

THREE-DIMENSIONAL POINT-CLOUD REGISTRATION USING A GENETIC ALGORITHM AND THE ITERATIVE CLOSEST POINT ALGORITHM

D. Torres and F. J. Cuevas

*Computer Vision and Artificial Intelligence Group, Centro de Investigaciones en Óptica A.C.
Loma del Bosque 115, Lomas del Campestre 37150, León, Mexico*

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Abstract: We present a method for three-dimensional surface registration which utilizes a Genetic Algorithm (GA) to perform a coarse alignment of two scattered point clouds followed by a slight variation of the Iterative Closest Point (ICP) algorithm for a final fine-tuning. In this work, in order to improve the time of convergence, a sampling method consisting of three steps is used: 1) sample over the geometry of the clouds based on a gradient function to remove easily interpolating singularities; 2) a random sampling of the clouds and 3) a final sampling based on the overlapping areas between the clouds. The presented method requires no more than 25% of overlapping surface between the two scattered point clouds and no rotational or translational information is needed. The proposed algorithm has shown a good convergence ratio with few generations and usability through automated applications such as object digitalization and reverse engineering.

1 INTRODUCTION

The problem of geometrically aligning a point cloud to a surface is known as surface registration or point cloud registration. Many techniques have been developed in order to solve such problem. One of the most used is the ICP which is an iterative algorithm that applies a transformation to the current position of the point cloud (Besl and McKay, 1992) in order to achieve a minimum squared distance between the two point-clouds. The main issue of the ICP is that it frequently converges to a local minimum (Pottmann et al., 2004) and needs a rather good manual pre-alignment in order to provide a satisfactory solution.

In order to overcome this problem many authors have resorted to many Evolutionary Computing methods such as Parallel Evolutionary Algorithms (Robertson and Fisher, 2002), and Genetic Algorithms (Brunnström and Stoddart, 1996; Chow et al., 2004). Even though these approaches provide acceptable solutions when registering surfaces with a high rate of overlapping points, they fail when outlier points are dominating and thus, are not useful to fully reconstruct objects whose acquisition

process requires of more than one scan.

In this paper, a novel method is proposed to take on the registration problem given two or more different surfaces belonging to the same object from different viewing locations with an overlapping surface as low as 25% of each cloud total points. The aim of the GA is to find the transformation parameters between two point-clouds in order to minimize a custom fitness function. Once the GA has achieved a critical point, an ICP begins to minimize the least median of squares (LMS), known to be a more robust estimator than the standard least squares (LS) of the common ICP (Masuda et al., 1996).

The rest of the paper is organized as follows. Section 2 briefly explains the application of ICP algorithm and Section 3 explains how we formulated the first alignment as a GA. Real and simulated experiments are described in Section 4 to demonstrate the effectiveness of the proposed method. A conclusion on the performance and possible applications as well as some current issues of the proposed algorithm is given in section 5.

2 THE ICP ALGORITHM

Let there be two set of points, an input image $\{P_i\}$ and a target image $\{Q_i\}$. The objective of the ICP is to determine the Euclidean transformation T between these two sets to minimize E_i such that

$$\min E_i(T) = \min[|T(P_i) - Q_i|] \text{ for all } i \quad (1)$$

Since the correspondences of $T(P_i)$ are unknown, a temporary correspondence must be computed, which is defined as the point with minimum distance among all points in the set Q_i . If the set of points P_i has size N_1 and the set Q_j has N_2 elements, then the registration function transformation, F is defined as

$$F(T) = \text{Median}(E_i) \text{ for } 1 \leq i \leq N_1 \quad (2a)$$

$$E_i(T) = \min_j |T(P_i) - Q_j| \text{ for } 1 \leq j \leq N_2 \quad (2b)$$

The iterative process of the algorithm can be summarized as follows:

- 1) Find a correspondence between the point clouds. The closest points are paired.
- 2) Compute the rigid transformation T given the pairing.
- 3) Apply T to the data P_i and compute the LMS as in equations 2a and 2b.
- 4) If the change in F is not less than a threshold or the maximum number of iterations has been reached, stop the algorithm.

It is highly recommended to use a Singular Value Decomposition (SVD) to improve the execution time of the algorithm, to find the rigid transformation T (Arun *et al.*, 1987) and to classify the points in a *kd-tree* in order to surf through the set of points faster (Friedman *et al.*, 1977).

3 GA FOR POINT-CLOUD REGISTRATION

In order to achieve a good pre-alignment of the point-clouds, a SGA is used as a pseudo-ICP method, which is defined in section 3.2. Additionally, to ensure a good convergence and running time, it is necessary to choose a good sampling method (explained in section 3.4).

The common parts of the GA (chromosomes definition, selection, mutation and crossover) are explained in sections 3.1 and 3.3.

3.1 Formulation of Chromosomes

Let us define two surfaces or sets of points namely a floating cloud and a fixed cloud given by $P = \{\vec{p}_i\}$ and $Q = \{\vec{q}_i\}$, respectively. Each point \vec{p}_i or \vec{q}_i is a vector containing its *xyz* coordinates.

As explained earlier, the objective of the GA is to find the rigid transformation applied to the floating cloud P to minimize a fitness function paired with the cloud Q . Each chromosome will be given by six parameters or genes, being three for displacement and three for rotation. In such case, for a population of N_{pop} size, each chromosome will be defined as

$$\chi_i = [\alpha_i, \beta_i, \gamma_i, T_{xi}, T_{yi}, T_{zi}] \text{ for } i = 1 \dots N_{pop} \quad (3)$$

where α , β and γ represent the rotations about the *x*, *y* and *z* axis, respectively, while T is a translation of the given axis.

Given the high sensitivity of the rotational parameters to small changes in binary coding, it was chosen to use continuous coding with double precision for the whole chromosome.

The transformation to the set P is applied as follows

$$T(P) = R \cdot [P + T] \quad (4a)$$

where $R = R_x R_y R_z$ and

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{bmatrix} \quad (4b)$$

$$R_y = \begin{bmatrix} \cos(\beta) & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) \end{bmatrix} \quad (4c)$$

$$R_z = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4d)$$

$$T = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} \quad (4e)$$

The sign convention used to transform any point in the set is shown in Figure 1.

Each chromosome in the population is initialized randomly within a given interval and then processed to obtain its fitness as explained in the next section.

3.2 Fitness Function

In order to determine the performance of each chromosome, a GA uses a fitness function. In this case, the fitness function has to measure the quality

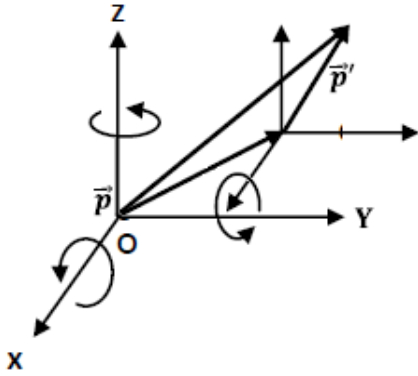


Figure 1: Sign convention for a transformation of a point \vec{p} with positive parameters.

of the registration in function of the quantity of points paired, the total error of the pairing and the overlapping region obtained.

The sub-spaces necessary to evaluate the fitness function are described in Table 1 and shown in Figure 2.

Table 1: Sub-spaces defined to evaluate the fitness function.

S_{OV}^P	Overlapping points in floating cloud.
S_{OL}^P	Points of floating cloud within the outlying area.
S_{OV}^Q	Overlapping points in fixed cloud.
S_{OL}^Q	Points of fixed cloud within the outlying area.

It can be seen from Figure 2 that overlapping areas do not frame exactly the overlaid regions of the two circles. This error is allowed due to a threshold distance necessary for the correct performance of the algorithm.

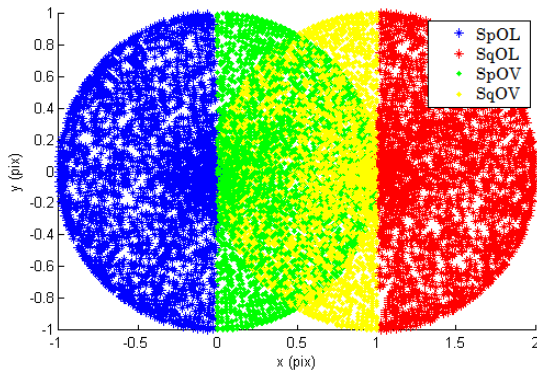


Figure 2: Sub-spaces for outlier and overlapping points for two unit circles.

The fitness f for each chromosome χ is defined as

$$f(\chi) = |d_{OL} - \Upsilon d_{OV} - \varepsilon|^2 \quad (5)$$

where d_{OL} represents the minimum average distance between outlier points, d_{OV} is the minimum average distance between the overlapping regions, Υ is an adjustment factor due to the ratio of successful pairing and ε is an error term due to the sampling process.

To compute parameter d_{OL} it is necessary to calculate the individual Euclidean distances from any point in the S_{OL}^P space to every point in the S_{OL}^Q set and save the minimum distance. A pairing or matching takes place if the minimum distance obtained is less than a threshold th previously established. Once a closest neighbor has been found, points from both sets are deleted. Repeating this process for every point in the set S_{OL}^P yields

$$d_{OL} = \frac{1}{N_{OL}^P} \sum_{i=1}^{N_{OL}^P} \min [D(s_{OLi}^P, S_{OL}^Q)] \quad (6)$$

where $D(a, B)$ represents a vector containing the Euclidean distances between point a and set B and N_{OL}^P is the number of elements in S_{OL}^P . The same procedure is followed to compute d_{OV} .

Each time a point matching occurs, a counter λ (initially set to zero) will be increased by two. Parameter Υ will then be given by

$$\Upsilon = \frac{\lambda}{N_{OV}^P + N_{OV}^Q} \quad (7)$$

This last term represents exactly the ratio of points successfully matched in the overlapping surfaces and is used to reduce the weight of the d_{OV} in order to reward a good ratio even if distances between the overlapping points are big.

3.3 Genetic Operators

Another important factor to ensure the convergence of the GA is the election of the right operators to act upon the population. Such operators are selection, crossover and mutation. This is a particular difficult choice, given the fact that a certain combination might work perfectly in a problem and completely fail in another, depending on their nature.

In this section, the parameters chosen are briefly explained. Many other variations of these operators can be found on (Chambers, 1995) and (Goldberg, 1977).

3.3.1 Selection

In the case of a registration problem, it is recommended to choose a selection method that

applies little pressure on the population since even the less fitted individuals could provide important data for the optimization. A complete analysis on the selection operator can be found on (Baker, 1989).

It was chosen to use a selection by lineal ranking because it allows offspring from most part of the population depending on a parameter η . The first step is to order the n individuals according to their fitness's and calculate a new fitness based on the function

$$f'(n) = \eta - \frac{2n(\eta-1)}{N_{pop}-1} \text{ for } k = 0 \dots N_{pop} - 1 \quad (8)$$

This assigns a value of η to the less fitted individual and a value close to N_{pop} for the best one.

Once f' has been computed, a roulette selection is used to decide on the parents that will give rise to the new offspring. Additionally, the selection can be set to be elitist, that is, to preserve some of the best fitted individuals in order to maintain the minimum fitness stable.

3.3.2 Crossover

Crossover refers to the operation of exchanging information with a certain probability between two individuals, namely parents. Many crossover methods are described in (Chambers, 1995). Given the short length of the chromosome used in this work, a single point crossover has been chosen, with the crossing point chosen randomly. However, to introduce new information, the crossover model introduced by (Radcliff, 1991) has been applied as well. This model considers adding a random variable to each gene based on the data from their parents, this is

$$p_1 = \xi p_f + (1 - \xi) p_m \quad (9a)$$

$$p_2 = p_f(1 - \xi) + \xi p_m \quad (9b)$$

where p_1 and p_2 represent the values for the new genes, ξ is the random variable within the range [0,1] and p_f and p_m are the current values of the genes from the first and second parents, respectively.

3.3.3 Mutation

Like crossover, mutation is a critical operator for the correct execution of a GA. Mutation introduces new information and can be determining to converge to the global optimum. Under mutation, each gene has a probability of changing its value.

In binary coding, mutation consists on changing 1's to 0's and vice versa. A continuous coding requires adding or subtracting a random value from

the current value of the gene within a given range. This work considers a dynamic range of mutation, based on the maximum fitness value and the overall, the new value for the gene m_{new} will be given by

$$m_{new} = \xi \cdot \left[2 - \frac{k}{N_{pop}} - \left(1 - \frac{f_{av}^{k-1}}{f_{max}^{k-1}} \right) \right] \quad (10)$$

where ξ is again a random variable whose range depends on the nature of the gene (rotation or translation), k is the current generation, f_{av}^{k-1} is the average fitness of the previous generation, and f_{max}^{k-1} is the maximum fitness of the previous generation. The constant 2 is selected so that the new value is constraint within the interval [0, 2], being the first expected in the later generations.

An analysis on the advantages of choosing a dynamic mutation model is better explained in (Chow, 2004).

4 EXPERIMENTAL RESULTS

The proposed method was tested on three different sets: a) a simulated surface generated and sectioned in MATLAB, b) a model acquired by projecting fringes over a surface and sectioned in MATLAB and c) a model acquired by the same means as b) and fully reconstructed to compare with the reconstruction obtained with a commercial 3D scanner.

4.1 Computer Simulated Surface

First, a graphic was generated using the function PEAKS with a size of 200×200 which then was sectioned in a floating and a fixing cloud, each one formed by 125 pixels. Both surfaces were standardized to a range [-0.5, 0.5] in their x and y axis and to [-1, 1] in their z axis.

After standardizing, the floating cloud was transformed with random parameters as mentioned in Eq. (4a). The rotations were within the range [-120, 120] and the displacements in [-1, 1].

The experiment was repeated ten times, of which three are shown in Table 2. The error is measured as the total average distance between the overlapping points. A result of one of the experiments is shown in Figure 3.

4.2 Real Surface Synthetically Sectioned

A frontal view of a real surface was digitalized using

Table 2: Results obtained from registering a computer simulated surface under random transformations.

Original		Obtained		Error	Time(s)
(α, β, γ)	(T_x, T_y, T_z)	(α, β, γ)	(T_x, T_y, T_z)	initial (final)	
(33.50, 90.81, -44.41)	(0.09, -0.71, 0.70)	(35.48, 88.31, 45.49)	(0.12, -0.73, 0.68)	0.4927 (0.00373)	237.57
(59.53, -50.61, -117.94)	(-0.52, -0.75, -0.63)	(58.72, -49.87, 116.29)	(-0.49, -0.76, -0.63)	0.5397 (0.00197)	217.64
(-5.83, 3.63, 82.47)	(0.46, 0.25, 0.84)	(-6.19, -3.28, -83.14)	(0.428, 0.23, 0.82)	0.4756 (0.00104)	219.83

Table 3: Results obtained from registering a real surface under random transformations.

Original		Obtained		Error	Time(s)
(α, β, γ)	(T_x, T_y, T_z)	(α, β, γ)	(T_x, T_y, T_z)	initial (final)	
(39.11, 2.89, 111.02)	(-69.74, -29.34, 15.97)	(37.38, 1.68, 107.73)	(-66.28, -30.73, 17.06)	35.2532 (0.04661)	385.73
(37.76, 48.69, 99.78)	(-56.34, -31.01, 6.56)	(38.76, 48.91, 96.38)	(-58.08, -31.92, 5.68)	39.6762 (0.03982)	374.29
(101.06, 49.83, 35.06)	(-65.01, 48.87, 60.75)	(99.34, 47.92, 34.73)	(-63.83, 49.23, 62.38)	47.2784 (0.04251)	382.95

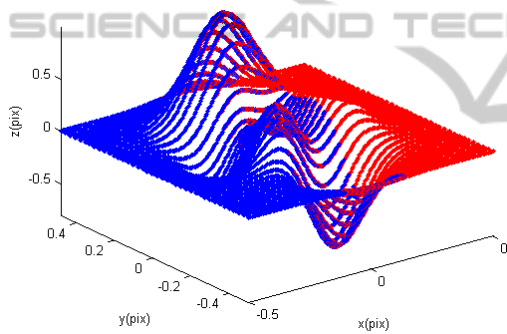


Figure 3: Result obtained from first experiment.

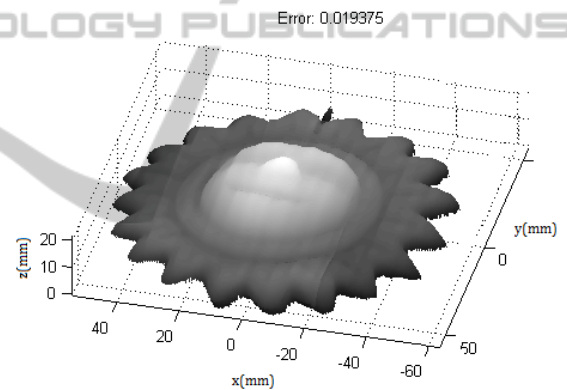


Figure 5: One of the result after applying the proposed method.

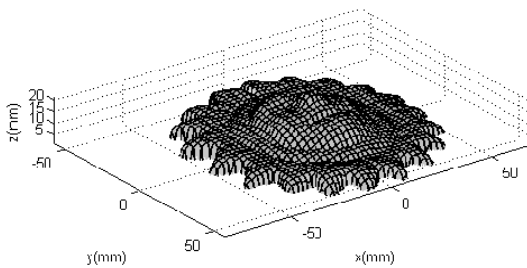


Figure 4: Range image obtained from a real surface.

a fringe projection system. The range image obtained is shown in Figure 4. The same procedure of sectioning and transforming was followed to produce the differently modified clouds with a range of displacements of $[-70, 70]$.

The experiment was again repeated ten times and three of the results obtained are detailed in Table 3 and one of them shown in Figure 5.

The error is measured once again as the total average distance between the overlapping surfaces.

4.3 Real Surface Reconstructed

For the last experiment, an object was digitalized and fully reconstructed from four different acquisitions. The reconstructed object was then compared against the result of the same object obtained with a commercial 3D scanner, being these the floating and fixed clouds, respectively. The acquisition was done using structured light projection and reconstructed with the proposed method. The final result of this experiment is shown in Figure 6.

Both clouds were paired with an average error of 0.000116 mm/point. The reconstruction process took

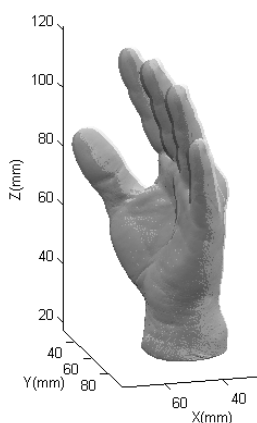


Figure 6: Surface reconstructed (light) and surface acquired with a commercial scanner (dark).

738.47 seconds and the final pairing ended in 283.38 seconds.

5 CONCLUSIONS

The proposed method works well for dense clouds (of about 300,000 points) and has proven its efficiency in reconstructing tasks particularly for big objects where many acquisition steps are needed. With little refinement, it can also be used to compare CAD modeled pieces with pieces machined in the real world to give a better quality control where high precision is needed.

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