Point-based registration and its error analysis

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Short description: We investigated registration methods based on interactively identified point pairs used in medical image registration. We proposed an affine search method and gave a sufficient existence condition for the unique solution. The properties of rigid-body and affine methods were examined via numerical simulations.

Description:
A general and easily applicable solution for registration problems is selecting points as features. A general point-based method consists of three steps. First, the points are identified, then points in the floating image are corresponded with points in the reference image, finally a spatial mapping is determined. The transformation that aligns the point sets best is then used to align the images.

In our approach we assumed that the identification of points and point correspondence is done interactively by the user. Such a scenario is usual in medical image registration when usually 5-20 point pairs are selected.

We proposed a solution for the affine problem using the partial derivatives of the least-squares cost function. It was shown that if the points selected in the image to be registered span $\mathbb{R}^k$, the solution is unique. [23]. In practical applications it means that in 2D we need at least three non-collinear, in 3D four non-coplanar point pairs. Furthermore, we gave a 3D example illustrating the existence of a degenerated solution.

Since the alignment of the images is indirect when point-based methods are considered, it is important to determine how the identification of point pairs influences the actual registration error. What happens if more and more point pairs are selected? What is the effect of the localization error of the points? What role the orientation and position of the points play? If there are many solutions for a given problem, which should we choose? Which is the faster or more stable in numerical sense?

When examining the error of point-based registration in medical image registration problems, the fiducial (point) localization error (FLE), the fiducial registration error (FRE), and target registration error (TRE) are considered, as proposed by Fitzpatrick et al.

In practical applications only FRE is available for use. FLE and TRE play an important role in the theoretical examination of transform type and search method properties. When an approximation is given to the localization error, it is possible to examine the effect of different parameters using numerical simulations. Many papers from several research groups investigate rigid-body
translations, which is undoubtedly the most popular transformation type. The following important statements were deducted.

- For a given number of point pairs, TRE is proportional to FLE.
- TRE is approximately inversely proportional to the square root of the number of point pairs.
- TRE models the actual registration error more reliably than FRE which can be misleading.

We performed the error analysis of four point-based methods (rigid-body based on SVD, iterative rigid-body, affine, thin-plate spline) using numerical simulations. We determined that the expected target registration error is

- proportional to the fiducial localization error assuming affine motion,
- approximately inversely proportional to the square root of the number of point pairs assuming affine motion,
- inversely proportional to the volume spanned by the points assuming rigid-body and affine motions,
- constant in iso-ellipses around the centroid of the point sets in 2D assuming affine motion,
- and a strategy for determining the number of point pairs to be used and their selecting order was given for a particular registra


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