Multi-Feature Matching Algorithm for Free-Form 3D Surface Registration

C. Schütz, T. Jost, H. Hügli
Institute for Microtechnology, Neuchatel, Switzerland
christian.schutz@imt.unine.ch

Abstract

Applications such as object digitizing, object recognition and object inspection need efficient surface matching algorithms. Several variants of an iterative closest point (ICP) matching algorithm have been proposed for such tasks. This paper proposes and analyzes a multi-feature ICP matching algorithm that includes the surface color and the surface orientation information. The matching error minimization keeps the original closed-form solution. Therefore, the convergence of the multi-feature ICP algorithm cannot be proven anymore. However, experiments show successful convergence. Further experimental results applying the multi-feature ICP to free-form objects show a significant increase of the range of successful convergence range.

1. Introduction

Several applications such as object digitizing, object inspection and object recognition need computer vision tools to match different object surfaces. Different algorithms have been proposed to perform the surface matching at a geometric level. One of the best known is an iterative closest point (ICP) algorithm introduced by Besl [1]. Basically, it consists of a closest point search and a matching error minimization which are applied iteratively to the two surfaces to be matched.

The original ICP algorithm couples every point on one surface with the one having the smallest geometric distance on the other surface. In order to register the surfaces the mean square distance of these couplings is then minimized using a closed-form solution. Successful convergence depends a lot on the point correspondences established in the closest point search.

The geometric distance is not always sufficient to obtain successful convergence for the ICP algorithm. For example, it may fail for objects like a ball or a cylinder where two views of such an object do not differ in shape and therefore no unique matching solution exists.

This paper presents a multi-feature ICP algorithm which integrates geometry, color and surface orientation to establish couplings of corresponding points. The purpose is to escape ambiguous cases where the surface geometry is not sufficient for a successful matching assuming however the object surface is of varying color or orientation.

The next sections present the integration of the different features in a total coupling distance and discuss the convergence of the multi-feature ICP algorithm. Finally, several experiments evaluate the quality of the matching

2. Multi feature surface registration

2.1 Standard ICP matching algorithm

The ICP algorithm registers two surfaces referred as P and X. It proceeds iteratively. First, it pairs every point on P with the point on X that has the smallest coupling distance. These couplings are used to calculate the rigid transformation ($\mathbf{R}$, $\mathbf{t}$), which minimizes the matching error. The surface P is then translated and rotated by the resulting transformation and the algorithm starts again with the coupling. The ICP algorithm has been shown to converge but not necessarily towards the optimal solution [1].

2.2 Multiple features in the closest point search

The coupling of corresponding points of two surfaces is a key operation in the ICP algorithm. Wrong or bad conditioned couplings prevent it from successful matching. In the original ICP algorithm. the couplings are established by assigning to a point $\mathbf{g}_p$ of P the point $\mathbf{g}_x$ of X with the smallest geometric distance (distance of Cartesian point coordinates).

$$d_g = \left\| \mathbf{g}_p - \mathbf{g}_x \right\|^2 \qquad (1)$$

The following sections propose the use of surface color and orientation to improve the surface coupling.

Surface color. For some objects the surface geometry information is not sufficient to locate corresponding regions and to obtain a correct matching. If the object surface is of varying color, this information allows to find better couplings as shown in [3] [5] [6]. The color feature vector $\mathbf{c}$ contains the red, green and blue color space components. The color distance is defined by

$$d_c = \left\| \mathbf{c}_p - \mathbf{c}_x \right\|^2 \qquad (2)$$

Since modern 3D scanners allow to acquire surface geometry registered with the corresponding surface color, the color feature is available for every surface point.

Surface orientation. Several authors proposed to use the surface orientation to improve the ICP matching [2] [7]. Sometimes, surface points may be close in geometric distance but not correspond since they represent the object surface from a different points of view. The surface orientation allows to exclude such bad couplings. It is represented by the surface normal vector **n** and can be easily integrated in the closest point search as the vector difference reflects the difference in surface orientation if the vector lengths are normalized. Therefore, the difference in orientation is defined by

$$d_n = \left\| \mathbf{n}_p - \mathbf{n}_x \right\|^2 \tag{3}$$

Feature normalization. The different feature distances are added to a total coupling distance d_m. The color and normal features have different value ranges compared to the geometric distance. Therefore, the different feature distances have first to be normalized before they can be added to the total coupling distance. Otherwise one feature may dominate the other in the closest point search. This leads to the following total coupling distance

$$d_m = \frac{d_g}{\alpha_g} + \frac{d_n}{\alpha_n} + \frac{d_c}{\alpha_c} \tag{4}$$

For every feature a corresponding normalization factor α_g, α_n and α_c is defined empirically. Now points of P are coupled with points of X having the smallest total coupling distance d_m.

2.3 Convergence of multi-feature ICP algorithm

Besl proofed the convergence of the original ICP algorithm where both the coupling distance and the matching error correspond to the geometric distance d_g.

Since the color information of a surface point is not affected by the calculated transformation (**R**, **t**) there is no need to include it into the matching error minimization.

This is obviously not the case for the surface orientation feature because the normal vectors are changed by the rotation matrix **R**. In order to minimize the matching error including the normal and the geometric feature, iterative methods as for example extended Kalman filtering have to be applied [2].

This work considers a multi-feature ICP algorithm where d_m is used for the point coupling and d_g to calculate the optimal rigid transformation. This allows the use of a closed-form solution to minimize the matching error.

3. Results

This section introduces SIC-maps and then uses them to compare the quality of convergence for different coupling features.

3.1 Range of successful convergence

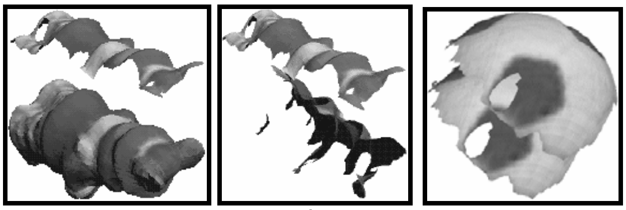
Successful convergence is obtained when the ICP algorithm registers two surfaces correctly with a minimal error. Success depends on the relative pose of the two surfaces when the ICP algorithm is launched: the initial configuration. The range of successful initial configurations (SIC) is proposed as a measure of the quality of convergence. To measure this range, a dedicated pose setup for two surfaces has been presented in [4].

This method reduces the 6D space (3 rotation and 3 translation parameters) of all possible initial configurations to a 3D space. It places one surface at several points on the circumsphere of the other surface. Each of these configurations can be expressed by a zenith angle ϕ and an azimuth angle θ. Furthermore, the so placed surface is rotated by the angle ω around the view axis defined by the circumsphere center and the current position on the circumsphere.

The matching results of all initial configurations defined by (ϕ, θ, ω) are plotted in a 2D SIC-map. The ω range is represented as a small circle drawn at the position having the following polar coordinates (radius, angle) = (ϕ, θ). The initial configurations which result in successful matching are plotted as black sectors.

3.2 Improved range of convergence

The experiments involve three setups and various coupling distances. The setups are shown in Fig. 1. Fig. 1a shows the matching of a colored view with a complete colored model of a toy rabbit. Such configurations are encountered in object recognition or object inspection. Fig. 1b shows the alignment of two partially overlapping object views. This disposition is observed in object digitizing where a complete model is assembled out of several views.
Fig .1c shows two identical colored ball surfaces P and X.



a b c

Fig. 1. Setups for different experiments

The resulting SIC maps for the setups shown in Fig. 1 and different coupling features are presented in Fig. 2, Fig. 3 and Fig. 4.

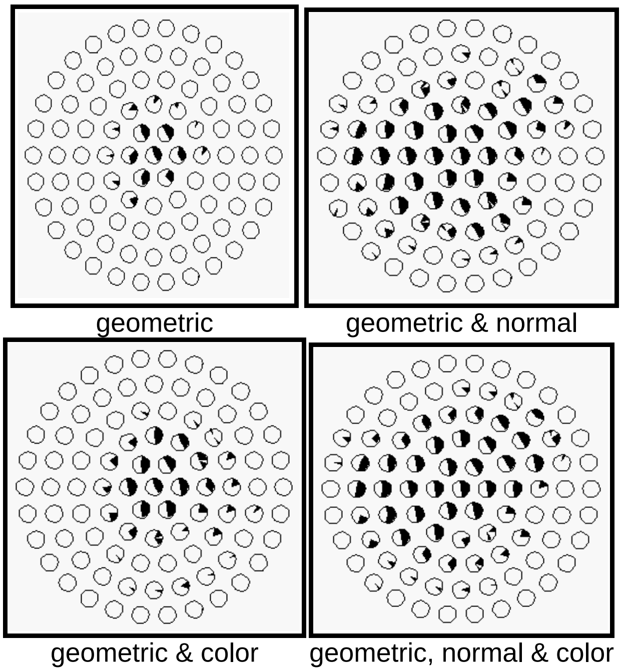


Fig. 2. SIC maps of experiment a

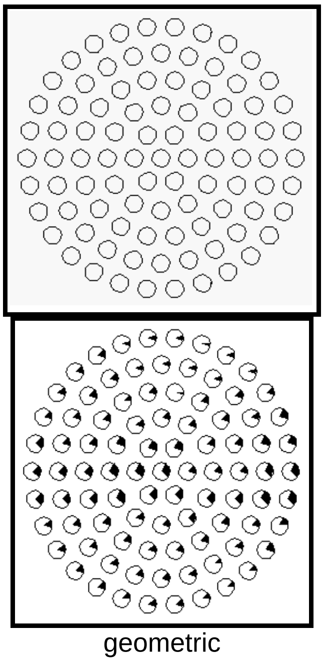


Fig. 3. SIC maps of experiments b

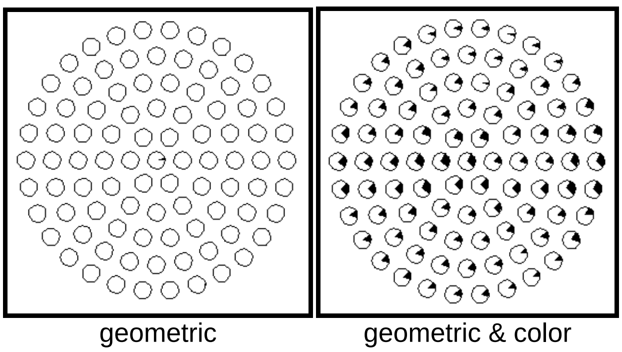


Fig. 4. SIC maps of experiments c

The resulting SIC maps show that the range of successful convergence is considerably improved when color and orientation features are included in the closest point search. The original ICP algorithm does not converge at all to the correct pose for the setups shown in Fig. 1b and 1c. Only the surface normal information permits a correct registration of the two object views of Fig. 1b. Since the surface in Fig. 1c is rotation symmetric only the color information helps to align the color spots correctly.

4. Conclusions

This paper presents and discusses the application of a multi-feature ICP algorithm. Surface geometry, color and orientation information are integrated in a total coupling distance.

Practically, the multi-feature algorithm converges to a minimum although the optimal rigid transformation minimizes only the geometric error.

The matching results for different surface setups show increased range of successful convergence. The color and surface orientation features improve the surface matching where the surface geometry is not discriminative enough to obtain successful convergence.

5. Acknowledgments

Part of this research has been funded by the Swiss national science foundation under project number 2100-43530.

6. References

[1] P.J. Besl and N.D. McKay, “A Method for Registration of 3-D Shapes,” Proceedings of IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI), vol. 14, no. 2, pp. 239-256, 1992.

[2] J. Feldmar, N. Ayache, F. Betting, “3D-2D projective registration of free-form curves and surfaces,” Sophia Antipolis, INRIA, no. 2434, 1994.

[3] G. Godin, M. Rioux, and R. Baribeau, “3-D registration using range and intensity information,” Proceedings of SPIE Videometrics III, Boston, vol. 2350, pp. 279-290, 1994.

[4] H. Hügli, C. Schütz, “Geometric Matching of 3D Objects: Assessing the Range of Successful Initial Configurations,” Proc. Int. Conf. on Recent Advances in 3-D Digital Imaging and Modeling, pp. 101-106, 1997.

[5] A. Johnson and S.B. Kang, “Registration and Integration of Textured 3-D Data,” Proc. International Conference on Recent Advances in 3-D Digital Imaging and Modeling, Ontario, pp. 234-241, 1997.

[6] Fernando C. M. Martins and José M. F. Moura, “Video representation with 3D entities,” IEEE Journal on Selected Areas in Communications, 1997.

[7] A. J. Stoddart, S. Lemke, A. Hilton, T. Renn, “Estimating pose uncertainty for surface registration,” Proc. British Machine Vision Conference, Edinburgh, pp. 23-32, 1996.