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# Spline-Based Hybrid Image Registration using Landmark and Intensity Information based on Matrix-Valued Non-radial Basis Functions

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**Abstract** We introduce a new approach for spline-based elastic image registration using both point landmarks and intensity information. With this approach, both types of information as well as a regularization based on the Navier equation are directly integrated in a single energy minimizing functional. For this functional we have derived an analytic solution, which is based on matrix-valued non-radial basis functions. With our approach the full 3D intensity information is exploited, i.e., all voxels are considered and subsampling using a grid is not required. A special case of our hybrid approach is obtained by disregarding the landmark information, which results in a pure intensity-based elastic registration approach. We have successfully applied our approach to 3D synthetic images, 2D MR images of the human brain, 2D gel electrophoresis images, and 3D CT lung images.

**Keywords** Elastic image registration · Hybrid registration · Gaussian elastic body splines · Analytic solution

## 1 Introduction

Registration of 2D and 3D images is an important task in medical image analysis. Typical applications are the registration of intra-patient images of different modalities [e.g., computed tomography (CT) and magnetic resonance imaging (MRI)] or at different points in time (e.g., pre- and post-operative), the registration of images of different patients, as well as the registration of images with an anatomical atlas. A main challenge is to cope with the broad range of applications as well as the large spectrum of imaging modalities. Concerning the underlying transformation model, generally elastic (nonrigid) schemes have to be used (for surveys see, e.g., Zitova and Flusser 2003; Crum et al. 2004; Holden 2008). In particular, physically-based elastic transformation models (e.g., incorporating material properties) allow representing deformations of biological tissues (e.g., caused by tumor growth) more realistically and are better suited in applications where the properties of the imaged material are well modeled. Also, more generally, by using an improved physical deformation model more meaningful results can be obtained compared to a coarse deformation model.

Elastic registration approaches are, in general, based on an energy functional or the related partial differential equation. Often, *spline-based* approaches have been used for elastic registration, which can be subdivided into schemes based on a *uniform* grid of control points (e.g., using B-splines, Rueckert et al. 1999; Hartkens et al. 2002; Kybic and Unser 2003; Stewart et al. 2004; Papademetris et al. 2004; Sorzano et al. 2005; Teng et al. 2006; Paquin et al. 2007; Hub et al. 2010; Cao et al. 2010; Gorbunova et al. 2010), and schemes based on a *nonuniform* grid of control points (e.g., Bookstein 1989; Joshi and Miller 2000; Rohr et al 2001; Johnson and Christensen 2002; Chui and Rangarajan 2003).

The latter type of spline-based schemes generally requires a smaller number of control points (landmarks). Examples of such schemes are based on *thin-plate splines* (TPS, e.g., Bookstein 1989; Rohr et al 2001; Johnson and Christensen 2002; Chui and Rangarajan 2003; Park et al. 2004; Wang and Feng 2004; Šerifović-Trbalić et al. 2006; Wu et al. 2010; Murphy et al. 2011), *clamped-plate splines* (CPS, e.g., Marsland and Twining 2004; Rogers and Graham 2007), *elastic body splines* (EBS, e.g., Davis et al. 1997; Sato et al. 1999; Bergvall et al. 2008), and *Gaussian elastic body splines* (GEBS, e.g.,

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