformation, the influence is significantly more global.

A further extension of the above schemes is the inclusion of *higher-dimensional landmarks* (e.g., line and surface landmarks), for which it is necessary to compute landmark correspondences automatically [2].

4 Biomechanical Modelling of Brain Deformations

A main advantage of the spline-based registration approaches described above is their computational efficiency. Alternatively, we are also working on computationally more expensive *biomechanical models* of brain deformations to further improve the accuracy as well as to extend the range of applications. Within this topic the central task is to cope with *nonhomogeneous* tissue properties (e.g., rigid, elastic, and fluid parts). Besides surgical simulation, an important application is the correction of a preoperatively acquired image w.r.t. the current anatomical situation for the purpose of accurate intraoperative navigation. Anatomy changes result from opening the skull and the dura mater (brain shift) or due to tumor resection.

To include different material properties we have developed an approach based on the Navier equation from elasticity theory, which is solved numerically by applying the *finite element method (FEM)*. Material parameter values for tissues of the human head have been obtained through a comprehensive literature study [6]. As input data we use landmark correspondences, which are incorporated into the FEM model as described in [9]. Our approach has been applied, e.g., to the preoperative MR image in Fig. 4 on the left, which has been routinely acquired in conjunction with the resection of a tumor. Instead of an intraoperative image (e.g., a CT or an ultrasound image) we here use a postoperative MR image for demonstration purposes (Fig. 4 middle/left). In both images the contours of the tumor have been extracted manually by a medical expert and a snake algorithm has been applied to compute correspondences. In addition, the preoperative image has been segmented coarsely into four regions: combined skull/skin, brain, ventricular system, and image background (Fig. 4 middle/right), and different material parameter values have been assigned to these regions. The corrected preoperative image is shown in Fig. 4 on the right with overlaid edges of the postoperative image.

So far, we have modelled different material properties based on *one* physical model, in this case a purely elastic model. Recently, we have introduced an approach, where an elastic model has been coupled with a fluid model. This extension allows to model deformations of *combined elastic/fluid* parts more accurately [7].

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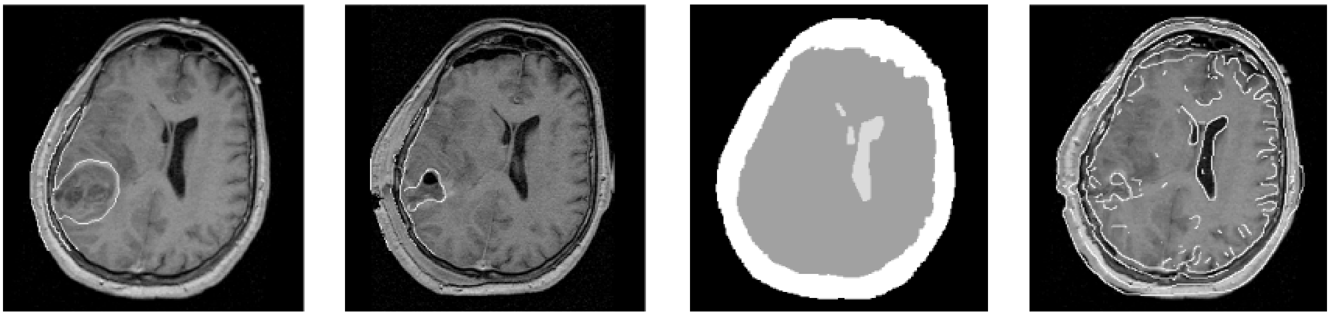

Figure 4: Preoperative (left) and postoperative image with extracted contours (middle/left), region-segmented preoperative image (middle/right), and corrected preoperative image with overlaid contours of the postoperative image (right).

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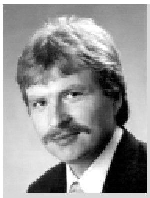

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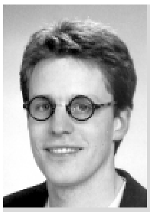

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