Available online at www.sciencedirect.com
SCIENCE DIRECT
Robotics and Autonomous Systems 54 (2006) 428–441
Robotics and Autonomous Systems
www.elsevier.com/locate/robot

Projecting registration error for accurate registration of overlapping range images

Yonghuai Liu[a,*], Baogang Wei[b], Longzhuang Li[c], Hong Zhou[a]

[a] Department of Computer Science, The University of Wales, Aberystwyth, Ceredigion SY23 3DB, Wales, UK
[b] College of Computer Science, Zhejiang University, Hangzhou 310027, PR China
[c] Department of Computer Science, Texas A and M University, Corpus Christi, TX 78412, USA

Received 7 June 2004; received in revised form 23 December 2005; accepted 21 February 2006
Available online 29 March 2006

Abstract

In this paper, we propose a novel algorithm for the automatic registration of two overlapping range images. Since it is relatively difficult to compare the registration errors of different point matches, we project them onto a virtual image plane for more accurate comparison using the classical pin-hole perspective projection camera model. While the traditional ICP algorithm is more interested in the points in the second image close to the sphere centred at the transformed point, the novel algorithm is more interested in the points in the second image as collinear as possible to the transformed point. The novel algorithm then extracts useful information from both the registration error and projected error histograms for the elimination of false matches without any feature extraction, image segmentation or the requirement of motion estimation from outliers corrupted data and, thus, has an advantage of easy implementation. A comparative study based on real images captured under typical imaging conditions has shown that the novel algorithm produces good registration results.

Keywords: Automatic registration; Overlapping range image; Registration error; Projected error; Histogram; False matches; ICP

1. Introduction

Recent developments in optics and electronics are enabling direct acquisition of depth information from real world objects or environments of interest in the form of range images using affordable laser range finders (range cameras). The analysis of such range images has wide applications in many areas such as motion estimation, path planning, obstacle avoidance [32], 3D map construction [11], object modelling [10], etc. It is expected that range cameras will be a basic component of a robotic system in future. Due to the camera's limited field of view, the coverage of the whole object surface or environment often requires a number of images to be taken from different viewpoints. These images are depicted in local camera centred coordinate systems. Thus, registration of these images is normally required so that the camera motion parameters can be estimated, leading the robots to be located in a 3D environment and different images to be aligned in a single global coordinate system. The latter is a prerequisite step for the integration of these images, resulting in the construction of full 3D models without redundant data of the object or environment of interest necessary for path planning in the process of robot autonomous navigation. In this paper, we limit our attention to the automatic and efficient registration of overlapping range images which is still an open question due to interdependence between the establishment of possible point matches and the camera motion estimation from these point matches.

1.1. Related work

Many methods have been proposed to solve the difficult automatic and efficient registration problem, such as techniques based on scatter matrix [13], iterative closest point (ICP) [2,5,37], reverse calibration [3], interactive method [34], geometric histogram [1], softassign [6] and genetic algorithm [21,30], among many others. In particular, the intuitive and practical idea implemented by the ICP algorithm has attracted much attention from the machine vision community since it was

* Corresponding author. Tel.: +44 1970 621688; fax: +44 1970 628536.
E-mail address: yyl@aber.ac.uk (Y. Liu).

0921-8890/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.robot.2006.02.008

Table 1
Examples of techniques used to improve the standard ICP algorithm

Aspect	Proposed techniques
Initialisation	Bitangent points based distance matching [8] Bitangent curve matching [35] Surface signature matching [36] Spin image matching [11,4]
Distance measurement	Point to triangular mesh [33] Colour [12] Normal vector [8] Invariants [27,28] Curvature weighted distance [31]
Closest point search	Constrained nearest point [33] K-D tree [12] Grid closest point [36]
False matches	Discarding boundary points [33] Threshold [12] Normal vectors [23] Point-to-point distance consistency [7] Orientation consistency [37] Correspondence vectors [17,15] Reflected correspondence vectors [16,24]
Motion estimation	Simulated annealing [22] Weighted LS [33] Extended Kalman Filter [8]

independently proposed in 1992 by several researchers [2,5,37]. Since then, a large number of techniques have been proposed to improve the traditional ICP algorithm. These techniques are summarised in Table 1.

An overall analysis of these techniques reveals that (1) most of them are based on invariant features such as interpoint distances, bitangent points, bitangent curves, surface signatures, spin images, and invariant features, which are described in a single coordinate frame, and (2) some of them require the motion parameter estimation from possible point matches based on the geometric properties of correspondence vectors or reflected correspondence vectors. However, neither the extraction of such invariant features nor the motion estimation from the correspondence data corrupted by outliers is an easy task in the machine vision community.

1.2. Our work

Range image registration directly determines the accuracy of the camera motion parameters estimated and the 3D model reconstructed. The traditional closest point criterion [2,5,37] is so natural and effective in practice for the registration of overlapping range images that it has attracted a great deal of effort to improve it (Table 1) and it has actually become a *de facto* standard approach for image registration. However, it introduces false matches in almost every iteration of the algorithm due to a number of reasons to be discussed in Section 2. While false matches often lead iterative registration algorithms either to converge prematurely or to oscillate without convergence [20], relatively accurate point matches generally result in accurate camera motion estimation. Thus, the key problem for a successful application of the closest point criterion to image registration lies in accurate evaluation of the possible point matches established. To this end, while it is relatively difficult to compare the registration errors of different point matches, we propose to project the registration error vectors onto a virtual image plane so that it provides a uniform reference for the characterization of the quality of different point matches, leading them to be more accurately evaluated, yielding thus more accurate registration results.

Intuitively, the same error may be acceptable with regard to visualisation for distant point matches, but not for nearby ones. The same inaccurate camera motion parameters thus have various impacts on point matches with different locations. To compare different point matches fairly, we project them onto a single virtual image plane using the classical pin-hole perspective projection camera model. Consequently, projected errors provide a novel measure for comparing different possible point matches. Minimising the projected errors is equivalent to enforcing a constraint that real point matches must be collinear. This constraint is justified by the assumption that the scanning error occurs mainly *along* the ray shooting from the range camera [26]. Thus, while the traditional ICP algorithm is more interested in the points in the second image close to the sphere centered at the transformed point, the novel algorithm is more interested in the points in the second image as collinear as possible to the transformed point. Then we extract useful information from the histograms of both the registration and projected errors for the evaluation of the possible point matches established by the traditional ICP criterion. Since the construction of histograms is often robust to occlusion and noise [1], it is widely used for object recognition and surface matching. A geometric histogram was used in [1] to encode the perpendicular distance between two facets and the including angle between the normal vectors of these two facets. A histogram was used to construct spin images in [4, 11] that encode the distances between two points $\mathbf{p}_1$ and $\mathbf{p}_2$ perpendicular to and along the normal vector at the point $\mathbf{p}_2$. A histogram of surface orientation variation lengths was used to represent the overall appearance of partial views for object recognition [14].

For a better understanding of performance of the proposed algorithm, the Geometric ICP algorithm (GICP) [16] was also implemented and applied to real images. The GICP algorithm is actually based on statistics. To estimate some motion parameters of interest from outliers' corrupted point matches, the Monte Carlo resampling scheme is first employed. The resulting candidates to the parameters of interest are secondly synthesized using the medial filter. Once the motion parameters of interest have been estimated, the relative quality of possible point matches is thirdly measured. Finally the point matches whose relative qualities are larger than a multiple κ of standard deviation from the mean quality over all possible point matches are regarded as false ones. While the proposed algorithm applies histograms to eliminate false matches, the GICP algorithm employs statistics for the same purpose. Such a comparative study is thus valuable since it can reveal which strategy is more effective for the elimination of false matches