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Target Registration Error minimization involving deformable organs using elastic body splines and Particle Swarm Optimization approach

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ABSTRACT

In minimally invasive surgery one of the main challenges is the precise location of the target during the intervention. The aim of the study is to present usability of elastic body splines (EBS) to minimize TRE error. The method to find the desired EBS parameters values is presented with usage of Particle Swarm optimization approach. This ability of TRE minimization has been achieved for the respiratory phases corresponding to minimum FRE for abdominal (especially liver) surgery. The proposed methodology was verified during experiments conducted on 21 patients diagnosed with liver tumors. This method has been developed to perform operations in real-time on a standard workstation.

1. Introduction

In minimally invasive surgery one of the main challenges is the precise location of the lesion (target) during the intervention. The solution addressed to overcome this challenge is image-based navigation system, which are widely used for rigid tissue, while application for soft tissues are in the preliminary implementation stage [1–4], because of the major challenge which is precise positioning of the target point during minimally invasive procedures. In the previous works Fitzpatrick proposed target position point estimator [5,6], and then found no statistical correlation between Fiducial Registration Error (*FRE*) and Target Registration Error (*TRE*) [7]. Datteri in Ref. [8] proposed an Assessing Quality Using Image Registration circuits method (*AQUIRC*), which measures the quality of registration correlated with the *TRE*. The algorithm was first presented in Ref. [9] and has been used to estimate the quality of the fit rigid image registration in Ref. [10]. The method is based on the idea of a register, which was presented by Woods [11] and Holden [12]. Fitzpatrick [13] proved that using only one chain of registration may lead to underestimation of errors registration. *AQUIRC* algorithm uses multiple chains, by making modifications to the positions of the markers for the estimated fault FLE and then making the registration between the modified positions markers. Fabian et al. [14] achieved a significantly smaller value of the median *TRE* on the basis of the deformation using splines and a set of sequential positions of surface markers.

The aim of the study is to present usability of elastic body splines (*EBS*) to minimize *TRE* error. The method to find the desired values of *EBS* parameters are presented using Particle Swarm optimization approach. This ability of *TRE* minimization has been achieved for the respiratory phases corresponding to minimum *FRE* for abdominal surgery.

2. Materials and methods

The exact position of the target point during surgery is unknown. In the previous work Fabian et al. proposed the following approach to minimalize *TRE* [14]:

1. Measurement of marker positions on the body surface during the respiratory cycle.
2. Registration of the marker position in the tracking device coordinate system to the CT coordinate system was performed (for a set of accepted transform algorithms such as the rigid or affine transformation) [15].
3. Calculation of *FRE* and waveforms in the respiratory cycle:

$$FRE^2 = \frac{1}{N}\sum_{i=1}^{N}|Rx_i + t - y_i|^2 \quad (1)$$

where: N = number of markers, x_i = i-th marker position in first coordinate system, y_i = i-th marker position in second coordinate system, R = rotation matrix, and t = translation matrix.

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List of abbreviation

AQUIRC	Assessing Quality Using Image Registration circuits
EBS	Elastic Body Spline
TPS	Thin Plate Spline
FLE	Fiducial Localization Error
FRE	Fiducial Registration Error
H_0	null hypothesis
H_1	alternative hypothesis
PSO	Particle Swarm Optimization
$target_{estim}$	the estimated position of the target point
$target_{real}$	the real position of the target point
TRE	Target Registration Error
TRE_{estim}	value of TRE estimator
TRE_{real_EBS}	measured value of TRE using the deformation field based on elastic body spline
TRE_{real_rigid}	measured value of TRE using the rigid transformation registration

4. Determination of the *TRE* estimator TRE_{estim} value [5,6]:

$$\left\langle \mathrm{FRE}^2 \right\rangle = (1 - 2/N)\left\langle \mathrm{FLE}^2 \right\rangle \tag{2}$$

$$< TRE_{estim}^2 > = \frac{1}{N}\left[1 + \left(\frac{d_1^2}{f_1^2} + \frac{d_2^2}{f_2^2} + \frac{d_3^2}{f_3^2} + \right)\bigg/ 3\right]\left\langle \mathrm{FLE}^2 \right\rangle \tag{3}$$

where: N = number of markers, d_k^2 = square of the distance between the target point and the k-th main axis configuration markers, d_1 = distance of a target point on the x-axis, d_2 = distance of a target point on the y-axis, d_3 = distance of a target point on the z-axis, f_k^2 = the mean square distance between the points of markers on the k-th axis, f_1 = the average marker distance on the x-axis, f_2 = the average marker distance on the y-axis, and f_3 = the average marker distance on the z-axis.

5. Calculation of the actual value of error, TRE_{real_rigid}:

$$TRE^2 = |target_{estim} - target_{real}|^2 \tag{4}$$

where: $target_{estim}$ = estimated target position and $target_{real}$ = actual (true) target position.

6. Calculation of the deformation field

The assumption of no change in shape is a simplifying assumption. Therefore, local transformations, or rather combinations thereof, were also applied to the registration based on the collection of points. The transform equation is then shown as in Ref. [16]:

$$F(x) = C^T \cdot G(x) + Rot \cdot x + Trans \tag{5}$$

where: C^T = vector scales, G = basis functions for each point, *Rot* = rotation matrix (containing the scaling factor), *Trans* = translation vector, and *F(x)* = a collection of independent functions of the deformation field at the point x [10]:

$$F(x) = [f_1(x), \ldots, f_{\dim}(x)]^{\mathrm{T}} \tag{6}$$

The most commonly used functions include the base functions for thin plate splines (*TPS*) [17]. These functions take the following form:

$$G(x) = r(x)*I \tag{7}$$

$$r(x) = \sqrt{x_1^2 + x_2^2 + x_3^2} \tag{8}$$

where: r(x) = standard Euclidean distance and I = identity matrix.

Details of the proposed methodology can be found at [14]. As mention above, the experiments was performed using *TPS* basis functions. In this work the *EBS* basis functions are used and the method to find the desired values of *EBS* parameters are presented.

2.1. Elastic body splines

EBS are designed as a physical model of a flexible material intended for uses spatial deformation under the action of a force field. Functions are the solution to the Navier's equation, describing the deformation state of equilibrium of the body trench-treated flexible force field. Davis et al. proposed a different form of *EBS* functions for different force fields [10]. For the purposes of the registration form is most commonly used functions:

$$G(\boldsymbol{x}) = \left[\propto + r(\boldsymbol{x})^2 \cdot I - 3 \cdot \boldsymbol{x} \cdot \boldsymbol{x}'\right] \cdot r(\boldsymbol{x}) \tag{9}$$

where: $\propto = 12(1 - \nu) - 1$, ν = Poisson's ratio and *r(x)* = standard Euclidean distance.

2.2. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a computational method, based on bird and Herring swarm observations, that optimizes a problem iteratively, in each iteration trying to maximize or minimize a candidate solution with regard to a given measure of quality [18]. It searches for best problem solution, by having a population of candidate solutions, here particles which can move in 2 dimensions, and moving these particles in N-dimensional search-space according to mathematical equations over the particle's position and velocity. After each iteration, algorithm searches for the particle with best known solution in the swarm, and that particle is marked as swarm leader. Each particle's movement is affected by its local best known position, but is also guided toward the swarm leader position in the search-space, which is updated after each iteration, as better positions are found by other particles. This is expected to find global minimum or maximum of the search space and move the swarm toward the optimal solutions.

2.3. Method to find the desired values of EBS parameters

EBS are used as basic functions in equation (5). The experiments were performed using default values of *EBS* parameters: $\propto$ equal 8, ν equal 0.25 and stiffness equals 0 and comparing to values founded using *PSO* approach. In the *PSO* approach, dataset consist of available markers' positions recorded for every patient and its markers' configuration during treatments. The dataset has been divided into a training and a test group at a ratio of 50 to 50%. Training set are used to find the values of $\propto$ and stiffness parameters, in the following way. The values of parameters in moments of time corresponding to the minimum *FRE* are averaged for every patient and its markers' configuration independently. Then, those values are used to estimate target position in test group.