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A Review of Methods for 2D/3D Registration

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Abstract**—**2D/3D registration is a special case of medical image registration which is of particular interest to surgeons. Applications of 2D/3D registration are [1] radiotherapy planning and treatment verification, spinal surgery, hip replacement, neurointerventions and aortic stenting. The purpose of this paper is to provide a literature review of the main methods for image registration for the 2D/3D case. At the end of the paper an algorithm is proposed for 2D/3D registration based on the Chebyssev polynomials iteration loop.

Keywords**—**Medical image registration, review, 2D/3D

I. Introduction

2D-3D registration 2D/3D registration is a special case of medical image registration which is of particular interest to surgeons. According to [1] "the 2-D–3-D registration can be a means to non-invasively register the patient to an image volume used for image-guided navigation by finding the best match between one or more intra-operative X-ray projections of the patient and the preoperative 3-D volume". Applications of 2D/3D registration are [1] radiotherapy planning and treatment verification, spinal surgery, hip replacement, neurointerventions and aortic stenting.

With the help of 2d-3d registration methods surgical robots may be programmed using a pre-surgical 3D dataset and a set of intraoperative fluoroscopic X-ray images. In this way, there is no need for fiducial markers.Gueziec et al [2] use such an approach for CT-X-ray registration with the use of the bony anatomy for robot navigation. Specific applications for spinal surgery are presented by Kraats et al [1], Tomasevic et al [3], Penney et al [4], Russakov et al [5],]. . They use vertebrae bodies, spine segments or spine phantoms and register CT/MR volumes to intra-operative X-Ray images.

In a neuroradiological context Vermandel et al [6] present a method for 2D/3D medical image registration which facilitates the use of Digital Subtraction Angiography (DSA) images for treatment and diagnosis. They report that their method can be used during the treatment of Aneurysms.

Aneurysms, after their initial treatment have to be followed up for several years with the use of Magnetic Resonance Angiography(MRA)/DSA images. The matching procedure is usually "mental" but an automatic 2D/3D registration method would facilitate the matching and give a "more objective and more accurate monitoring of the pathology". A similar imaging procedure with the use of MRA/DSA images is followed for the treatment planning of arteriovenous malformations. These images are obtained with a stereotactic frame. According to [6] 2D/3D registration could "enable to avoid the stereotactic X-ray examination by using the first DSA examination obtained during the diagnosis step". A similar application of 2D/3D registration is presented by Byrne et al[7]. The only difference is that they register 3D DSA with 2D DSA images.

In a radiological context, Baert et al [8] use 2D/3D registration methods for guide wire display in endovascular interventions. They report that "during endovascular interventions, it is important for the radiologist to accurately know the 3D position of the guide wire at any time during the procedure". The problem they try to solve with the 2D/3D registration method is the establishment of the position of the guide wire relative to the 3D imaging system. They try two approaches in order to meet this goal. In both approaches they use a pre calibrated motorized X-ray angiography system to get a 3D reconstruction of the vasculature immediately prior to the intervention. The guide wire is tracked in the biplanar fluoroscopic images and its position is reconstructed in 3D. The main difficulty is that "in order to produce a 3D reconstruction of the guide wire and relate it to the 3D coordinate system of the 3D vascular data, accurate knowledge of the C-armgeometry is required". In the first approach the system geometry is estimated in a precalibration step that only has to be carried out once. The disadvantage of the method is that "to maintain the relation between the 3D vascular data and the projection images, the patient should be stabilized or tracked during the intervention." In the second approach 2D/3D registration methods are used to relate the 3D vascular data to projection images. This is called imagebased calibration. A similar type of application in neurosurgery is presented by Mc Laughlin et al [9] and Masutany et al.[10].

According to [9] "the registration of 2D-3D data sets is important in minimally invasive neurointerventions, such as the coiling of brain aneurysms or glueing of arteriovenousmalformations (AVM)". During such interventions a catheter is guided through the brain vasculature using 2D X-ray images. In order to navigate and position the catheter accurately a pre-operative MRA 3D scan is registered to the 2D X-ray images. Various methods for 2D/3D medical image registration exist. According to Kraats et al [1] they can be divided into feature based, signal intensity based, gradient based and hybrid. In the following parts of this reports the main characteristics of these method categories will be presented. The results presented usually estimate the accuracy of the registration methods by comparing it with a gold standard

II. 2D/3D Registration Method Categories

A. 2D/3D registration using signal intensities

Intensity based techniques use the values of pixels or voxels to register images. They usually use a metric computed from pixel/voxel values and they try to maximize/minimize this metric in order to achieve registration. The metrics developed and tested for 2D/3D registration are similar to the ones used in 3D/3D registration.

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The main metrics used are[11]:

- Cross Correlation
- Entropy
- Mutual Information
- Pattern Intensity

There are also gradient based methods that use signal intensities but they will be presented in the gradient methods part.

In order to register 3D volumes to radiographs [11] the signal intensity methods create Digitally Reconstructed Radiographs (DRRs). The DRRs are created by integrating the voxel values of the 3D volume along simulated casting rays from the source and by projecting these values onto the imaging plane. The result is an image which simulates a radiograph. More extended analysis of the production of DRRs is presented in [12]. The DRR is then used in conjunction with the Xray image for the computation of the registration metric. Depending on the registration method this metric is then maximized/minimized using various numerical analysis techniques.

The most characteristic representative [13] of signal intensity methods in image registration is Normalized Cross Correlation. The main drawback of the Cross-Correlation is that it is heavily dependent on the signal intensity. As reported in [11] "a few large differences in intensity (such as may be caused by an interventional guidewire) can hace substantial effect on the similarity measure". Other drawbacks are[13]:

- Cross-Correlation like methods are difficult to maximize due to the flatness of the similarity measure maxima.
- They have high computational complexity.

Advantage of the method is that it has easy hardware implementation which makes it suitable for real-time applications. The Entropy measure is coming from the theory of information and for

2D/3D registration it operates [11,12] on the difference image which is created by subtracting the DRR from the fluoroscopy image . A suitable

scaling factor s needs to be applied prior to the subtraction. Because of the use of histograms the same weight is given to all pixels. This makes the method more robust in the case a guide wire is used when a small number of pixels have large singal intensity differences[11]. Another significant measure which comes from the information theory is the Mutual Information (MI) measure. According to Zitova et al [13] the group of MI methods represent the leading technique for 3D/3D multimodal registration. Penney et al [11] report that it has been found to be very effective for 3D MR/PET and MR/CT registration.

For the computation of MI the joint histogram has to be computed. Maximizing the mutual information is equivalent to minimizing the spreading of the joint histogram. This is described in [11] as "Mutual information does not assume a linear relationship between the pixel values of the two images, but instead assumes that the cooccurrence of the most probable values in the two images is maximized at registration". This property is extremely useful for multimodal 3D/3D registration. In 2D/3D registration one of the two images is the DRR which is created to resemble the fluoroscopy image and therefore a near-linear relationship between the two images exists (similar to one-modality registration).

Another signal intensity measure introduced by WEESE et al [14] is the Pattern Intensity measure. It operates on the difference image which was introduced in the description of

the Entropy method. When the images are registered [11] the there will be a minimum number of structures (like vertebrae) in the difference image. According to the Pattern Intensity method[11] "a pixel belongs to a structure if it has a significantly different intensity value from its neighboring pixels". The neighboring pixels are within a radius r.

Penney et al.[11] have compared the above signal intensity measures using a spine phantom and have come to the following conclusions:

- Correlation measures can be affected by thin line structures, such as an interventional stent, which introduces pixels that have a large difference in intensity.
- Entropy-type measures are insensitive to thin line structures, but fail when soft-tissue structures create slowly varying changes in background intensity.
- Pattern intensity accounts for thin line structures by having a factor $1/(1+x2\ )$ and for soft tissue structures using a region r within which there is little variation in tissue intensity and works successfully in both cases.

B. 2D/3D Registration Using Gradients

Gradient based techniques exploit the relationship between the gradients in

CT or MR and X-Ray images. The main methods which belong in this category are those in [15] and [3].

The method of Livyatan et al [15] has the following characteristics:

- They developed an algorithm for preoperative CT to intraoperative fluoroscopic X-Ray image registration.
- It uses a hierarchy of 3 steps to bring the data progressively closer:

landmark point-based registration, geometry (surface) based registration which registers the CT bone surface mesh with the bone contours on the X-Ray image and Gradient Projection Registration which maximizes the sum of 3D gradient magnitudes which are incident on the rays from the source to the X-Ray contours which are tangent to the 3D surface.

- Landmark point-based registration is used for initial pose estimate. It

brings the images within 10-20mm and 5-15degs of the final pose

- The last step Gradient Projection Registration refines the geometry based registration result and it achieves good accuracy even in the presence of foreign objects and other anatomical structures. It does not rely on the accuracy of segmentation as rely geometry-based approaches and is more efficient than intensity-based registration although it has a narrow convergence range.

- The experimental results show a mean error of 1-1.5mm within 60sec

95% of the time.

A similar method is presented by Tomazevic et al [3]. It has the following characteristics:

- The bone surfaces are preoperatively defined in MR and CT volumes.
- The normals to these surfaces are computed.
- The gradients of the intraoperative X-ray images at locations defined by the X-Ray source and the 3D surface points are computed.
- These gradients are back-projected and the best match between the surface normals and the back-projected gradients is computed.
- Errors are below 0.5mm for CT-X-Ray registration and 1.5 mm for MR to X-Ray registration.
- Compared to intensity based methods the method is fast.
- Compared to geometry based methods the method needs no intraoperative segmentation.

An intermediate step between the above two methods and the intensity based methods is the Gradient Correlation method presented by PENNEY et al.[4] In this method the Digitally Reconstructed Radiograph is used and instead to applying the Correlation based registration to the signal intensities intermediate images with gradients are correlated and matched. According to Penney et al [4] :

- Gradient measures have the advantage that they filter out low spatial frequency differences between the images, such as those caused by soft tissue.
- They concentrate the contributions to the similarity measure on edge information, which intuitively appears sensible.
- Because this measure uses cross correlation, it is expected to be effected by a few large differences in intensity. In particular, the presence of interventional instruments in the fluoroscopy image may effect the performance of this measure.

C. 2D-3D Registration Using Feature Based Methods

The feature based (or else geometry based) methods rely [13] on the extraction of salient structures (features) in the images. Examples of features are significant regions, lines, curves, points. The features must have the following characteristics[13]:

- They should be distinct spread all over the image and efficiently detectable in both images.
- They are expected to be stable in time to stay at fixed positions during

the whole experiment.

- The number of common elements of the detected sets of features should be sufficiently high, regardless of the change of image geometry, radiometric conditions, presence of additive noise and of changes in the scanned scene.
- Feature-based methods do not work with signal intensities directly but

rather represent information on higher level. According to Zitova et al [13] this makes these methods suitable for situations when illuminationchanges are expected or multisensor analysis is demanded. On the other hand usually their accuracy relies on the quality of the segmentation of the features step.

- Usually the minimization step is performed with the Iterative Closest Point [16,17] algorithm.
- Feature based techniques are faster than intensity based methods and are suitable for real time applications.

Feature based techniques are presented in [16],[17],[18] and [2].

D.2D-3D registration using hybrid methods

Hybrid techniques combine feature based and signal intensity methods in order to achieve better accuracy than feature based methods and better speed than signal intensity methods. Such a method is presented in [6].

III. Algorithm for 2D-3D registration

For 2d/3d registration the following algorithm is proposed:

- The surface points of the preoperative 3D volume are segmented and projected onto the fluoroscopic plane.
- The vertebrae areas of the X ray images are also segmented.
- The projected points are matched to the 2d areas iteratively using the Chebyshev polynomial based iteration loop.

For the projection the following theorem from [19] has to be used:

“ The projection with homogeneous viewpoint V and viewplane with plane vector n is the 3D transformation given by the matrix M=nT V-(n.V)I4”

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