SURFACE REGISTRATION USING LOCAL SURFACE EXTENDED POLAR MAP

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Keywords: Surface Registration, Surface Signature, Surface Matching, 3D Object Representation.

Abstract: In this paper, we are presenting a new surface signature-based representation that is orientation-independent and can be used to match and align surfaces under rigid transformation. The proposed scheme represents the surface patches in terms of their signatures. The surface signatures are formed as extended polar maps using the neighbours of each surface patch. Correlation of the maps is used to establish point correspondences between two views; from these correspondences a rigid transformation that aligns the views is calculated. The effectiveness of the proposed scheme is demonstrated through several registration experiments.

1 INTRODUCTION

Many applications require the construction of precise 3D object models of physical objects, preserving as much information as possible (Bernardini et al., 2002; Ikeuchi and Sato, 2001). It is usually necessary to scan the scene from different viewpoints in order to build a complete 3-D model of a complex scene. The registration of the acquired data sets into a common coordinate system has been a subject of much research during the last 15 years.

Several of the proposed methods (Rusinliewicz and Levoy, 2001; Zhang et al., 2004; Blais and Levine, 1995; Zhang, 1994; Eggert et al., 1997; Okatani and Sugimoto, 2004; Sharp et al., 2002) can be seen as extensions or improvements of the Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992). ICP is an iterative procedure minimizing the mean squared error (or the sum of the squared distances) between points in one view and the respective closest points in the other view. At each ICP iteration, the geometric transformation that best aligns the two images with respect to this criterion is calculated.

Another approach (Fan et al., 2002; Robertson and Fisher, 2002; Silva et al., 2005) to registering two images is to find the geometric transformation through a pose-space search, rather than the correspondence-based search of ICP. The search space of geometric transformations contains solutions that can be used to align two views. In this case, the objective is to find, in a huge search space, a solution acceptably close to the global optimum, in a reasonable time.

Recently, researchers have developed and discussed different surface representations that are effective in finding point corresponding between the two sets to be registered. In this case, the registration problem is addressed in two steps, where the first step is to establish the point corresponding between the surface sets then to use these points to compute the transformation that aligns the two surfaces. These surface representations are known as surface signature-based representation. They include the splash representation (Stein and Medioni, 1992), the point signatures (Chua and Jarvis, 1997), the spin image representation (Johnson and Hebert, 1999), the spherical spin image representation (Correa and Shapiro, 2001), the surface point signatures (Yamany and Farag, 2002), the harmonic shape images (Zhang and Herbert, 1999), the local surface descriptors (Chen and Bhanu, 2004) and the point fingerprints (Sun et al., 2003). In this paper, we are proposing an extension for these representations to solve the registration problem.

The proposed representation technique, Local Surface Extended Polar Map (L-SEPMap), transforms the surface from the Cartesian coordinate system where surface descriptions vary with transformation to an extended polar coordinate system where surface descriptions are invariant to rigid transformation. In this artificial domain, every surface patch, its cen-

E. Hemayed E. (2006).
SURFACE REGISTRATION USING LOCAL SURFACE EXTENDED POLAR MAP.
In *Proceedings of the First International Conference on Computer Vision Theory and Applications*, pages 143-148
DOI: 10.5220/0001375601430148

ter of gravity, is represented by one L-SEPMap. As a surface signature-based representation, L-SEPMap places few restrictions on object shape and topology and can be used to match surfaces in the presence of clutter and occlusion.

Our approach to solve the surface registration problem is based on establishing point correspondences using the L-SEPMap scheme. Next, sets of geometrically consistent point correspondences are used to compute the transformation that aligns the views (Williams and Bennamoun, 2001).

This paper is organized as follows: The L-SEPMap scheme is described in Section 2. The alignment process using L-SEPMap scheme is described in Section 3. Experimental results are presented and discussed in Section 4. Finally, conclusion and future work are presented in Section 5.

2 L-SEPMap SCHEME

In this paper, surfaces are defined by a dense collection of 3D points and surface normals (Hemayed, 2003). In L-SEPMap, we are extending the surface signature representation to calculate the signature of neighbor points only. Our approach is to use three parameters (θ, ϕ, r) to represent the positions and the curvature of each point with respect to the basis of other neighbor points on the surface. In this representation, (θ, ϕ) capture the relative curvature while 'r' captures the relative displacement between the surface points. The three parameters are transformation (rotation and translation) invariant.

L-SEPMaps generated for two corresponding points on different surfaces would be similar, so oriented points can be matched based on a comparison of their L-SEPMaps. L-SEPMaps are descriptive enough that correspondences between points can be established based on a comparison of L-SEPMaps alone. Since L-SEPMaps is based on the neighbor locality of the surface's points of an object, the proposed algorithm will generate a representation that is robust to clutter and occlusion, so segmentation of scene data is not necessary for surface matching in cluttered scenes. In addition, the locality nature of the L-SEPMap representation speeds up the process and save the system memory. The process of generating the L-SEPMaps are presented in this section along with the object model representation.

2.1 Object Model Representation

The object model is defined by a set of triangles. Each triangle composed of three-vertices defined by their Cartesian coordinates in the object coordinate systems. In order to simplify the L-SEPMap generation process, the triangle's center-of-gravity and its normal are used instead of the actual triangle. So the object model can be seen as a set of oriented points (represent the triangle's center-of-gravity) and the surface normal at these points. Mathematically, the object model is defined by Eq. 1.

$$G = \{g_i = (p, n_p)_i,\ i = 1..N\} \tag{1}$$

Where $p = (x, y, z)$ is the Cartesian coordinate of the triangle's center of gravity and $n_p = (n_x, n_y, n_z)$ is the triangle's surface normal. g is known as an oriented point.

2.2 L-SEPMap Generation

In the L-SEPMap generation process, each surface patch (triangle) in the model is represented by a map that is independent of the object coordinate system. The map is generated at each surface patch by recording the relative curvature and displacement of that surface patch and its neighbors surface patches in the model. The following terms are helpful in explaining the generation process.

Neighbor Degree: This term is used to indicate how two oriented points are close to each other. For example, if an oriented point p is adjacent to another oriented point q, i.e., their triangle patches share one side, then we say that p is a neighbor to q with degree 1. And if w is not adjacent to p but it is adjacent to q, then w is a neighbor to p with degree 2 and so on. Fig. 1(a-c) shows the neighbors of a triangle patch for 1-, 2-, and 3-degree.

L-Degree Neighbors $P_L(g)$: This is the set of all points that are neighbors to point g with degree $1, 2, ..L$. If a point has an L-degree neighbors then it may have an L+1 degree neighbors. However, if a point does not have L-degree neighbors then it will not have neighbors of any degree higher than L. We'll say that a point does not have an L-degree neighbors if any of its L-1 degree neighbors has any of its side at the edge of the model and as such it is not shared with any other patch in the model. Fig. 1(d) illustrates that triangle patch 1 and 2 lie on the edge and as such the shaded triangle patch does not have a 4-degree neighbors.

Inner Points of L-Degree: This is the set of all oriented points that have at least L-degree neighbors. In the other side, those points who do not have an L-degree neighbors, they will be known as outer points of L-degree. Fig. 1(d) shows that the shaded triangle patch (oriented point) can be considered an inner patch (oriented point) of 3-degree but an outer point in case of 4 or higher neighbor degree.

For an object model G defined by Eq. 1, the L-SEPMap M of an oriented point $g \in G,\ g = (p, n_p)$ is defined by Eq. 2 (where N_L is the number of L-

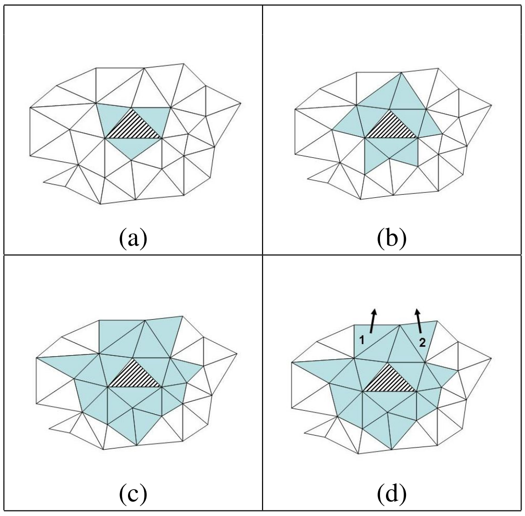

Figure 1: The neighbors of the shaded triangle patch of (a-c) 1-, 2-, and 3-degree, respectively. (d) Patches 1 and 2 are edge patches.

Degree neighbors $P_L(g)$), and is generated as follows:

$$M_L = \{m_j = (\theta, \phi, r)_j,\ j = 1..N_L\} \tag{2}$$

For each oriented point $g_j \in P_L(g),\ g_j = (q, n_q)_j$,

1. Define v = the vector $\overrightarrow{pq}$,
2. Calculate (θ, ϕ, r) as follows, see Fig. 2.
   (a) θ = the angle between n_p and v
   (b) ϕ = the angle between n_q and v
   (c) r = the length of v (the distance between p and q)
3. Record $m_j = (\theta, \phi, r)$ in M

The L-SEPMap generation process is repeated for all inner points of L-degree $g_i \in G$, each will produce an L-SEPMap, $M_i,\ i = 1..N$. The set of L-SEPMaps are used to represent the object model G. So the model L-SEPMap representation G_L is defined as

$$\begin{array}{l} G_L = \{M_i,\ i = 1..N\}, \\ M_i = \{m_j = (\theta, \phi, r)_j,\ j = 1..N_i\} \end{array} \tag{3}$$

where N is the number of inner points of L-degree in the model G and N_i is the number of L-Degree neighbors of the point g_i.

3 REGISTRATION PROCESS USING L-SEPMaps

The problem of registering two different surfaces defined by their L-SEPMaps is solved in a two-step process, L-SEPMap matching and the transformation matrix estimation. In the first step, the L-SEPMaps of the two surfaces's points are matched establishing points corresponding between the two surfaces. The matched points are then fed into the second step where a modified ICP algorithm is used to estimate the rotation and translation matrices to align the two surfaces. The L-SEPMap matching and the transformation estimation are presented in this section.

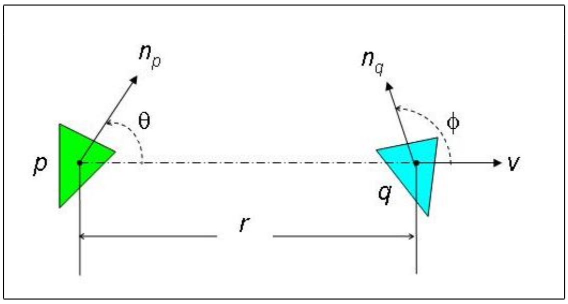

Figure 2: The calculation of an L-SEPMap tuple $m = (\theta, \phi, r)$ of two oriented points (p, n_p) and (q, n_q).

3.1 L-SEPMap Matching

The idea of the L-SEPMap matching is to establish point corresponding between the two surfaces that maximize the similarity between them. In our case, the two objects are represented by their L-SEPMaps. Mathematically, the L-SEPMap matching problem is defined as follows:

Given the L-SEPMap representation of two objects

$$\begin{array}{l} G = \{M'_i,\ i = 1...N'\}, \\ H = \{M''_i,\ i = 1...N''\} \end{array} \tag{4}$$

where N' and N'' are the number of oriented points in G and H, respectively. Find the point correspondence between the two objects that maximizes the similarity between them.

Let's define the term **Candidate Match Pair**. This term is used to indicate that two map points $m'_i = (\theta, \phi, r)'_i$ and $m''_j = (\theta, \phi, r)''_j$ form a possible match pair. m'_i and m''_j are possible match pair if they have similar relative curvature and displacement, that is $\theta'_i \approx \theta''_j$, $\phi'_i \approx \phi''_j$ and $r'_i \approx r''_j$.

In order to measure the similarity between two objects G and H, we first measure the similarity, P, between their pair-wise L-SEPMaps defined in Eq. 4. The similarity, P, between two L-SEPMaps, M' and M'', defined in Eq. 5, is measured by the percentage of matching records between the two L-SEPMaps.

Given two L-SEPMaps

$$\begin{array}{l} M' = \{m'_i = (\theta, \phi, r)'_i,\ i = 1..N'\}, \\ M'' = \{m''_j = (\theta, \phi, r)''_j,\ j = 1..N''\} \end{array} \tag{5}$$

The matching process can be summarized in the following steps:

1. $\forall M'_i \in G$ and $M''_j \in H$, calculate the similarity measure, P_{ij} as follows:
   (a) Count the number of candidate match pair between all $m'_k \in M'_i$ and $m''_l \in M''_j$
   (b) The similarity measure between M'_i and M''_j, P_{ij}, is the maximum count recorded in the previous step.
   (c) If $P_{ij} > \Delta$ then M'_i and M''_j are said to be a matched pair. Δ is used to account for sampling noise.
2. The overall similarity measure, P, between G and H, is determined by a simple counting approach. First, we form matching pairs between each $M'_i \in G$ and $M''_j \in H$ such that each will appear only once in all the matching pairs. Since M'_i can have several match with M''_j, we keep only the match that have higher similarity measure P_{ij}. The number of matching pairs formed is considered to be the overall similarity measure P.

The matching pairs formed during the matching process is the corresponding list that is fed into the second step where a modified ICP algorithm is used to estimate the rotation and translation matrices to align the two surfaces.

3.2 Transformation Matrix Estimation

The aim of the registration process is to compute the transformations, which, when applied to the points in that view, it brings the two surfaces into alignment. The desired transformations are expressed by the 3x3 rotation matrix R and 3x1 translation vectors t. The registration procedure can be posed as the minimization of a cost function which measures the sum of squared distances between the transformed corresponding points.

$$\mathrm{E} = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} u_{ij} \left\| p'_i - (R p''_j + t) \right\|^2, \qquad (6)$$

$$u_{ij} = \begin{cases} 1 & if\ (p'_i, p''_j) \text{ forms pairwise correspondence} \\ 0 & otherwise \end{cases}$$

where N_1 and N_2 are the numbers of points in the two surfaces. The Iterative Closest Point (ICP) algorithm proposed by Besl and McKay (Besl and McKay, 1992) is a commonly used framework for solving this surface registration problem. In our work, we used an enhanced ICP algorithm, developed by Williams and Bennamoun (Williams and Bennamoun, 2001) to solve the registration problem.

4 EXPERIMENTAL RESULTS

The registration process using SEPMap scheme has been applied to several object models. In this paper, we present the results of experimenting with four object models (from 3D CAFE website); a chess king, rook, queen, and bishop as shown in Fig. 3.

In the first experiment, we applied rigid transformation (rotation, translation) to the four whole-sized models to form our full-size object set. Fig. 4 shows the model and the transformed object. Table 1 shows the transformation parameters of the experimental objects. The transformation parameters shown are the rotation axis, rotation angle and the translation vector.

In the second experiment, we simulate a form of occlusion where the object does not have a complete 3D-model. In this experiment, we cut a piece of the models and applied to it rigid transformation to form our partial-size object set. Fig. 5 shows the model and the transformed partial-sized object. The transformation paramters are shown in Table 2.

the registration process using L-SEPMap scheme has been applied to the full-size object sets and their corresponding model. Fig. 6 shows the object and the model after registration. Models are shown in light grey-level (gold color) while objects are shown in dark grey-level (purple color).

Similarly, the registration process using L-SEPMap scheme has been applied to the partial-size object sets and their corresponding model. Fig. 7 shows the object and the model after registration.

To verify the accuracy of the registration process, we calculate the sum of the squared distance error, defined in Eq. 6. Table 3 shows the registration errors of the registration experiments. The results demonstrate the effectiveness of the proposed technique visually and analytically. and the ability of the technique in handling the general registration problem of full and partial objects.

All experiments were conducted in a laptop computer with Pentium-M processor 1.8 GHz and 512 MB RAM and assuming 5-degree of neighbors. The average L-SEPMap generation total time (user + I/O + CPU) is less than 2 seconds in a model of 1000 original triangles. The matching total time (registration time is negligible) between a model and object with 1000 triangle patches is less than 10 seconds. The computational and memory requirements are proportional to the number of original triangle patches and the neighbors degree selected in the generation process and can be reduced by applying the L-SEPMap scheme to selected surface patches instead of the comprehensive search applied in this paper.

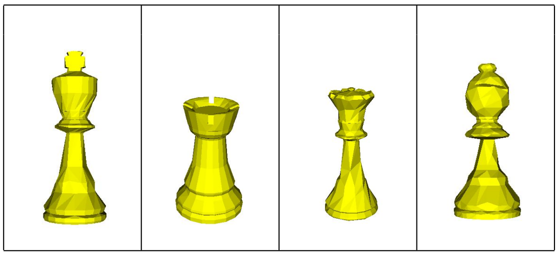

Figure 3: The models library, four chess pieces models, from left to right, king, rook, queen, and bishop.

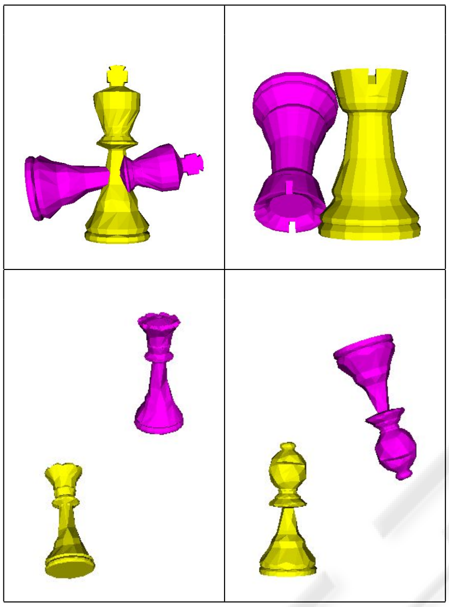

Figure 4: The models (yellow or light) and their transformed objects (pink or dark).

Table 1: Transformation parameters for the full-size objects.

	Rotation Axis	Rotation Angle	Translation Vector
King	z-axis	30	[00, -05, 00]
Rook	y-axis	15	[-20, 00, -20]
Queen	x-axis	45	[30, 30, 33]
Bishop	z-axis	60	[30, 30, 20]

Table 2: Transformation parameters for the partial-size objects.

	Rotation Axis	Rotation Angle	Translation Vector
King	x-axis	-30	[04, 00, 00]
Rook	y-axis	-45	[30, 30, 20]
Queen	x-axis	-45	[30, -20, 30]
Bishop	y-axis	60	[-15, 20, 20]

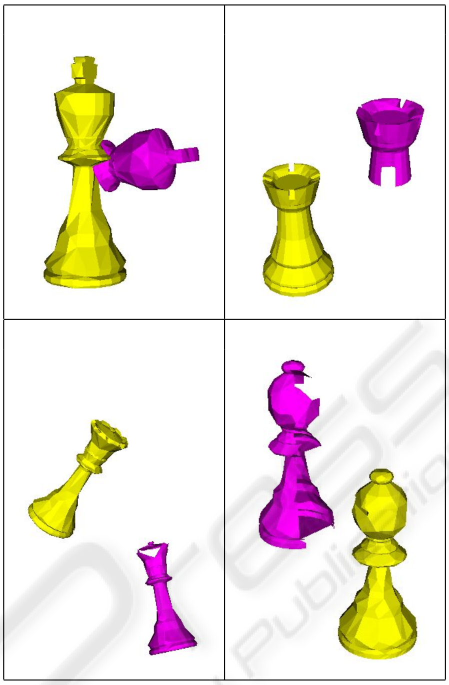

Figure 5: The models (yellow or light) and the transformed partial objects (pink or dark).

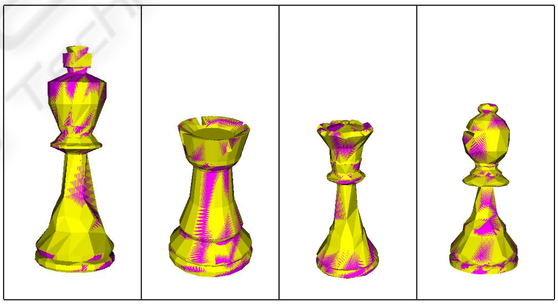

Figure 6: The models (yellow or light) and the transformed objects (pink or dark) after registration.

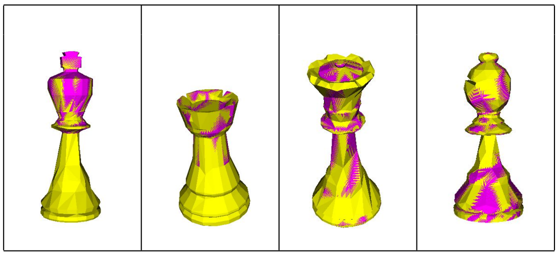

Figure 7: The models (yellow or light) and the transformed partial objects (pink or dark) after registration.

Table 3: The registration errors.

Object	Full Object	Partial Object
King	0.2174	0.0001
Rook	0.0001	0.0844
Queen	0.0001	0.0001
Bishop	0.1011	0.0460

5 CONCLUSION AND FUTURE WORK

L-SEPMap is a surface signature-based representation scheme that is orientation-independent and can be used to align surfaces under rigid transformation. The experimental results demonstrate the effectiveness of the proposed technique and the ability to handle general registration problem of full and partial objects. Several items will be considered in future work. Among those items are , studying the impact of noise on the discrimination effectiveness of the L-SEPMap, experimenting with clutter scenes and different triangulation sampling, applying the L-SEPMap scheme to the 3D segmentation problem, and extending the matching algorithm to handle uniform scaling.

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