CENTER FOR
MACHINE PERCEPTION

CZECH TECHNICAL
UNIVERSITY

REPRINT

Range Image Registration Driven by a Hierarchy of Surface Differential Features

Pavel Krsek
Tomáš Pajdla
Václav Hlaváč
Ralph Martin [1)]

krsek@cmp.felk.cvut.cz

[1)] Dept of Computer Science,University of Wales, Cardiff,
PO Box 916, The Parade, Cardiff, CF2 3XF, UK.

Available at
`ftp://cmp.felk.cvut.cz/pub/cmp/articles/krsek/oagm98.ps.gz`

Pavel Krsek, Tomáš Pajdla, Václav Hlaváč, and Ralph Martin. Range image registration driven by a hierarchy of surface differential features. In *22st Workshop of the Austrian Association for Pattern Recognition*, pages 175–183, May 1998.

Center for Machine Perception, Department of Control Engineering
Faculty of Electrical Engineering, Czech Technical University
Karlovo náměstí 13, 121 35 Prague 2, Czech Republic
fax Intl. 420 2 2435 7385, phone Intl. 420 2 2435 7465, www: `http://cmp.felk.cvut.cz`

RANGE IMAGE REGISTRATION DRIVEN BY A HIERARCHY OF SURFACE DIFFERENTIAL FEATURES [1)]

Pavel Krsek, Tomáš Pajdla, Václav Hlaváč [2)] and Ralph Martin [3)]

Abstract:
This work proposes a way how to register overlapping range images automatically. We explore the fact that the Euclidean transformation is determined by three pairs of corresponding points only. The main idea of the proposed approach is to reduce the number of points by finding intrinsic (significant) ones first. For that, differential structures of the surface as curves of zero-mean curvature which are invariant to Euclidean transformation are used. The differential structures on a surface provide us with a hierarchy of intrinsic features, i.e. in a top down manner: surface $\rightarrow$ curves $\rightarrow$ points. The first estimate of the Euclidean transform is done using points then it is refined on curves and finally improved on surfaces. The performance of the approach is satisfactory for complicated surfaces which have rich differential structure.

1 Introduction and task formulation

This contribution tackles the problem of registration of two range images of the same 3D scene captured from two different viewing directions. Such a task is of practical importance, e.g. for the reverse engineering (related to CAD) in automotive industry or elsewhere. The first instance of the object is often designed by a designer from a clay. The reverse engineering creates a 3D CAD model from a clay scene by capturing set of overlapping range images that are transformed into one coordinate system. The 3D model is then created by fusing all these range images.

The range images are related by an unknown Euclidean transformation, i.e. rotation and translation. The task solved in this contribution in a novel way is to find this Euclidean transformation between two overlapping range images automatically. Such task is called

[1)] This research was supported by the Czech Ministry of Education grant VS96049, the Grant Agency of the Czech Republic, grants 102/97/0480, 102/97/0855 and European Union grant Copernicus CP941068.

[2)] Center for Machine Perception, Faculty of Electrical Engineering, Czech Technical University Prague, Karlovo nám. 13, 121 35 Prague 2, Czech Republic, e-mail: krsek@vision.felk.cvut.cz

[3)] Dept of Computer Science, University of Wales - Cardiff, PO Box 916, The Parad, Cardiff, CF2 3XF, United Kingdom

registration of range images. Surface itself are not restricted, i.e. we consider general curved surfaces.

2 Related works

The 3D model reconstruction task has been tackled by a number of works. One of the possibilities how to solve the task of two range images registration is to use the methods of nonlinear minimization of the distance function between all points from the first and the second image. An example of such a registration method is the *iterative closest points* (ICP) algorithm [1]. The distance function is defined as a sum of distances of two closest points, one from surface S and the second from surface S'. This relation may not be symmetric and thus it is assumed that the algorithm operates only on the $S \cap S'$.

The improved version of the ICP is called *iterative closest reciprocal points* ICRP [6]. Only such pairs of points are taken into account for which holds: for the point $x \in S$ the closest point to it is $x' \in S'$ and vice versa. Points having no counterparts in both ways are ruled out. Such reciprocal relation is symmetric and does not require $S \subset S'$.

The ICP and ICRP algorithm provide precise match. The algorithms are slow and if there is not available a good initial guess they tend to get stuck in a local minima of a non convex optimization criterion.

Recently, interesting approaches to finding the initial guess appeared [2, 7]. They use all points of the surface to either generate and test large number of hypotheses [2] or to do a stochastic optimization [7]. Both approaches can become quite impractical if there is a large number of points on the surfaces.

The way towards reducing the computational effort is to estimate the Euclidean transformation using much less matching points. Similarly as in stereo, motion analysis or object recognition the reduced set of surface points is used. These points are located using some invariants to Euclidean transform. The first example of such algorithm can be found in [3].

Our aim is to perform initial registration automatically and use intrinsic differential structures for this purpose. Similar idea appeared in slightly different field for registration, in single photon emission tomography [8].

Our algorithm combines advantages of both approaches. Firstly, differential invariants are used for locating interesting points. It significantly reduces amount of points from tens of thousands points to hundreds of points. Secondly, the ICRP algorithm is then used to improve the initial guess of the registration.

3 Main idea of the search for initial registration

When searching for an initial registration, it is not necessary to use all tens of thousands points for establishing a correspondence among surfaces. The number of all possible pairings is tremendous. The hypothesis - test cycle would be prohibitively slow.

We explore the fact that the Euclidean transformation is determined by three pairs of corresponding points only. The main idea of the proposed algorithm is to reduce the number of points by finding intrinsic (significant) ones first. Features that are invariant to Euclidean transformation are used. In our case, we explore differential structures of the surface as curves of zero-mean curvature [4]. The hundreds of intrinsic points are typically obtained and the number of hypotheses testing is reduced.

The differential structures on a surface provide us a hierarchy of the intrinsic features, i.e. in a top down manner: surface → curves → points. The first estimate of the Euclidean transform is done using points then it is refined on curves and finally improved on surfaces.

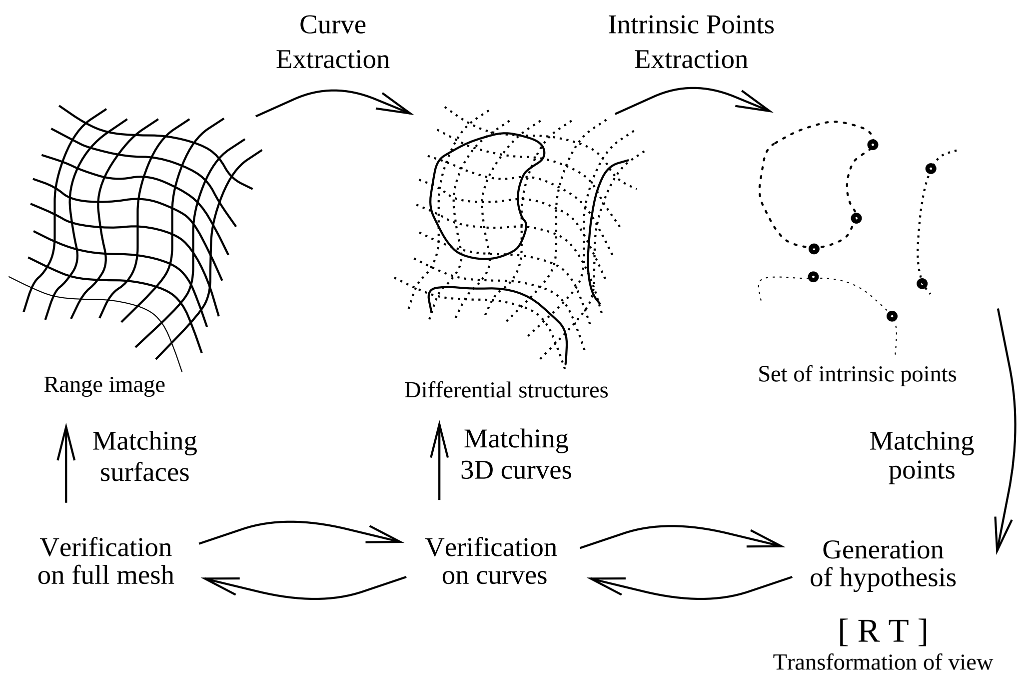


Figure 1: Main idea of the registration.

4 Intrinsic points from differential structures

The surface is represented by a cloud of all surface points measured by a range finder. The extraction of differential structures from the surface, i.e. intrinsic curves, is the first step of our algorithm. The curves of zero mean curvature are found first [4]. These curves are sometimes open sometimes closed.

To further reduce the number of intrinsic points, we extract line segments connecting curves in the same range image. We chose as invariant features to Euclidean transformation the shortest line segments connecting each curve with other curves. This allows us to look for the line segment of the same length in the second range image if the corresponding feature is looked for. Actually, there is a tolerance interval given by the known precision of the range finder. Notice that our line segments are in some sense similar to matching by a geometrical hashing using semi-differential invariants [6].

Initially, we believed that differential structures generate a graph describing more global topological entities. Curves correspond to graph vertices and line segments to graph edges. During our experiments we encountered that graph as an entity describing topology is extremely unstable due to sensitivity to self-occlusion.

The line segments connecting the end points of open curves are not invariant to Euclidean transformation as they typically suffer from self-occlusion. Even so, we use them as they bring significant amount of information about position because they often connect short but distant curves with the most significant ones.

5 Generation of hypothesis

The Euclidean transformation, that is searched for is determined by two pairs of line segments from many candidates found in the previous step. These candidate line segments constitute hypotheses for surface registration.

The number of hypotheses that are taken into consideration is reduced by the constraint that only line segments of roughly same length are allowed. The rough match is performed using a length tolerance interval that is set manually in the current implementation. The line segments eligible for match are ordered according to length difference between them. Hypotheses are verified starting from those of more similar length.

6 Hypotheses verification and improvement of the registration

The hypotheses verification that rules out incorrect matches of line segments follows. Generated hypotheses correspond to a Euclidean transformations and their quality is judged by performing registration. The quality is assessed according to number of reciprocal points (cf. ICRP algorithm mentioned is section 2).

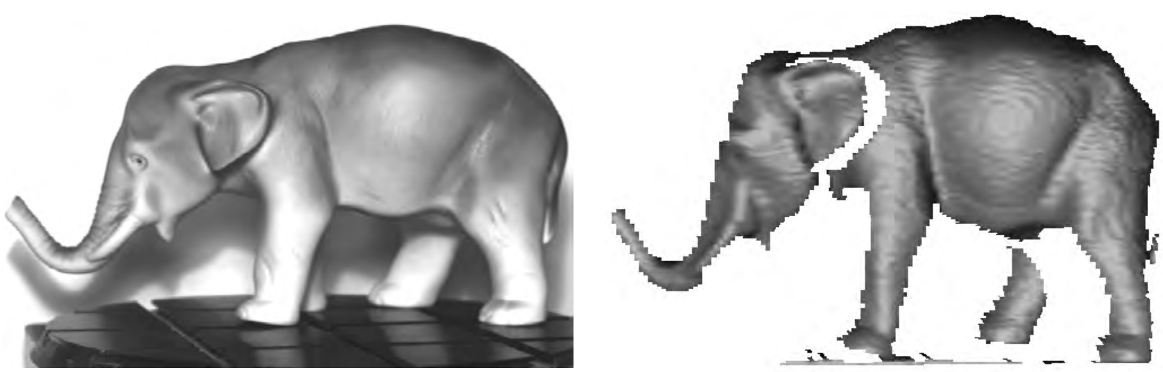
The algorithm is as follows. The intrinsic curves are transformed to a common coordinate system. The coordinate system of the first range image is used for this purpose. A hypothesis is accepted if the number of reciprocal points is higher than 80% of the previous maximum.

If the hypothesis is accepted, the Euclidean transformation is improved by the ICRP algorithm applied to the points on matched intrinsic curves. The Euclidean transformation given by matched line segments is used as ICRP initial guess. All other curve points are then used for improvement.

Now the hypotheses come to the second verification round. The hypotheses that do not reach the predefined number of reciprocal points (e.g. 80% of the maximal value) are rejected. Typically, about ten hypotheses remain to be further considered. All remaining hypotheses are tested on the two entire point clouds by running ICRP algorithm and consequently the Euclidean transformation estimate is improved. The best hypothesis yields the registration that was the aim of the whole task.

7 Experiments

Results of the registration algorithm are shown on real range images captured by the Laser Plane Range Finder (triangulation based, laser plane illumination, translating rig of the camera and the laser) [5]. The object is placed on the turn table to get overlapping range images from different view directions. Measured data points lie in a rectangular mesh with the distance between neighboring points about 2 millimeters and error of the position in x, y, and z axes is 0.2 millimeters.



(a) (b)

Figure 2: The snapshot and one range image of the measured object – the ceramic statue of an elephant.

The object used for experiments is a ceramic statue of an elephant of size about 12 centimeters. The snapshot and one range image of the elephant is shown in the Figure 2. Twenty images were obtained to construct the entire 3D CAD model of the elephant. Here we report only about registrations and only two range images were used for this purpose. The view directions differ approximately by a 15^o rotation around z axis and small unknown translation.

Figure 3: The range images obtained from two different view directions with extracted intrinsic curves.

The range images with extracted intrinsic curves are shown in Figure 3. Figure 4 presents the registration estimates in different stages of our algorithm.

(a) (b) (c)

Figure 4: The intrinsic curves from two views in a common coordinate system. a) Before registration. b) The best initial estimate from correspondence of line segments. c) Final registration after improvement on the entire point clouds.

Figure 4a shows intrinsic curves used for the registration. Figure 4b shows the result of intermediate registration step using pairs of line segments. Figure 4c demonstrates final registration of the intrinsic curves and Figure 5 demonstrate registered range images after improvement on the entire point clouds.

The error in each step of registration can be described by the average distance between reciprocal points. Average distance is computed as a sum of distances between the reciprocal

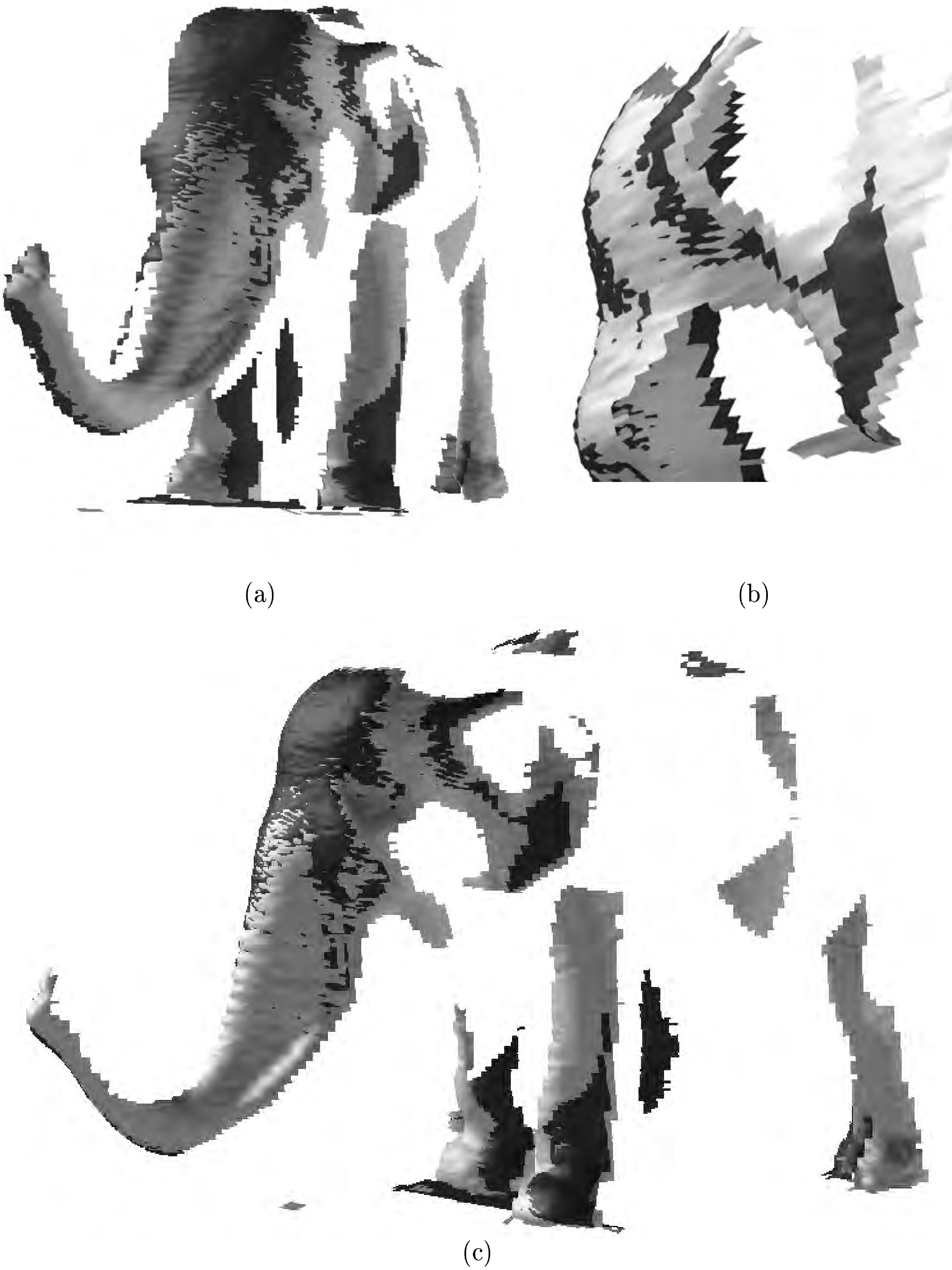


Figure 5: The entire range images after registration in one coordinate system (a), (c). A detail showing the precision of the registration (b).

points divided by the number of these points. The distances and number of points for some steps of our algorithm can be found in Table 1.

	number of reciprocal points	average distance
before the registration	542	5,7 mm
registration using line segments	3677	0.77 mm
registration using curves	4086	0.57 mm
registration using surfaces	4086	0.49 mm

Table 1: Error in selected steps of registration algorithm.

The parameters of the algorithm (tolerance of line segments lengths, hypotheses rejection ratio) have little influence on the precision of results but they determine the number of generated hypotheses. If the values of the parameters are set incorrectly either no or too many hypotheses are generated.

8 Conclusion

A method for completely automatic surface matching have been proposed and demonstrated. The performance of the algorithm is satisfactory for complicated surfaces which have a rich differential structure.

It is the lack of differential structures on the surface which can lead to failure of the proposed algorithm. On the other hand, the strategy of hierarchical generation and verification of the hypotheses can use any features, e.g. the drawings on the surfaces extracted from images of the scene or corner points and edges. Corners and edges play the important role for man made objects.

There still remain a number of opened problems. For instance, we have observed certain instability in generating the shortest connections between the curves. It happens mainly due to occlusions or if the curves are almost parallel.

References

[1] P. Besl and N. D. Kay. A method for registration of 3D shapes. *IEEE Pattern Analysis and Machine Intelligence*, 14(2), 1992.

[2] C.S. Chen, Y.P. Hung, and J.B. Cheng. A fast and robust approach for registration of partially overlapping range images. In *6th International Conference on Computer Vision, Bombay, India*, pages 242–248, 1998.

[3] K. Higuchi, M. Hebert, and Ikeuchi K. Building 3-D models from unregistered range images. *Graphical Models and Image Processing*, 57(4):315–333, July 1995.

[4] Pavel Krsek, Tomáš Pajdla, and Václav Hlaváč. Estimation of differential structures on triangulated surfaces. In *21st Workshop of the Austrian Association for Pattern Recognition*, May 1997.

[5] Tomáš Pajdla. Laser plane range finder - the implementation at the CVL. Technical Report Nr. K335-95-98, Czech Technical University, Prague, October 1995.

[6] Tomáš Pajdla and Luc Van Gool. Matching of 3-D curves using semi-differential invariants. In *5th International Conference on Computer Vision*, pages 390–395, Cambridge, MA, June 1995. IEEE Computer Society Press.

[7] A.J. Stoddart and K. Brunnstrom. Free-form surface matching using mean field theory. In *British Machine Vision Conference*, pages 33–42, 1996.

[8] J.P. Thirion. New feature points based on geometric invariants for 3D image registration. *International Journal of Computer Vision*, 18(2):121–137, 1996.