A Fast and Flexible Image Registration Toolbox

Design and Implementation of the general approach

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Abstract. In the last decades there has been tremendous research towards the design of fully automatic non-rigid registration schemes. However, apart from the ITK based implementation of Rueckerts B-spline oriented approach, there is a lack of sound publicly available implementations of the modern schemes. The Flexible Image Registration Toolbox (FLIRT) is an attempt to close this gap. It focuses on non-parametric schemes as popularized in the book by Modersitzki [1]. To be successful, it is crucial for any registration scheme to reflect the special properties of the underlying registration problem. Consequently, FLIRT has an open object-oriented architecture which allows for the incorporation of user prescribed building blocks. In its present form, some of the most prominent blocks are already implemented. They may be arranged in a consistent way and cover a wide range of applications. Apart from the flexibility issue, great care has been taken towards fast execution times. The most computationally intensive part, the solution of the underlying linear systems, is implemented by state-of-the-art solution techniques.
The FLIRT package is publicly available, it comes with a user guide and a collection of example problems. It is the purpose of this note, to describe some of the features of the toolbox.

1 Introduction

Registration of medical images is an active field of current research and still constitutes one of today's most challenging image processing problems [1,2,3,4]. In basic terms, registration is the process of finding a geometric transformation between two or more images such that corresponding image structures correctly align. These images may have been acquired with the same or different imaging modalities, at the same or different times, from one or several patients. Accurate image registration is a necessary prerequisite for many diagnostic and therapy planning procedures where complementary information from different images has to be combined. All existing registration schemes can be divided in two approaches, a parametric approach, describing the transformation as a linear combination of pre-selected basis functions, and a non-parametric approach, describing the transformation as the solution of an associated partial differential equation [1]. The Flexible Image Registration Toolbox (FLIRT) focusses on non-parametric non-rigid registration techniques. This registration strategy is one of the most promising non-linear approaches currently used in medical imaging. The approach attempts to minimize an appropriate functional. It typically consists of two building blocks. The first is responsible for external forces, which are computed from the reference image R and the template image T, whereas the second computes the internal forces, which are defined for the wanted displacement field u itself. The internal forces are designed to keep the displacement field smooth during deformation, while the external forces are defined to obtain the desired registration result. The registration problem may be phrased as

$$\mathcal{J}[u] := \mathcal{D}[R, T; u] + \alpha \mathcal{S}[u] = \min, \tag{1}$$

with some additional boundary conditions. Here, $\mathcal{D}$ represents a *distance measure* (external force), whereas $\mathcal{S}$ denotes a *smoother* for u (internal force). The parameter α may be used to control the strength of the smoothness of the displacement versus the similarity of the images. The most common choices for distance measures in image registration are the *sum of squared differences* (SSD), *cross correlation* (CC), and mutual information (MI) [1]. The smoother $\mathcal{S}$ is also called *regularizing* term. This term is unavoidable. Arbitrary transformations may lead to cracks, foldings, or other unwanted deformations. With an appropriate smoother it becomes possible to distinguish particular transformations which seem to be more likely than others. Typical regularizer are the *elastic* [5], *diffusive* [6] and *curvature* [7] smoother.

2 State of the art and advances by the presented contribution

In contrast to the wealth of literature, surprisingly only a few publicly available non-rigid image registration software packages are available. Possibly the most well-known is the one designed by Rueckert [8], which is part of the software library ITK (www.itk.org). In non-rigid registration one distinguishes between parametric and non-parametric approaches. The just mentioned package belongs to the class of parameter-dependent schemes. That is, the thought after transformation is prescribed with respect to a given space, like, e.g. B-splines. To our best knowledge, there exists no publicly available software package for parameter-free non-rigid image registration.

The FLIRT package consists of a variety of non-parametric, non-rigid registration routines, written in C/C++. The toolbox realizes the concept outlined in a paper by Fischer and Modersitzki [9]. It is designed for easy use and its versatile concept allows for the application to a wide range of registration problems. In addition, the object-oriented architecture does permit a straightforward implementation of further building blocks. Great care has been taken in the design of solution strategies for the underlying optimization problem. The outcome is a highly competitive implementation both in terms of reliability and computing time.

3 Methods

Our software design is highly related to the structure of the energy functional $\mathcal{J}$, see (1). At this point we give only a short repetition to motivate our design, for more details we refer to the literature, for example [1,9]. Using an optimize-discretize approach and the calculus of variations we arrive at the so called Euler-Lagrange equations

$$f(x, u(x)) + \alpha A[u](x) = 0, \tag{2}$$

which constitute a necessary condition for u being a minimizer of (1). Its summands are directly related to the used distance-measure and regularizer, i.e. the so-called force f corresponds to the measure $\mathcal{D}$ and the smoothness operator A to the regularizer S. To solve these non-linear equations, it is common to linearize them by means of a fixed-point type iteration or by introducing an artificial time and employing a time-marching scheme. Discretizing the force f and the operator A leads to an iteration process, where at each step a large linear system has to be solved. Here, the structure of the system matrix depends only on the chosen regularizer, the force constitutes the right hand side of the system. To arrive at an efficient algorithm, special care has to be taken for the solution of the linear system. Therefore, for each smoother in FLIRT a highly specialized solver has been designed and implemented, resulting in very competitve running times.

Our software design deals with two main aspects:

1. the variability of the approach, i.e. the interchangeability of distance measure, regularizer etc
2. the necessity for fast numerical algorithms, i.e. solvers for linear systems, interpolation.

First of all we have chosen an object oriented software design. This allows us to compose abstract classes, which are used to define interfaces between the convertible components. In the following we list the regarded components, give an overview about their functionality and in brackets a list of possible derived classes, that implement the interfaces:

- **distance-measure**, evaluation of the functional, providing the derivative of the functional, i.e. the force f(sum of squared differences (SSD), mutual information, normalized gradient field)
- **regularizer**, evaluation of the functional, providing the derivative of the functional, i.e. the smoothness operator A (elastic regularizer, curvature regularizer, diffusive regularizer)

- **optimizer**, the way the nonlinear Euler-Lagrange equation is linearized (fixed-point iteration, time-marching iteration)
- **stopping criteria**, condition for stopping the iteration (stopping criteria from Gill, Murray and Wright [10])

Furthermore we have composed abstract classes for images and displacement-fields, dealing with parameters like image size, voxel size and managing storage. These classes can be concretized for $2D$ or $3D$. All of this is implemented using C/C++.

Embedded into the object oriented part we have developed a machine oriented library. This is associated with the second aspect of our design: the necessity for fast algorithms. The library provides fast codes for solving the arising linear systems as described above. For each regularizer a special solver is implemented. For more details on the the underlying numerics, we refer to [11,1]. Since two of these solvers depend on fast Fourier transformation techniques, the fftw-library (www.fftw.org) is included. Beside the solvers we have implemented interpolation and gradient calculation schemes. This machine oriented part of our library is written in the C-language, so it cooperates easy with other software, like, for example, MatLab using its `mex`-interface.

The software can be downloaded from the homepage of the SAFIR group `http://www.math.uni-luebeck.de/safir/FLIRT-Download`. It is available for Linux and - in future - for the Windows platform. Furthermore it is planed to include the toolbox as an additional part of MeVisLab.

4 Results

For lack of space this paper contains only one example to illustrate the efficiency and capability of the implemented software. We use CT-images of the lunge, showing two different states of the respiration cycle. These images are provided by Thomas Netsch, Philips, Hamburg. The image size is 256×171. The calculation was performed on an AMD 64 3000+ with 1 GB RAM using the SSD distancemeasure, the elastic regularizer and fixed-point optimizer with 25 iterations. The overall computation time was approximatly 2 seconds. The energy $\mathcal{J}$ was reduced to 30%. The results are illustrated in figure 1.

5 Discussion

An object-oriented toolbox for non-parametric and non-linear registration problems is presented. To our best knowledge, the discussed toolbox is the first publicly available package out of this class. In its present state, the most well-known smoothers are incorporated. However, due to its versatile style, an extension to additional smoothers or distance measures is straightforward and it is part of the project to enhance the package step by step. The toolbox is publicly available and everybody is highly welcome to test its performance and to report any flames or praises to the SAFIR group.

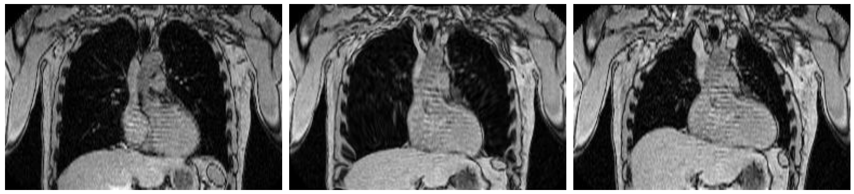

Fig. 1. Example. *left:* reference image *middle:* deformed template image after registration, *right:* template image

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