Robust feature-based image registration using modified Hausdorff distance measure with the evolving quantile rank[1)2)]

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Abstract:

The vital problem of analysing incomplete and partially erroneous data in image registration is solved with the use of the robust dissimilarity measure based on the Hausdorff distance, with the quantile rank evolving during the dissimilarity minimisation. The rank changes up and down to push the optimisation process out from local minima. The results for the last used values are presented to the user to let the human decide on the best registration result. The method is applied to quality assessment of oncological radiotherapy.

1 Introduction

Image registration methods can be used to find correspondence between images having partial similarity. The similarity stem from that in both images the same or similar objects are visualised, and its partiality can be the result of many factors, like the different imaging method, different time, viewing conditions etc.

A good example can be the precise overlaying of the details present in a pair of aerial photographs, where the fragments of both images contain the same physical objects. In this paper another challenging application is considered. It is related to radiotherapy of cancer with the use of external beams. To assess the quality of each session of the radiation therapy it is necessary to measure the precision with which the geometry of the treatment conforms to the planned geometry of the system, formed by the relevant part of the patient's body, the beam of the therapeutical radiation and the shields.

[1)] F. Leberl and A. Ferko, editors. *Proc. East-West Vision EWV'02. Int. Workshop and Project Festival on Computer Vision, Computer Graphics and New Media*, pages 23–28, Graz, Austria, Sept 12-13, 2002. Austrian Computer Society.

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The actual geometry in a specified therapeutical session is recorded in the *portal image*. The planned geometry is recorded in the *simulation image*, normally made before the therapy. The simulation image should be registered with each of the portal images, made during each of the therapeutical sessions. The simulation image is an X-ray of high quality. The portal image is produced by the therapeutical beam of the ionising radiation, and is of low contrast due to that tissues with different density attenuate the radiation very similarly.

Automation of registering the simulation and portal images, with edges used as the matched features, has been attempted, as for example in [5, 6, 7, 8]. Algorithms in which landmarks to be matched should be shown manually were also quite recently used [2]. The literature on image registration in general is extremely broad. The surveys can be found in [1, 10, 13].

2 The problem

In image registration the vital problem is to cope with incomplete and partly erroneous data. Let us state the registration problem as follows. Let $\tilde{B}$ be the base image, with a set of pixels B marked, $B \subset \tilde{B}$. The *majority* of these pixels indicate some important features of $\tilde{B}$, like, for example, edges of an object. Let $\tilde{O}$ be the overlaid image, with a set O of pixels marked, $O \subset \tilde{O}$. In the image $\tilde{O}$, *approximately* the same objects as in $\tilde{B}$ are visualised. As before, the *majority* of O indicate the same important features of $\tilde{O}$, as B of $\tilde{B}$. In consequence, there are pixels in O which have their counterparts in B. Let us call them the *coinciding* pixels. There are also such pixels in O as well as in B, which have no counterparts. When the images $\tilde{B}$ and $\tilde{O}$ are registered, the coinciding pixels overlap with their counterparts. But before the registration is carried out, the question which pixels of B and O are coinciding, and hence, should be used as correct data in the registration process, is open. Moreover, it would be even more difficult to show explicit correspondences between the specific pixel pairs in the base and overlaid image.

3 The proposed solution

The proposed image registration method solves this problem in a relatively simple way. The similarity function using the modified Hausdorff distance measure according to [12] is used. Let $d(o,b)$ be the Euclidean distance between any two pixels $o \in O$ and $b \in B$. The partial Hausdorff distance is

$$H^r(O,B) = Q^r_{o \in O} \min_{b \in B} d(o,b) \ , \qquad (1)$$

where $Q^r_{x \in X} g(x)$ is the *quantile* of rank r, $r \in \langle 0,1 \rangle$, of the variable $g(x)$ over the set X. In the considered application, B and O are the sets of edge pixels in the simulation and the portal image, respectively. The Hausdorff distance is actually the *dissimilarity measure*, and should be minimised.

For the discrete case, the definition of the quantile is as follows. Let v be a discrete random variable with the probability density $P(v)$. Then,

$$Q^r v = q : P(v \leq q) \geq r \ \wedge \ P(v \geq q) \geq 1 - r \ . \tag{2}$$

For each pixel of the overlaid set $o \in O$ we have one measurement of distance; this should be substituted for v in the above equation, which now is indexed with the pixels of the overlaid set: $v(o) = \min_{b \in B} d(o, b)$. The density $P(v)$ is replaced by the frequency in the set of the minimum distances for all the pixels in O: $\{v(o), o \in O\}$.

The dissimilarity measure has a single parameter – the quantile rank r. In the known applications of the Hausdorff distance measure this parameter was fixed [3, 9, 11]. Here, it will evolve during the process of minimising the dissimilarity. This evolution has two targets: to let the user investigate the whole range of the parameter to choose the best value in the end of the process, and to let the process avoid local minima in the dissimilarity measure.

The rank r is actually the *share* of the *corresponding* pixels in the overlaid set O, or the *inliers*, while the remaining pixels are the *outliers* in O. This share is not known before the registration is done, however. In the literature there are examples of an *a priori* choice of r (see for example [3, 11]), equivalent to the requirement that the *majority* of the results are correct: slightly more than 50%, or 60%. As described in [9], and further developed here, we resign of this arbitrariness. The method for this is presented in the next paragraph.

4 Minimising the dissimilarity measure

The experience of the radiotherapy physicists indicate that as the admissible geometrical transformations the partial affine transformation is sufficient: uniform scaling, displacement and rotation. As the starting point, the mutual position of images in which the edges of the irradiation field are precisely registered is used. This is the first registration. Then, the edges of the anatomical structures are registered, and the edges of the irradiation field move according to the deformation pattern found in this second registration. The difference in the location of the irradiation field in the simulation and the portal image, attained during the second registration, is the sought result of the measurement. At present the quickest descent optimisation in the space of transformations is used to minimise the dissimilarity function.

In general, to find the right value of the quantile rank, or the share of inliers r, the optimisations should be performed for various values of $r \in (0, 1\rangle$, and the best result should be chosen. To avoid this, in the beginning of the optimisation r is set to the "reasonable initial value" $r = \alpha_1 \in (0.5, 1\rangle$ and the minimum is found for this value of r. If the dissimilarity measure is zero (which is very unlikely), the algorithm stops. Otherwise, r is reduced by a small value, say, 0.01, and a new minimum is found. This is iterated until either the dissimilarity or r is

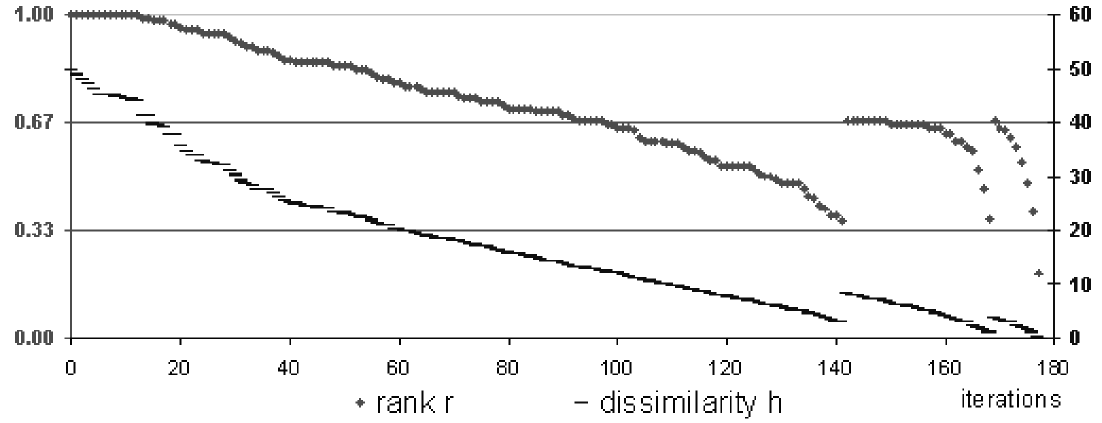


Figure 1: Dissimilarity measure and quantile rank evolution in an example optimisation process.

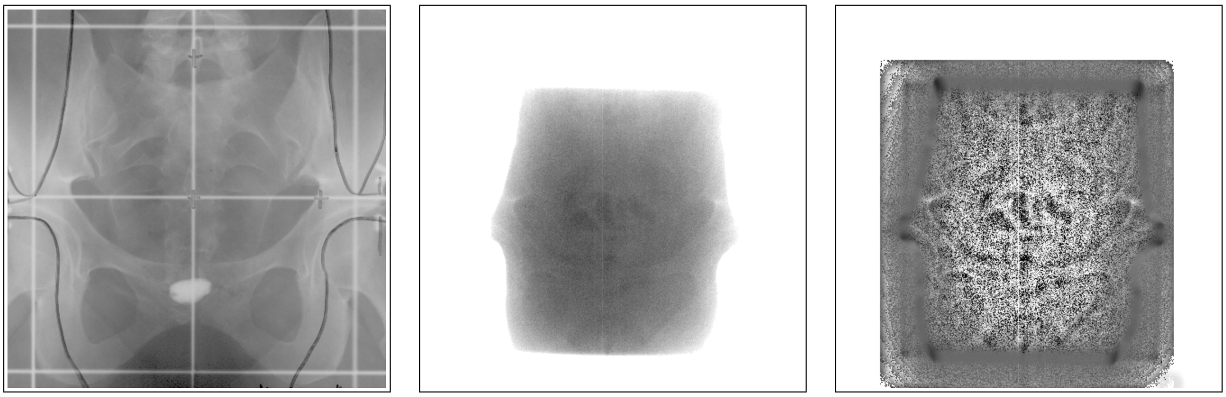
zero, which is the final stop condition. In this way a range of results for various values of r are obtained [9]. The best one is chosen manually by the operator. This is in conformity with the requirement of letting the most important decision be made by the human, not the software.

The dissimilarity function is not convex and the described algorithm can fall into local minima. To make this less likely, the following modification is introduced. As soon as the rank r attains some specified value $\alpha_2 < \alpha_1$, it is set to a larger value $\alpha_3 \in (\alpha_2, \alpha_1\rangle$, and the iterations continue. Hence, r is going down from $r = \alpha_3$ to α_2 several times. When $r = \alpha_2$, then a condition is checked, whether this time an improvement of similarity has been reached w.r.t. the previous time. If not, then the iterations are performed with r going further down, until the final stop condition is reached. If yes, then r is set to α_3 as before and the process goes on. The values currently used for the parameters α are: $\alpha_1 = \alpha_3 = 2/3$, and $\alpha_2 = 1/3$. It must be stressed that finally the user can choose *any* value of $r \in (0, \alpha_1\rangle$, irrespective of the other parameters, having the possibility to directly see the results calculated for all the considered values. In Fig. 1 an example of a graph of the rank evolution and the corresponding dissimilarity measure is shown.

The rationale for the described procedure can be explained as follows. If the current minimum of the dissimilarity function is the global one, then a larger number of matched pixels reach their counterparts, than in the case of a local minimum. Increasing the rank will throw the process out from the "worse" minima more forcefully than from the "good" ones. A correspondence between this simple strategy and the simulated annealing can be noticed, as far as the rank r is considered as the temperature analogon.

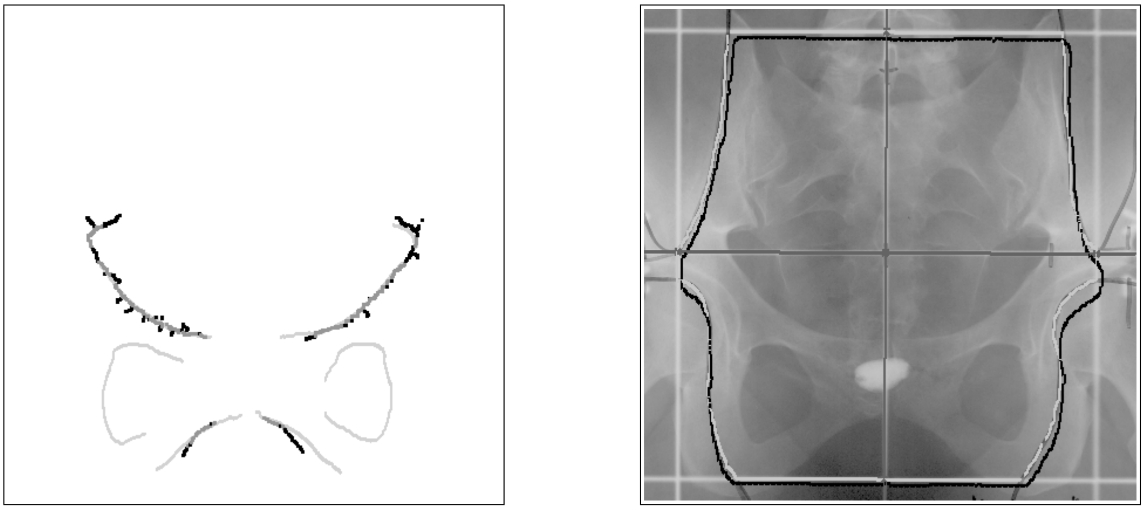
5 Example

The registered images are: the simulation image and the portal image (Fig. 2). The quality of the portal image is low and not much can be done to enhance it (Fig. 2b, c), however,



a b c

Figure 2: A pair of images of pelvis to be registered. a: simulation image; b, c: portal image, enhanced by linear brightness transformation (b) and local adaptive histogram equalisation (c).



a b

Figure 3: Example of the registration. a: edges of the anatomical structures (bright grey: reference edges; dark grey: overlaid edges, inliers; black: overlaid edges, outliers); b: actual irradiation field (black) moved w.r.t. the planned position (grey) by 1.1$*$1.4 mm.

significant edge fragments can be chosen from those found with the zero-second-derivative edge detector. The example of the registration of edges of the anatomical structures are shown in Fig. 3. The found discrepancies between the planned and realised geometry were: 1.1 mm to the right, 1.4 mm down, 0° rotation. The final Hausdorff distance measure was 2 pix $\equiv$ 0.56 mm, at the share $r = 0.59$. The first registration – edges of irradiation fields – was performed in 9 iterations and took 2.5 s, and the second registration – edges of anatomical structures – was performed in 18 iterations and took 4.5 s on a 1000 MHz Pentium III.

The method implemented in the program `AutoPort` has been used in the normal clinical practice at the Holycross Centre of Oncology for over a year now and made the irradiation quality analysis more accurate and more comfortable. The statistical analysis of the results of quality assessment of radiotherapy performed with the described methodology will be published in [4].

6 Conclusion

The modified Hausdorff distance measure with the evolving quantile rank is a good and efficient registration accuracy measure. It has been tested and proved effective in everyday clinical practice of quality assessment of radiotherapy. The possibility of choosing the share of inliers in the data, performed by the user after the calculations are made, is in conformity with the requirement that the human, not the software, should decide in the medical problem.

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