Medical Image Registration

CT

MR

PET

SPECT

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Introduction
Medical images are increasingly being used within healthcare for diagnosis, planning treatment, guiding treatment and monitoring disease progression. Within medical research (especially neuroscience research) they are used to investigate disease processes and understand normal development and ageing. In many of these studies, multiple images are acquired from subjects at different times, and often with different imaging modalities. The most widely used application of medical image registration is aligning tomographic images. That is aligning images that sample three-dimensional space with reasonably isotropic resolution.

Image registration
Image processing is not only used in analyzing an image but also for comparing or combining information given by different images. Thus image registration is one of the fundamental tasks within image processing. Traditionally, the image registration problem has been stated as: Find the transformation ‘H’ that maps the template image volume ‘T’ into correspondence with the target image volume . Alternatively, the problem can be stated as: Find the transformation ‘g’ that transforms S into correspondence with T.

Image registration has many uses in medicine such as multimodality fusion, image segmentation, deformable atlas registration, functional brain mapping, image-guided surgery, and characterization of normal versus abnormal anatomical shape and variation. The fundamental assumption in each of these applications is that image registration can be used to define a meaningful correspondence mapping between anatomical images collected from imaging devices such as computed tomography (CT), magnetic resonance imaging (MRI), cryosectioning, etc.

The imaging modalities employed can be divided into two global categories:

Anatomical - Anatomical modalities depict primarily morphology. These include X-ray, CT (computed tomography), MRI magnetic resonance imaging) and US (ultrasound) to name a few.
**Functional** - Functional modalities depict, primarily, information on the metabolism of the underlying anatomy. These include (planar) scintigraphy, SPECT (single photon emission computed tomography).

Since information gained from two images acquired in the clinical track of events is usually of a complementary nature, proper *integration* of useful data obtained from the separate images is often desired. A first step in this integration process is to bring the modalities involved into spatial alignment, a procedure referred to as *registration*. Image registration refers to matching two images so that corresponding coordinate points in the two images correspond to the same physical region of the scene being imaged. It’s also referred to as image fusion, superimposition, matching or merge.

Image registration is used to find an optimal geometric transformation between corresponding image data.

Medical image registration has been applied to the diagnosis of breast cancer, colon cancer, cardiac studies, wrist and other injuries, inflammatory diseases and different neurological disorders including brain tumors, Alzheimer's disease and schizophrenia. This method has also been utilized in radiotherapy, mostly for brain tumors, and by cranio-facial surgeons to prepare for and simulate complex surgical procedures.
**Classification**

Eight basic criteria are used, each of which is again subdivided on one or two levels. The nine criteria and primary subdivisions are:

1. **DIMENSIONALITY**
   The main division here is whether all dimensions are spatial, or that time is an added dimension. In either case, the problem can be further categorized depending on the number of spatial dimensions involved.

   a. **Spatial dimensions only:**
      1. 2D/2D
      2. 2D/3D
      3. 3D/3D

      3D/3D registration normally applies to the registration of two tomographic datasets, or the registration of a single tomographic image to any spatially defined information, e.g., a vector obtained from EEG data. 2D/2D registration may apply to separate slices from tomographic data, or intrinsically 2D images like portal images. Compared to 3D/3D registration, 2D/2D registration is less complex by an order of magnitude both where the number of parameters and the volume of the data are concerned, so obtaining a registration is in many cases easier and faster than in the 3D/3D case. 2D/3D registration is used for the direct alignment of spatial data to projective data.

   b. **Time series (more than two images), with spatial dimensions:**
      1. 2D/2D
      2. 2D/3D
      3. 3D/3D

      *Time series* of images are acquired for various reasons, such as monitoring of bone growth in children (long time interval), monitoring of tumor growth (medium interval), post-operative monitoring of healing (short interval), or observing the passing of an injected bolus through a vessel tree (ultra-short interval).
2. NATURE OF REGISTRATION BASIS

I. Extrinsic – Based on foreign objects introduced into the imaged space. Extrinsic methods rely on artificial objects attached to the patient, objects which are designed to be well visible and accurately detectable in all of the pertinent modalities.

1. Invasive - A commonly used fiducial object is a stereotactic fram. Such frames are used for localization and guidance purposes in neurosurgery. The following methods are used:
   A. Stereotactic frame
   B. Fiducials (screw markers)

2. Non-invasive - extrinsic methods by definition cannot include patient related image information, the nature of the registration transformation is often restricted to be rigid.
   The following methods are used here:
   A. Mould, frame, dental adapter, etc.
   B. Fiducials (skin markers)

II. Intrinsic – Based on the image information as generated by the patient. Registration can be based on a limited set of identified salient points (landmarks), on the alignment of segmented binary structures (segmentation based), most commonly object surfaces, or directly onto measures computed from the image grey values (voxel property based).

1. Landmark based – Landmarks are salient and accurately locatable points of the morphology of the visible anatomy, usually identified interactively by the user. Identifying corresponding points in the images and inferring the image transformation
   A. Anatomical
   B. Geometrical

2. Segmentation based - Segmentation based registration methods can be rigid model based where anatomically the same structures (mostly surfaces) are extracted from both images to be registered, and used as sole input for the alignment procedure.
They can also be *deformable model based* where an extracted structure (also mostly surfaces, and curves) from one image is elastically deformed to fit the second image.

A. Rigid models (points, curves, surfaces)

B. Deformable models (snakes, nets)

Since the segmentation task is fairly easy to perform, and the computational complexity relatively low, the method has remained popular. A drawback of segmentation based methods is that the registration accuracy is limited to the accuracy of the segmentation step.

3. **Voxel property based** - The *voxel property based* registration methods stand apart from the other intrinsic methods by the fact that they operate directly on the image grey values, without prior data reduction by the user or segmentation. There are two distinct approaches: the first is to immediately *reduce* the image grey value content to a representative set of scalars and orientations, the second is to use the full image content throughout the registration process.

A. Reduction to scalars/vectors (moments, principal axes) – these methods the image center of gravity and its principal orientations (principal axes) are computed from the image zeroth and first order moments. Registration is then performed by aligning the center of gravity and the principal orientations

B. Using full image content – *these* are the most interesting methods researched currently. Theoretically, these are the most flexible of registration methods, since they –unlike all other methods mentioned– do not start with reducing the grey valued image to relatively sparse

III. **Non-image based (calibrated coordinate systems)**

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3. NATURE AND DOMAIN OF THE TRANSFORMATION

I. Nature of transformation

a. Rigid - An image coordinate transformation is called rigid, when only translations and rotations are allowed.

b. Affine - An image coordinate transformation is called affine if the transformation maps parallel lines onto parallel lines it is called affine.

c. Projective - If it maps lines onto lines, it is called projective.

d. Curved - If it maps lines onto curves, it is called curved or elastic.

II. Domain of the transformation

A transformation is called global if it applies to the entire image, and local if subsections of the image each have their own transformations defined.

The term local transformation is reserved for transformations that are composites of at least two transformations determined on sub-images that cannot be generally described as a global transformation.

Hence, a single transformation computed on some volume of interest of an image, is a global transformation.

4. INTERACTION

Concerning registration algorithms, three levels of interaction can be recognized.
a. **Interactive** – where the user does the registration himself, assisted by software supplying a visual or numerical impression of the current transformation, and possibly an initial transformation guess.

b. **Semi-automatic** - where the interaction required can be of two different natures: the user needs to *initialize* the algorithm, *e.g.*, by segmenting the data, or *steer* the algorithm, *e.g.*, by rejecting or accepting suggested registration hypotheses.

c. **Automatic** - where the user only supplies the algorithm with the image data and possibly information on the image acquisition.

5. OPTIMIZATION PROCEDURE

a. Parameters computed

b. Parameters searched for

The parameters that make up the registration transformation can either be *computed* directly, *i.e.*, determined in an explicit fashion from the available data, or *searched for*, *i.e.*, determined by finding an optimum of some function defined on the parameter space.

6. MODALITIES INVOLVED

Four classes of registration tasks can be recognized based on the modalities that are involved.

a. **Monomodal** - In *monomodal* applications, the images to be registered belong to the same modality.

b. **Multimodal** – In multimodal applications, the images to be registered stem from two different modalities.

c. Modality to model and

d. Patient to modality – only one image is involved and the other “modality” is either a model or the patient himself.
The following are examples of the above types of modalities involved.

- For diagnostic purposes, two myocardial SPECT images are acquired of the patient, under rest and stress conditions. Their registration is a monomodal application.
- To relate an area of dysfunction to anatomy, a PET image is registered to an MR image. This is a multimodal application.
- In radiotherapy treatment, the patient can be positioned with the aid of registration of in-position X-ray simulator images to a pre-treatment anatomical image. Although the registration task is performed using only the images acquired, the actual task of patient positioning is clearly an example of patient to modality registration.

7. SUBJECT

a. Intrasubject - When all of the images involved in a registration task are acquired of a single patient, we refer to it as intrasubject registration.

b. Intersubject - If the registration is accomplished using two images of different patients (or a patient and a model), this is referred to as intersubject registration.

c. Atlas - If one image is acquired from a single patient, and the other image is somehow constructed from an image information database obtained using imaging of many subjects, we name it atlas registration.

8. OBJECT

The following list refers to the areas in the body that are commonly imaged.

a. Head
   1. Brain or skull 2. Eye 3. Dental

b. Thorax
   1. Entire 2. Cardiac 3. Breast

c. Abdomen

d. Pelvis and perineum

e. Limbs

f. Spine and vertebrae
Other issues in Registration

OPTIMISATION
Many registration algorithms require an iterative approach.
- an initial estimate of the transformation is gradually refined
- In each iteration, the current estimate of the transformation is used to calculate a similarity measure
- makes another estimate of the transformation, evaluates the similarity measure again, and continues until the algorithm converges
- no transformation can be found that results in a better value of the similarity measure, to within a preset tolerance.

VALIDATION
- **Accuracy**: Accuracy is defined as the “degree to which a measurement is true or correct”. For each sample of experimental data local accuracy is defined as the difference between computed values and theoretical values, i.e., known from a ground truth. This difference is generally referred to as local error. Under specific assumptions, a global accuracy value can be computed for the entire data set from a combination of local accuracy values.
- **Precision and Reproducibility or Reliability**: Precision of a process is the resolution at which its results are repeatable, i.e., the value of the random fluctuation in the measurement made by the process. Precision is intrinsic to this process. This value is generally expressed in the parameter space. Goodman defines reliability as “the extent to which an observation that is repeated in the same, stable population yields the same result”.
- **Robustness**: The robustness of a method refers to its performance in the presence of disruptive factors such as intrinsic data variability, pathology, or inter-individual anatomic or physiologic variability.
• **Consistency**: This criterion is mainly studied in image registration validation by studying the effects of the composition of ‘n’ transformations that forms a circuit. The consistency is a measure of the difference of the composition from the identity.

• **Fault Detection**: This is the ability of a method to detect by itself when it succeeds (e.g. result is within a given accuracy) or fails. Functional complexity and computation time: These are characteristics of method implementation. Functional complexity concerns the steps that are time-consuming or cumbersome for the operator. It deals both with man-computer interaction and integration in the clinical context and has a relationship with physician acceptance of the system or method. The degree of automation of a method is an important aspect of functional complexity (manual, semi automatic or automatic). Among the most important validation criteria applied in the U.S. market are those required to receive premarket approval for a medical device from the Food and Drug Administration (FDA).

**Other Applications**

**Real-Time Video-to-Site Registration**

The analysis of ground activities involving vehicles and humans is of interest in airborne surveillance applications. 3-D site models provide accurate topographic and geometric information about point sites, areas, and lines of communication, enabling the focusing of attention on portions of the image relevant to the activity being detected, and enabling the reduction of false alarms. Essential to the use of site models is the real-time registration of the aerial video to the site, because the activities detected in the video have to be “geolocated” with respect to the site model. Currently there is work going on develop to a semi-automatic video-to-site registration system that computes an approximate sensor geolocation from sensor metadata, and then refines it using known site features. This system has been implemented on a consumer-grade PC, and runs in real time using less than 2% of the CPU. It had known to reduce geolocation errors from about 100m to 5m for an aircraft altitude of 1500m, enabling the analysis of human activity on the ground.
Conclusion

The first algorithms for medical image registration were devised in the early 1980s, and fully automatic algorithms have been available for many intermodality and intramodality applications since the mid 1990s. Despite this, at the time of writing, image registration is still seldom carried out on a routine clinical basis. The most widely used registration applications are probably image-to-physical space registration in neurosurgery and registration of functional MR images to correct for interscan patient motion. Intermodality registration, which accounts for the majority of the literature in this area, is still unusual in the clinical setting.

Image registration is, however, being widely used in medical research, especially in neuroscience where it is used in functional studies. Increasing volumes of data and multimedia electronic patient records have already been referred to, and these practical developments may see registration entering routine clinical use at many centres. Also, increasing use of dynamic acquisitions such as perfusion MRI will necessitate use of registration algorithms to correct for patient motion. In addition, non-affine registration is likely to find increasing application in the study of development, ageing and monitoring changes due to disease progression and response to treatment. In these latter applications, the transformation itself may have more clinical benefit than the transformed images, as this will quantify the changes in structure in a given patient. New developments in imaging technology may open up new applications of image registration. It has recently been shown that very high field whole-body MR scanners can produce high signal to noise ratio images of the brain with 100 µm resolution.
Intramodality registration of these images may open up new applications such as monitoring change in small blood vessels. Also, while ultrasound images have been largely ignored by image registration researchers up until now, the increasing quality of ultrasound images and its low cost makes this a fertile area for both intramodality and intermodality applications.