Signal Processing ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Robust 3D Point Set Registration Using Iterative Closest Point Algorithm with Bounded Rotation Angle

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ARTICLE INFO

Article history:
Received 11 October 2014
Accepted 28 January 2015

Keywords:
3D registration
Iterative closest point (ICP)
Rotation angle with boundary
Inequality constraint
Closed-form solution.

ABSTRACTS

The iterative closest point (ICP) algorithm is an efficient method to register point sets which may fail as the rotation is various. To improve the robustness of registration and reduce the variety of rotation, the boundary of the rotation angle is introduced into the 3D point set registration problem in this paper, which is described as a least square registration model with inequality constraints. The new problem is solved by a more robust ICP approach with the bounded rotation angle which repeats two steps. Firstly, the correspondence between two point sets is set up according to the known rigid transformation. Secondly, to compute the rotation angle of the objective function with boundary, a closed-form solution of the transformation is obtained according to the monotonic property of the objective function in the given interval. The proposed algorithm is demonstrated to monotonically converge to a local minimum from any given initial value. Therefore, to obtain the desired results, the boundary of rotation angle and initial value are estimated by the principle component analysis. A series of experiments are conducted to demonstrate that the proposed method is much more robust without increasing the computational complexity compared with the state-of-the-art point set registration method.

1. Introduction

Point set registration plays an important role in image processing and pattern recognition, which is a preprocessing step for many applications such as image cropping [1,2] and object recognition[3–5]. To achieve the registration, there are two problems to solve: 1) establish correspondence between two point sets; 2) compute the transformation with which one point set aligns with the other one.

The iterative closest point (ICP) algorithm [6–8] is an efficient and accurate method for rigid registration problem, which has been applied widely, such as 3D reconstruction [9], face registration [10] and fingerprint verification [11]. However, the ICP algorithm greatly depends on the initial value. Therefore, a lot of works have been done to estimate the initial value and improve the robustness of registration. Stewart et al. [12] introduced the bootstrap region which achieved low order estimation accurately to set the initial value. A coarse registration method based on exhaustive search was introduced by Fukai et al. [3] to obtain the initial position for the following fine registration. Salient points were extracted from point sets by Herrmann et al. [13] to give the initial value of the ICP algorithm. Aghili et al. [14] estimated the initial value of ICP based on the state estimation of Kalman filter. Rogers et al. [15] introduced a novel distance metric combining Euclidean, shape context and image-related features to improve the robustness of ICP. The Euclidean invariant

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http://dx.doi.org/10.1016/j.sigpro.2015.01.021

Please cite this article as: C. Zhang, et al., Robust 3D Point Set Registration Using Iterative Closest Point Algorithm with Bounded Rotation Angle, Signal Processing (2015), http://dx.doi.org/10.1016/j.sigpro.2015.01.021

feature was used by Sharp et al. [16] to decrease the probability of being trapped into a local minimum. Silva et al. [17] reduced the influence of initial value and outliers by combining genetic algorithm with a new evaluation metric. Lee et al. [18] proposed a matrix that represented the reliability of rotation component with the surface normal vectors of the point sets. Censi et al. [19] introduced a point-to-line metric to improve the robustness of registration.

Besides of improving the robustness of registration, some other works have been done to decrease the computational complexity. A coarse to fine multi-resolution approach was presented by Jost et al. [20] to speed up the neighbor search. Weise et al. [21] employed three fast registration methods for coarse and fine alignment based on texture and geometry to accelerate the convergence speed. To reduce the computational time for shape matching, Yan et al. [22] applied a new approach to pre-compute the voxel closest neighbors. Kim et al. [23] improved the ICP algorithm by hierarchical model point selection and logarithmic data point search. Fitzgibbon [24] adopted the Levenberg-Marquardt to minimize the registration error. Moreover, the ICP algorithm was extended to the partial registration [25,26] and the non-rigid registration [27–29].

In addition, some other algorithms based on probability model or Kalman filter were proposed to solve the registration problem. The registration problem was treated as a maximum likelihood estimation by Luo et al. [30], which was solved by using the expectation maximization algorithm and singular value decomposition. Myronenko et al. [31] treated this problem as a probability density estimation problem and introduced an algorithm called coherent point drift (CPD). The point set was presented as Gaussian mixture model by Jian et al. [32] and then the registration was solved by minimizing the statistical discrepancy measure between two corresponding mixtures. Moghari [33] employed a unscented Kalman filter to solve the registration problem with Gaussian noise.

However, the shortcoming of these algorithms is that the registration is failed for the variety of rotation angle. To improve the registration robustness, the boundary of the rotation angle is introduced to reduce the variety of rotation in this paper. Firstly, a new registration model with the boundary of the rotation angle is established, and the boundary is estimated by the best aligned principle components which are extracted from two point sets. Secondly, an improved ICP algorithm is proposed to achieve the point set registration. At each iterative step of the proposed algorithm, the correspondence between two point sets is estimated, and then a closed-form solution of the transformation is obtained according to the monotonic property of the objective function in the given interval. The experimental results prove that our approach is robust and fast for 3D rigid point set registration and is capable to overcome the influence of noise and outliers.

The rest of the paper is organized as follows. In Section 2, the point set registration problem and the ICP algorithm are reviewed. In Section 3, a new registration model with bounded rotation angle is proposed. Moreover, a new registration algorithm for 3D point set is proposed. In the following section, the convergence property of the proposed algorithm is analyzed, and a method of boundary estimation is introduced. In Section 5, the experiments are carried out to demonstrate the robustness and efficiency of the proposed algorithm. In the last section, a conclusion is given.

2. Preliminaries

In this section, a least square (LS) problem of point set registration is presented, and then the ICP algorithm is reviewed.

2.1. Point set registration problem

Point set registration is a common task in many research fields, such as shape registration [6,22], object recognition [34,35], 3D scene reconstruction [9] and so on. The aim of registration is to compute the transformation with which two point sets are aligned. A mathematic model based on LS problem is established to describe the registration problem.

Given two point sets in $\mathbb{R}^n$, one is the model point set $M \triangleq \{\vec{m}_i\}, (i=1,\cdots,N_M)$ and the other one is the data point set $D \triangleq \{\vec{d}_j\}, (j=1,\cdots,N_D)$. The registration is to compute a transformation F with which M can best align with D, so it is presented as a LS problem as follows:

$$\min_F \sum_{i=1}^{N_M} ||F(\vec{m}_i) - \vec{d}_{c(i)}||^2 \tag{1}$$

where $F(\vec{m}_i)$ is the transformed model point, and $\vec{d}_{c(i)}$ is the corresponding point in D.

In rigid registration, the transformation F in (1) is expressed as $F(\vec{m}_i) = \mathbf{R}\vec{m}_i + \vec{t}$, where $\mathbf{R} \in \mathbb{R}^{n\times n}$ is a rotation matrix and $\vec{t} \in \mathbb{R}^n$ is a translation vector. Hence, the point set registration problem is formulated as follows:

$$\begin{aligned} \min_{\mathbf{R},\vec{t},c(i)\in\{1,2,\cdots,N_D\}} & \sum_{i=1}^{N_M} ||(\mathbf{R}\vec{m}_i + \vec{t}) - \vec{d}_{c(i)}||^2 \\ s.t. \quad & \mathbf{R}^T\mathbf{R} = I_n, \det(\mathbf{R}) = 1 \end{aligned} \tag{2}$$

2.2. The ICP algorithm

The classical ICP algorithm is widely adopted to deal with the rigid registration problem. There are two main steps of ICP, one is to search the closest points in the data point set for all model points, and the other one is to compute the transformation which aligns the model point set with the data point set. In addition, an initial rotation matrix R_0 and translation vector $\vec{t}_0$ are given before achieving the registration (2), and then the two computation steps can be descripted as follows.

Step 1: search the best corresponding point in D for each point in M according to the known rigid transformation R_k and $\vec{t}_k$:

$$c_{k+1}(i) = \mathop{\arg\min}_{c(i)\in\{1,2,\cdots N_D\}} ||(\mathbf{R}_k\vec{m}_i + \vec{t}_k) - \vec{d}_{c(i)}||^2 \tag{3}$$

Step 2: calculate the new rotation matrix $\mathbf{R}_{k+1}$ and translation vector $\vec{t}_{k+1}$ by the following formulation according to