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Editorial

A survey of medical image registration – under review

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ABSTRACT

A retrospective view on the past two decades of the field of medical image registration is presented, guided by the article "A survey of medical image registration" (Maintz and Viergever, 1998). It shows that the classification of the field introduced in that article is still usable, although some modifications to do justice to advances in the field would be due. The main changes over the last twenty years are the shift from extrinsic to intrinsic registration, the primacy of intensity-based registration, the breakthrough of nonlinear registration, the progress of inter-subject registration, and the availability of generic image registration software packages. Two problems that were called urgent already 20 years ago, are even more urgent nowadays: Validation of registration methods, and translation of results of image registration research to clinical practice. It may be concluded that the field of medical image registration has evolved, but still is in need of further development in various aspects.

1. Introduction

One of the early articles published in Medical Image Analysis was "A survey of medical image registration" by Maintz and Viergever (1998). The aim of the article was to present a comprehensive and structured record of approaches to registration of medical images. The article has been influential in the medical image analysis literature ever since, with > 3600 citations in Google Scholar and still 200 citations/year in the past few years.

This anniversary issue of the journal is a suitable occasion to review the contents of the article, in particular to take stock of what has changed over the last two decades in medical image registration. Is the classification proposed in the article still useful? Have observed trends continued, increased, or decreased? Are other striking observations still valid? Has the field changed in a way that was not foreseen then? And have the major problems identified at that time been addressed and solved?

These issues will be discussed in the following sections.

2. Is the classification proposed in 1998 still useful?

The article of Maintz and Viergever was not just a survey of image registration papers published until then, but in addition proposed a scheme to classify image registration methods in terms of nine distinctive characteristics. Slightly to our surprise, the classification setup is still quite functional, with as criteria (i) dimensionality (spatial or spatiotemporal 2D/2D, 2D/3D, 3D/3D), (ii) nature of the registration basis (extrinsic, intrinsic, non-image based), (iii) nature of the transformation (rigid, affine, projective, curved), (iv) domain of the transformation (global, local), (v) degree of interaction (interactive, semi-automatic, automatic), (vi) optimization procedure (parameters computed or searched for), (vii) modalities involved (mono-modality, multi-modality, modality to model, patient to modality), (viii) subjects involved (intra-subject, inter-subject, atlas), (ix) objects involved (e.g., brain, heart, breast).

The article typified extrinsic vs. intrinsic registration as the main dichotomy of the classification scheme. This is no longer valid. While extrinsic registration is not completely obsolete, it only features in a restricted number of applications. Furthermore, we would nowadays formulate some of the criteria slightly differently, and maybe add one or two as, e.g., pairwise (n = 2 images) vs. groupwise (n > 2 images) registration or asymmetric vs. symmetric formulations. Also, subdivisions of some of the categories

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would be due. For example, the category of optimization procedures could be divided into continuous and discrete methods, and for the category of curved transformations one could consider distinguishing small-deformation (or: elastic) and large-deformation (or: fluidic, based on integration of velocity fields) methods. And finally, the recent literature on curved registration comprises innovative proposals for transformation modelling, regularization, and optimization, which often appear intertwined. However, this does not preclude classification according to the original framework. It is still fairly straightforward to categorize these methods by the nature of the transformation and by the optimization procedure. So, overall, the classification scheme seems very usable a score of years after its conception. It could be readily updated to comprise all state-of-the art registration approaches, but this is beyond the scope of the present article.

3. Have observed trends continued, increased, or decreased?

Several trends in image registration approaches were formulated by Maintz and Viergever.

First, a shift from extrinsic to intrinsic registration was noted, even though clinically employed methods were generally extrinsic then. This trend has continued apace. In image registration research, extrinsic approaches are hardly found any more. In clinical applications where image registration is used, intrinsic methods are gaining ground, although in surgical and radiotherapeutical procedures, extrinsic matching remains in use.

Second, while surface-based methods were the most often used type of intrinsic registration at that time, it was observed that they had to give way to methods based on properties of individual voxels. This trend has certainly increased. Computational hurdles to applying voxel-based registration have rapidly diminished, so that it became feasible to take the full image contents into account in registration procedures rather than having to rely on segmentation of image objects that subsequently had to be aligned. It is noteworthy that point-based (often anatomical landmark-based) approaches still have their place in image registration, much more so than surface-based methods.

Third, it was mentioned that the need for creating public data bases of representative images and for assembling image registration validation protocols was emerging. These issues are still urgent, even though noticeable progress has been made on each of them. Several data sets with expert landmark annotations have become available in the last decade. Most of these concern manually delineated segmentations of structures, which are intended for evaluation of image segmentation methods but may also be used for evaluation of registration approaches. For example, public data sets of segmented MR brain images as IBSR (http://www.nitrc.org/projects/ibsr) and LPBA40 (http://www.loni.usc.edu/atlases/Atlas_Detail.php?atlas_id=12) have been used for this purpose in studies on evaluation of registration accuracy, see e.g. Klein et al. (2009). We would, however, like to draw the readers' attention to the study by Rohlfing (2012), which shows that the approach of evaluating registration algorithms on the basis of image similarity and tissue overlap measures has severe shortcomings and hence should be used with caution. Just a few data bases have been set up specifically for evaluation of registration methods, all concerning deformable thoracic image registration, and primarily aimed at registration of inspiration/expiration scans of the lungs. These annotated data sets are provided by: DirLab (http://www.dir-lab.com), POPI (http://www.creatis.insa-lyon.fr/rio/popi-model), and EMPIRE10 (http://empire10.isi.uu.nl). EMPIRE10 was launched as an evaluation challenge in conjunction with MICCAI 2010. Training data were made publicly available, and research groups could participate in the challenge by describing their approach and submitting its results, whereupon feedback was provided. The challenge is described in Murphy et al. (2011a). It is still open for submission, and currently lists 41 algorithm results from 28 first authors. Remarkably enough, it is the only challenge on image registration listed in the Grand Challenges repository (http://grand-challenge.org), the more so since one of the earliest medical image analysis evaluation challenges, if not the first, dealt with image registration. It was the Retrospective Registration Evaluation Project (RREP), set up by J. Michael Fitzpatrick (West et al., 1997). It concerned an evaluation of algorithms for rigid registration of CT, MR and PET images of the human head, aimed at support of neurosurgical procedures. The gold standard was obtained by registration of markers screwed into patients' heads (as part of the clinical protocol). The challenge was continued as the Retrospective Image Registration Evaluation (RIRE) project, and is hosted by Kitware since 2007 (http://www.insight-journal.org/rire). It is still active, and currently counts >400 submitting authors (!).

4. Are other striking observations still valid?

The article (Maintz and Viergever, 1998) furthermore contains several interesting observations, not explicitly formulated as trends. These include:

- *Registration is seldom used in diagnostic clinical practice, even though for some procedures the advantages of using registered images are obvious*. This assertion still largely holds true for diagnostic medical specialties, including notably radiology. Rigid registration, which is generally present in commercial medical image analysis packages, may be used for some multi-modality protocols. For many diagnostic processes, however, nonlinear registration would be due, e.g. to detect changes in disease progression. While relatively fast methods for nonlinear registration have been developed in research settings, such methods have not reached the status of inclusion in commercial software that supports clinical diagnoses, for lack of genericity and robustness. The possibility to build fast and reliable image analysis pipelines using generic modules (preprocessing, registration, segmentation) may change this for the better at short notice, at the very least within another score of years.
- *Intra-operative registration in surgical procedures and image registration for patient positioning in radiotherapy are used in the clinic with good results*. This observation appears to have been a bit optimistic as concerns surgical procedures. At that time, neurosurgery pioneered with image registration methods for surgical guidance, true, but these methods have not found their way to routine clinical practice with the exception of rigid registration based on fiducial markers for neuronavigation. Registration is more widespread, however, in the presurgical stages of therapy selection and therapy planning. Especially in functional neurosurgery – and in the associated discipline of clinical neurophysiology – registration of images from quite a few different modalities is part of the clinical workflow. Image registration is furthermore on the rise in interventional radiology and cardiology, where 3D/2D registration aimed at integrating pre-interventional 3D information (CT, MRI, 3DRX) with 2D X-ray intervention images for navigation purposes, is becoming available in clinical intervention software. And finally, for radiotherapy the picture is much more favourable. In fact, radiotherapy is probably the clinical specialty where image registration is used most prominently. Not only are fast and trusted rigid registration techniques at the disposal of the radiation oncologist for patient positioning in linear accelerators, image registration is also increasingly used in diagnosis and tumour staging, in treatment planning and guidance, and in response monitoring.