

*image registration, mutual information,
similarity measure*

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MUTUAL INFORMATION BASED REGISTRATION OF BRAIN IMAGES

Registration is one of the essential medical image processing techniques. The goal is to find a geometric transformation, that relates corresponding voxels in two different 3D images of the same object. The publication presents a registration technique based on maximization of mutual information.

1. INTRODUCTION

Various medical imaging techniques (CT, MRI, PET, etc.) provide information about different properties of the examined tissues. Since this information is often of a complementary nature, in medical diagnostics, planning and evaluating of surgical and radiotherapeutical procedures it is desired to use integrated useful data from different modality images. The integration task is not trivial due to unlike patient's spatial orientation, datasets' resolutions and voxel intensity profiles.

The goal of registration (matching, alignment) process is, given two images of the same object, to find a spatial transformation T , that relates them. The next step is a fusion of the registered datasets.

2. REGISTRATION METHODS

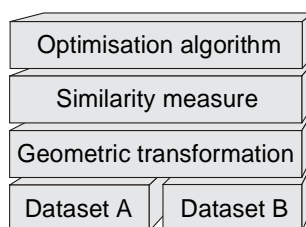


Fig.1. The optimisation framework

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There are two main groups of registration methods: feature-based and voxel-based techniques. In the first case some corresponding points need to be recognized prior to the registration. They can be either external markers (stereotactic frame, screw markers, skin markers), which are usually inconvenient for the patient, or some anatomical structures (localized by an expert after a segmentation step).

In voxel-based techniques a function of similarity of two images is computed with the intensities of all (or most of) voxels in the images. It does not require a segmentation step and can be performed almost automatically and accurately. This approach is becoming more and more popular. However it involves more computing time.

Regardless of the method used, the registration framework is always similar (fig. 1.). It is necessary to implement an efficient similarity measure optimisation procedure in order to find transformation T parameters.

3. 3D TRANSFORMATION

There is a wide class of local and global transformations (rigid, affine, projective, curved) [2], that can be applied for registration. A rigid or affine 3D transformation can be easily described using a single constant 4x4 matrix. The affine transformation implemented in our program is defined as follows:

$$T = \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(R_x) & -\sin(R_x) & 0 \\ 0 & \sin(R_x) & \cos(R_x) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(R_y) & 0 & \sin(R_y) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(R_y) & 0 & \cos(R_y) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(R_z) & -\sin(R_z) & 0 & 0 \\ \sin(R_z) & \cos(R_z) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, (1)$$

where $T_x, T_y, T_z, R_x, R_y, R_z$ are the transformation parameters.

4. INFORMATION MEASURES AND ALIGNMENT

We present here some basic results of information theory [1,5]. The most commonly used measure of information is the Shannon-Wiener entropy measure. The average information supplied by a set of n symbols whose probabilities are given by $\{p_1, p_2, \dots, p_n\}$, can be expressed as:

$$H(p_1, p_2, \dots, p_n) = -\sum_{i=1}^n p_i \log p_i. \quad (2)$$

The entropy H of a discrete random variable X with values in the set $\{x_1, x_2, \dots, x_n\}$ is defined as:

$$H(X) = -\sum_{i=1}^n p_i \log p_i, \quad (3)$$

where $p_i = \Pr[X=x_i]$.

The entropy definition of a single random variable can be extended to a pair of random variables. Let us consider random variable Y with the probabilities q_i . The joint entropy of a pair of discrete random variables (X, Y) with a joint distribution $p(x, y)$ is defined as:

$$H(X, Y) = - \sum_{i=0}^n \sum_{j=1}^m p_{ij} \log p_{ij}, \quad (4)$$

where $p_{ij} = \Pr[X=x_i, Y=y_j]$.

The conditional entropy is defined as:

$$\begin{aligned} H(X | Y) &= \sum_{j=1}^m q_j H(X | Y = y_j) = - \sum_{i=0}^n \sum_{j=1}^m p_{ij} \log p_{ij} \\ &= - \sum_{j=1}^m \sum_{i=1}^n p_{ij} \log p_{ij} \end{aligned} \quad (5)$$

where $p_{ij} = \Pr[X=x_i | Y=y_j]$, $p_{ij} = q_j p_{ij} = p_i p_{ji}$.

The mutual information between two discrete random variables X and Y is defined as:

$$I(X, Y) = H(X) - H(X | Y). \quad (6)$$

The mutual information represents the amount of information that one random variable gives about the other random variable. $I(X, Y)$ is a measure of the shared information between X and Y .

Normalized mutual information [6] is defined as:

$$NI(X, Y) = \frac{H(X) + H(Y)}{H(X, Y)}. \quad (7)$$

In communication theory mutual information $I(X, Y)$ is only used to measure signal similarity, and not to optimize it.

If we treat image datasets as random variables, we can calculate for them any measures defined above and apply statistical techniques in image processing. It can be shown, that when two images are properly matched, their mutual information is maximal [7]. Then it can be successfully used as a similarity measure for registration.

5. OPTIMISATION METHODS

The optimisation is an iterative process of searching for a global optimum (minimum or maximum, depending of a convention) of the optimisation criterion (similarity measure) in order to find the optimal transformation parameters. The main problems are computational complexity and occurrence of local extrema.

There is a great number of standard optimization techniques that may be applied. A survey of the most commonly used can be found in [2]. The Powell's algorithm is probably the most popular one [3]. Despite its simplicity in case of typical images in our experiments it led to correct solutions. More refined methods (Davidon-Fletcher-Powell, Levenberg-Marquardt, etc.) usually require not only evaluations of the function to be minimized, but also the derivatives of that function, which may be a non trivial task.

Non-deterministic methods (e.g. simulated annealing) have proven to be successful in many real-world tasks. The problem of finding global extrema in the presence of a large number of local extrema is directly addressed, but typically they require significantly more computing time.

A multi-scale approach is a frequent addition to any technique, to speed up the convergence, reduce the number of iterations and to avoid local extrema. We start with low resolution images and gradually increase the resolutions, obtaining more and more accurate solutions.

Another possibility is a template-matching approach. The global optimisation does not use entire images, but only some highly detailed and unique subvolumes (templates).

6. SOFTWARE TOOLS

The whole code has been written in C++ language. The GUI consists of a collection of Qt-3.0.x library widgets [4]. Thanks to this it is a cross-platform software. Currently it is running on a PC (RedHat Linux 7.x) and a SGI O2 workstation. It can be also compiled for any MS-Windows (using MS Visual C++ environment), Unix/X11 (Irix, Sun Solaris, HP-UX, Digital Unix, IBM AIX) or Mac OS X operating system.

7. MRI AND PET ALIGNMENT

PET (positron emission tomography) is a functional modality (depicting information on the metabolism of the underlying anatomy). It is hardly useful without information provided by anatomical modalities (like MRI or CT).

Fig. 2., 3. show MR and PET images, and their registration example. The main registration problem is the occurrence of local extrema of the similarity measure. Some potential places where the optimisation procedure may get stuck are visible in fig. 4.

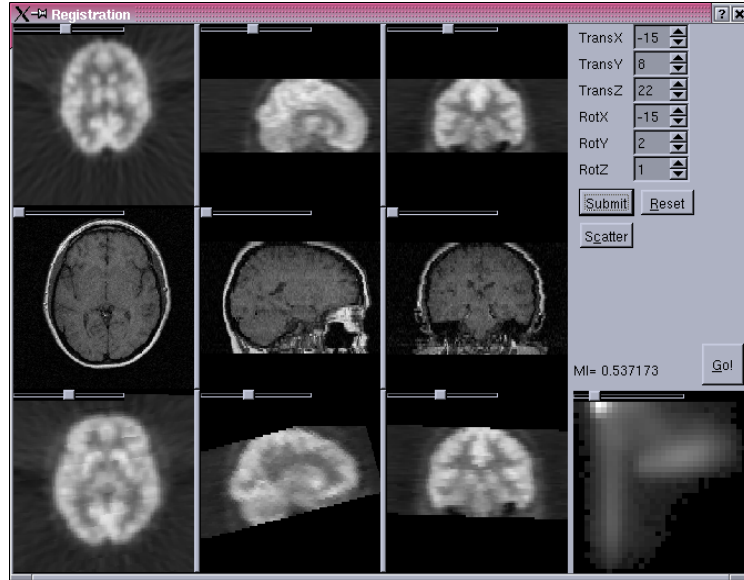


Fig.2. MR and PET registration

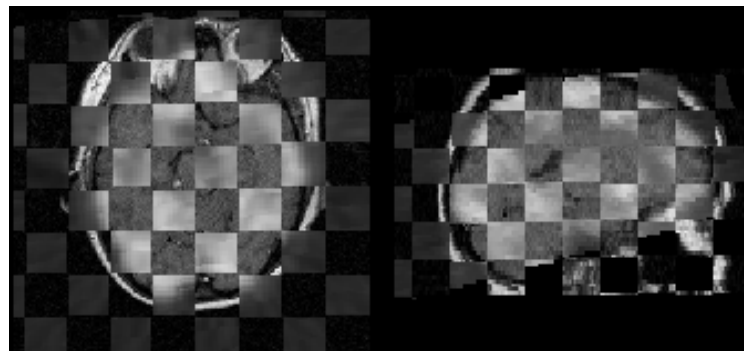


Fig.3. MR and PET registration – a checkerboard test

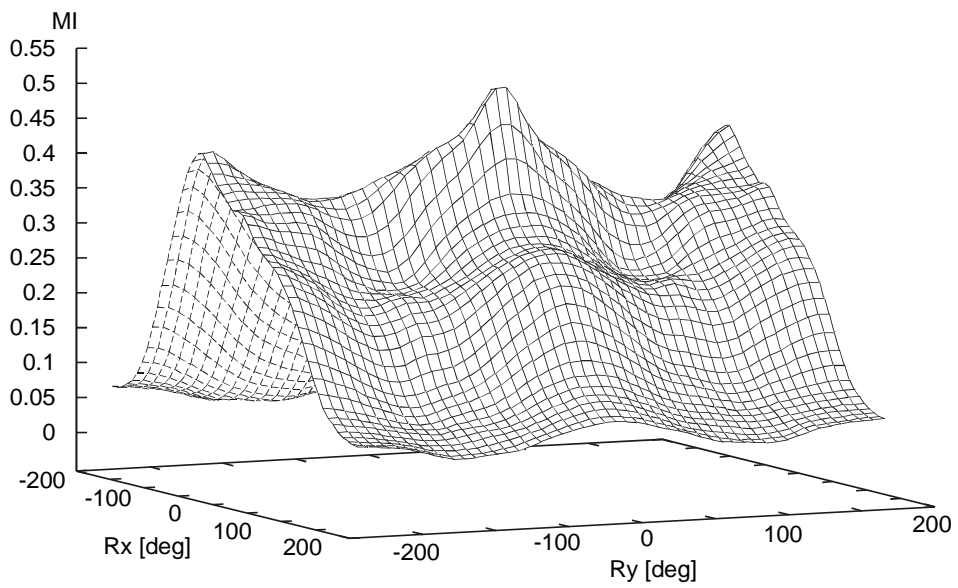


Fig.4. Mutual information as a function of R_x and R_y , while the other parameters are set at the optimum

8. MRI AND CT ALIGNMENT

In brain imaging it is common to acquire both MRI and CT scans. CT provides accurate anatomical information, especially about bones. Voxel intensities are proportional to the radiation absorption of the underlying tissues, which is useful in radiation therapy planning. MRI is less accurate, but soft tissues (including tumours) are delineated much better.

The registration result has been shown in fig. 7. Fig. 5., 6. show 2-D histograms of MR and CT images, before and after the registration process.

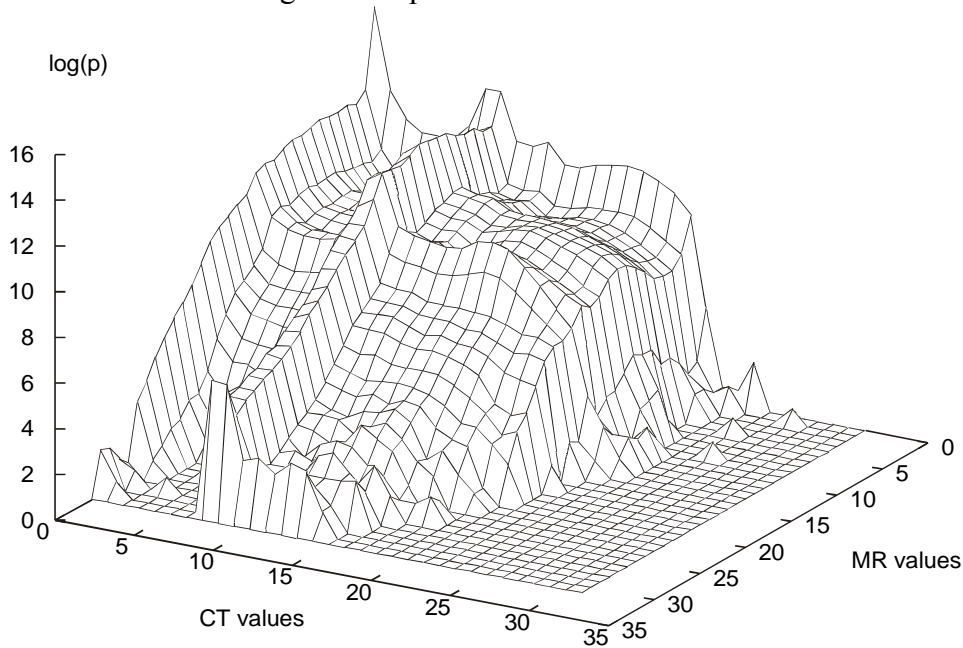


Fig.5. 2-D histogram for unregistered images ($I=0.20$)

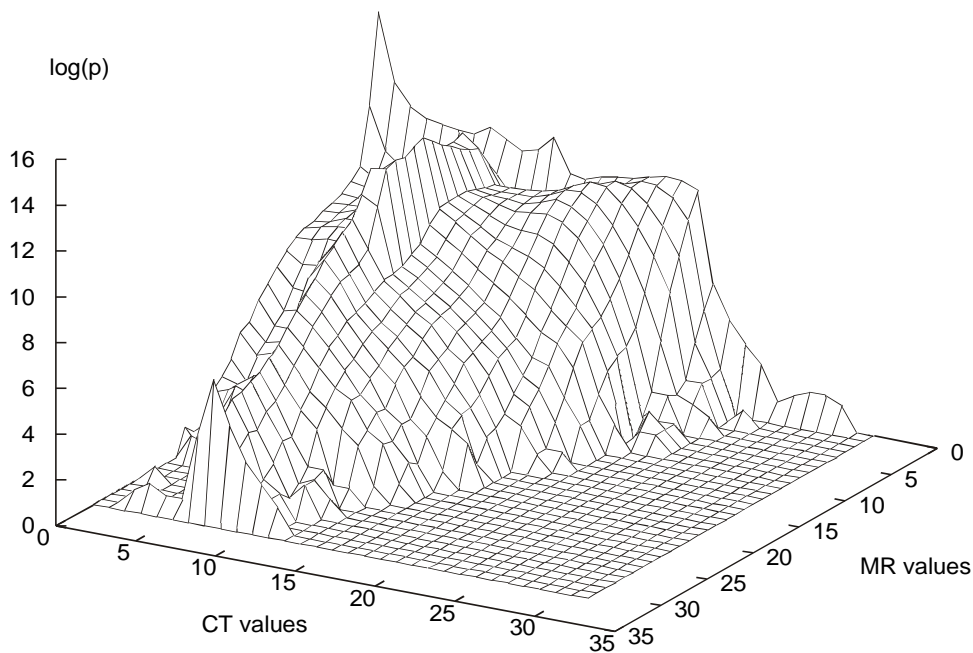


Fig.6. 2-D histogram after registration ($I=0.63$)



Fig.7. MR and CT registration

9. CONCLUSIONS

In modern, less and less invasive clinical treatment routines, that rely mainly on image data (like radiotherapy) there is a great demand for advanced imaging techniques. The future of registration will most likely include highly automated voxel-based techniques. However, the problem of finding a sufficiently accurate global optimum of the similarity measure within reasonable time is still difficult to accomplish.

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