A VARIANT OF POINT-TO-PLANE REGISTRATION INCLUDING CYCLE MINIMIZATION

Carles Matabosch[a], Elisabet Batlle[a], David Fofi[b] and Joaquim Salvi[a]

[a] Institut d'Informatica i Aplicacions, University of Girona Campus Montilivi, 17017
Girona, Spain -(cmatabos,bbatlle,qsalvi)@eia.udg.es
[b] Le2i UMR CNRS 5158, Université de Bourgogne, rue de la fonderie 12, 71200
Le Creusot, France - d.fofi@iutlecreusot.u-bourgogne.fr

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ABSTRACT:

3D models are very important in many industrial and scientific applications. Most part of commercial sensors obtain only a partial acquisition of the object, so that a set of views are required to build a complete model of the object. Although the motion between these views is usually unknown, it can be computed by means of registration algorithms. A survey of most important techniques is presented in this paper, in which they have been classified into coarse and fine registration and compared in terms of the number of views aligned at every step, the accuracy and the robustness against outliers. The second part of the article presents an improvement of point-to-plane registration, which includes the determination of cycles in a sequence of views with the aim of minimizing the propagation error or drift.

1 INTRODUCTION

The acquisition and representation of 3D information is a very important topic in Computer Vision. The main steps involved in this problem are: a) Surface acquisition; b) Registration and c) Integration. Surface acquisition is focused on the search of the depth usually by means of laser scanning (Forest and Salvi, 2002) or coded structured light (Salvi et al., 2004) among others such as stereovision (Matabosch et al., 2003) or structure from motion (Armangué et al., 2003). Registration is the process to determine the Euclidean motion between two or more views of a given surface that permits to align them with respect to the same reference (Besl and McKay, 1992). Integration consists of representing the set of views in a continuous and homogeneous surface (Curless and Levoy, 1996).

Although there are many papers focused on surface acquisition, only a few of them obtain a complete reconstruction. Most papers are based on one-shot acquisition, so that only a partial view of the surface is obtained(Salvi et al., 2004). Besides, other papers take advantage of some sort of mechanical system such as robot arms or rotating tables to obtain a set of views with respect to the same reference (Levoy et al., 2000). However, the reconstruction of the surface is still incomplete due to surface occlusions depending on the shape of the surface itself and the number of degrees of freedom of the mechanics. Finally, the accuracy of these kind of systems highly depends on the accuracy of the mechanics.

Range Image Registration is a sort of techniques that computes the motion between 3D views with the aim of aligning them with respect to the same reference without any prior knowledge of the pose from where such views where acquired. Most part of techniques are centered on pair-wise registration so that only two different views are aligned in every registration. Hence, a registration error is accumulated when we are aligning a sequence of views making necessary to use a further process (multi-view) to reduce the drift once all the views are already aligned. In summary, a complete reconstruction of objects is not a trivial problem in computer vision.

In this paper a survey of the most important registration methods is presented in section 2. Furthermore, a summary of the state-of-art is given in section 3. Then, section 4 details the new method proposed to reduce the propagation errors. Experimental results are provided in section 5. The article ends with conclusions.

2 REGISTRATION ALGORITHMS

Registration is defined as the set of techniques used to determine the Euclidean motion between two or more sets of points. There are several varieties of registration: a) 2D/2D Registration; b) 2D/3D Registration and c) 3D/3D Registration. The surveyed techniques differ as to whether initial information is required, so that a *Coarse Registration* can only be estimated without an initial guess. If an estimated motion between views is available, a *Fine Registration* can then be computed.

2.1 Coarse Registration

Coarse Registration techniques can be defined as the group of techniques that estimates the motion between two views without any prior information.

There exists lots of methods to obtain a coarse estimation of the motion. Some of them are especially used in registration applications, while others are adaptations of recognition algorithms. The main idea of them is to characterize some features (points, lines, etc) in both surfaces in order to find correspondences. Although points are the most used correspondences (Chen et al., 1998) (Johnson, 1997), other characteristics can be used such as lines (Stamos and Leordeanu, 2003) or principal axis (Kim et al., 2003). For instance, Johnson (Johnson, 1997) characterizes points by using the Spin Image. This image is a 2D representation of the neighborhood of one point on the surface. Comparing Spin-images from two different surfaces, point correspondences between them can be established. Another point descriptor is the point signature (Chua, 1997). This algorithm describes a point by using all the points located in a constant distance from it obtaining a vector descriptor of the point which is then compared with all points in the second surface to find matchings.

Some authors propose to use lines to find pairs of correspondences. Examples are the straight line-based method proposed by

Stamos (Stamos and Leordeanu, 2003) and the curved line-based method proposed by Wyngaerd (Wyngaerd, 2002). The first one is only applied in structured objects, not in free-form shapes. The second one is based on extracting curves from free-form shapes to find matchings between pairs of segments.

The main problem of most of these algorithms is the large computing time involved in obtaining a solution. This is because once some points on the first surface are characterized, they must be compared with all points in the second surface in order to find correspondences. In general, Spin Image presents the best ratio accuracy/time, and the solution obtained is good enough to be used as an initial guess in a further fine registration.

Although coarse registration techniques are used in many applications, in others the motion is provided by mechanical or manual alignment. Despite the method used to estimate the initial guess, usually the registration error is minimized using next a fine registration technique.

2.2 Fine Registration

Fine registration refers to the set of techniques that obtain the Euclidean motion between two or more surfaces by an iterative minimization. The main drawback of these techniques is the requirement of an initial guess to start the process which may be quite close to the solution to guarantee the convergence. Hereafter, the most known fine registration techniques are discussed

2.2.1 Iterative Closest Point (ICP) The ICP method was presented by Besl (Besl and McKay, 1992). The goal of this method is to obtain an accurate solution by minimizing the distance between point correspondences, known as closest point. When an initial estimation is known, all the points are transformed to a reference system by applying the Euclidean motion. Then, every point in the first image is taken into consideration to search for its closest point in the second image. A new motion is estimated by the minimization of the distances between these correspondences, and the process is iterated until convergence.

ICP obtains good results even in the presence of Gaussian noise. However, the main drawback is that the method can not cope with non-overlapping regions because outliers are never removed. Moreover, when starting from a rough estimation of the motion, the convergence is not guaranteed.

Some modifications of ICP have been presented in recent years. Greenspan (Greenspan and Godin, 2001) applied the Nearest Neighbor Problem to facilitate the search of closest points. The first range image is considered as a reference set of points, which is preprocessed in order to find for every point the neighborhood of points in the second view located at a certain distance. The points of the neighborhood are sorted according to that distance. The use of this pretreatment leads to consider the closest point of the previous iteration as an estimation of the correspondence in the current iteration. If this estimation satisfies the spherical constraint, the current closest point is considered to belong to the neighborhood of the estimate. This pretreatment decreases the computing time drastically. A year later, Jost (Jost and Hugli, 2002) presented the Multi-resolution Scheme ICP algorithm, which is a modification of ICP for fast registration. The main idea of the algorithm is to solve the first few iterations using down sampled points and to progressively increase the resolution by increasing the number of points considered. The author divides the number of points by a factor in each resolution step. The number of iterations in each resolution step is not fixed, so that the algorithm goes to the next resolution when the distance between correspondences falls below a threshold.

Some other approaches (Godin et al., 2001) (Sharp et al., 2002) are presented with the aim of incorporating features in the points to increase the efficiency in the matching. In addition, other authors (Trucco et al., 1999) (Zinsser and Schnidt, 2003) proposed some improvements to increase the robustness of ICP by removing correspondences whose distances are higher than a threshold.

Overall, ICP is the most common registration method used and the results provided by authors are very good. However, this method usually presents problems of convergence, lots of iterations are required, and in some cases the algorithm converges to a local minimum. Moreover, unless a robust implementation is used, the algorithm can only be used in surface-to-model registration.

2.2.2 Method of Chen The algorithm proposed by Chen (Chen and Medioni, 1991) is an alternative to the Iterative Closest Point. The main difference between both algorithms is in the matching algorithm. While ICP uses point-to-point matchings, Chen's approach is based on point-to-plane matchings. Concretely, considering a point in the first image, the intersection of the normal vector at this point with the second surface determines a second point in which the tangent plane is computed. The distance between this plane and the initial point is the function to minimize.

Although of most part of this paper is focused on pair-wise registration, at the end, the author proposed to fuse consecutive views in a single metaview, avoiding propagation errors. This approach can be considered as the beginning of the multiview approach.

Despite of the difficulty to determine the cross point between a line and a plane in a point of clouds, some techniques are presented to speed up this process (Gagnon et al., 1994) (Park and Subbarao, 2003).

Compared to ICP, this method is more robust to local minima and, in general, better results are obtained. The method is less influenced by the presence of non-overlapping regions. The reason is that only the control points whose normal vector intersects the second view are considered in the matching, deferring from ICP, where all points in the first cloud are used in the registration. Moreover, Chen's approach usually requires less iterations compared to ICP.

2.2.3 Matching Signed Distance Fields Masuda (Masuda, 2001) (Masuda, 2002) presented a new registration algorithm based on the Matching Signed Distance Fields. The main idea of a signed distance field is to store the distance to the nearest surface for each point in space. The method is robust so that outliers are automatically removed. Another advantage of this algorithm is that all the views of a given object are registered at the same time, which means a *multi-view registration*. Hence, the propagation error problem is drastically reduced.

Summarizing, all views are first transformed to a reference coordinate system using the initial estimations of the motion. A set of key points are then generated on a fixed-size 3D grid of buckets. Finally, the closest point from every key point is searched in every surface to establish correspondences.

The algorithm presents the advantage of a multi-view registration and the fact that an integration solution is directly given. Besides, this algorithm can not be used in real time applications such as simultaneous localization and mapping because it requires the knowledge of the complete set of views to start the minimization process.

2.2.4 Genetic Algorithms Chow (Chow et al., 2004) presented a dynamic genetic algorithm to solve the registration problem. The goal of this method is to find a chromosome composed of the 6 parameters of the motion that aligns a pair of range images accurately. The chromosome is composed of the three components of the translation vector and the three angles of the rotation matrix. In order to minimize the registration error, the median of distances between correspondences is chosen as the fitness function.

Therefore, only a sample of points of the first image are used to compute the error with the aim of decreasing the computing time. New chromosomes (potential solutions) are generated by cross-over and mutation operators. The cross-over operation consists in combining genes made by two chromosomes to create a new chromosome. The number of genes to be swapped is randomly selected in each iteration. The cross-over operation works well when the chromosome is far from the final solution but it is useless for improving the solution in a situation close to convergence. Therefore, the mutation operation was defined as follows: a gene is randomly selected and a value randomly obtained between the limits $[-MV, +MV]$ is added. The limits are very wide at the beginning and become narrower at every step in order to guarantee the convergence in the final steps.

A similar method was proposed the same year by Silva (Silva et al., 2003). The main advantage of this work is that a more robust fitness function is used and no initial guess is required. The author defined the Surface Interpenetration Measure (SIM) as a new robust measurement that quantifies visual registration errors. Another advantage compared to Chow's method is the multi-view registration approach. Finally, the hillclimbing strategy was used to speed up the convergence.

Overall, the use of genetic algorithms has the advantage of avoiding local minima, which is a common problem in registration, especially when the initial motion is not provided or it is given with low precision. This algorithm also works well in the presence of noise and outliers given by non overlapping regions. The main drawback of this algorithm is the time required to converge.

3 SUMMARY OF THE STATE-OF-ART

Referring to Pair-wise registration, Chen's approach presents the best results in terms of accuracy and convergence. Although, the fact of computing the normal vectors may be considered a drawback, most of the commercial sensors directly provide this information during the acquisition step. Otherwise, normal vectors can be estimated by local planar approximation. Another important aspect is that Chen's approach obtains the best results in case of low sampling data. The reason is that ICP needs point-to-point correspondences, so that in the presence of a low resolution it is very difficult to ensure that the same 3D point is present in both views. Besides, point-to-plane distances let us to establish correspondences between points in the second image that are not present but estimated by a local planar approximation. So, it is easier to find fine correspondences in a point-to-plane approach.

Another important aspect in registration techniques is the percentage of overlapping area. Although original ICP can not cope with non-overlapping area, robust variants presented by Trucco and Zinsser obtain good results because of the removal of outliers (Trucco et al., 1999) (Zinsser and Schnidt, 2003). In Chen's approach, as only correspondences are considered if the normal vector intersect with the other surface, some outliers are removed avoiding convergence problems. The method of Chow is also very robust against outliers, however the high computing time is an important drawback in genetic algorithms.

Most part of algorithms presented are based on Pair-wise registration, so that only two views are registered simultaneously. This fact implies that in the presence of more views, a sequence of pair-wise registration must be computed. As every registration presents errors in the computation, this error is accumulated through all the views producing a drift in the alignment. In order to solve this problem, a refinement step is required. There are several possibilities to apply this refinement. A solution is to apply a multi-view algorithm (Pulli, 1999) (Masuda, 2001). Although this is probably the most accurate solution, it presents some problems when lots of views are used. First, the time involved in the registration is very high. Second, due to propagation errors, initial guess of the multi-view algorithm can be far from the solution, producing errors in the convergence. Finally, it can only be used once all views are already acquired.

With the aim of solving these problems, some other proposals have been recently presented. The main idea is to determine loops between the views. A cycle is considered when the actual acquisition contains significant overlapping area with a previous surface. A minimum number of views is required in order to avoid loops in consecutive acquisitions. The idea of a loop is similar to robot navigation where a cycle is considered when the same place is revisited by a robot. When a cycle is determined, the accumulated registration error associated is computed by forcing the product of all matrices to be the identity. Some authors (Sharp et al., 2004) distributes the error through all the views of the cycle. However, some rules are required to distribute the error between views properly. Another important step is the way a cycle is determined. Registration errors can increase dramatically if a cycle is estimated between views that do not really form a cycle.

Although, the method proposed by Sharp solves the drift problem between the initial and the final view in a cycle, the propagation error is not always correctly distributed through the rest of views. The final view is forced to be well registered to the initial view, and the transformation involved in this motion is distributed through the rest of views depending on the weight associated to each view. Hence, the selection of the weights of every view is crucial to obtain good results. If these weights are not very accurate, the error is badly distributed, obtaining misalignments inside the loop. Views near the endings are good located, but not the views far from them. In order to solve this problem, we propose to analyze simultaneously all the views belonging to the loop, as explaining next section.

4 REFINEMENT STEP

In order to solve the problem of the propagation error without using all views in the minimization, we propose to minimize the error in a loop by only considering the views that have common information. Note that in large sequence of views, when views are registered simultaneously, a lot of time in general is wasted in searching potential correspondences between views that do not even contain overlapping area.

Our algorithm is based on Pair-wise registration of consecutive views until a cycle is determined reducing the search of correspondences to only the views with overlapping area. Then, all the views of the cycle are minimized simultaneously to remove propagation errors. Finally, the algorithm follows until another cycle is found or no more surfaces are acquired.

The goal of our application is to develop an algorithm to register surfaces acquired by a 3D hand-sensor. Our refinement approach

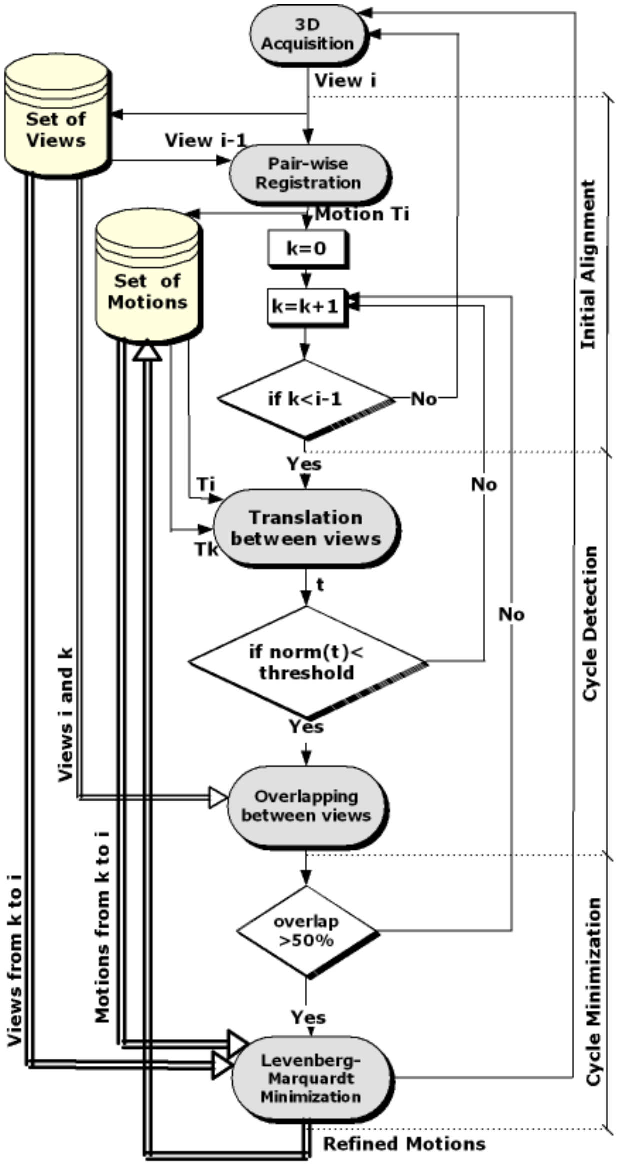

Figure 1: Flow diagram of the proposed method

is composed of three main parts: a) Initial alignment; b) Cycle detection; and c) Cycle Minimization. All the steps are shown in Figure 1 and detailed in the following section.

4.1 Initial alignment

The first part of the algorithm is focused on obtaining an initial alignment. As views are acquired consecutively, we assume that two consecutive views are close one to the other. This assumption only fails when we analyse two views that have not been acquired consecutively but they belong to a sequence. In this case, the motion between both views is computed by the product of all the motions in the sequence.

The algorithm selected is based on the method of Chen. However, some modifications have been done to increase the accuracy. The Normal Space Sampling defined by Rusinkiewicz (Rusinkiewicz and Levoy, 2001) is added in order to select the most representative points in the first image. Furthermore, the proposal of Park (Park and Subbarao, 2003) is used to speed up the process. An example of registration is presented in Figure 2.

Figure 2: Result of pair-wise registration between two consecutive views

4.2 Cycle detection

A cycle is defined as a set of views that forms a sequence and the initial and final views shares a large overlapping area. The cycle determination step consists in searching for surfaces whose overlapping region is significant. As two consecutive views contain lots of points in common but do not form a cycle, a minimum number of views in a sequence is required to check if they form a cycle.

In order to determine if two views are close enough, the motion between them is computed by using pair-wise registration. The motion (${}^{j}T_{i}$) between any view (i) and the last view acquired (j) is estimated by the product of all consecutive motions (${}^{k}T_{k-1}$) from i to j as shown in equation 1.

$$ {}^{j}T_{i} = \prod_{k=i+1}^{j} {}^{k}T_{k-1} \qquad (1) $$

Then, the translation is given by the fourth column of ${}^{j}T_{i}$. Finally, both views are considered close one to the other if the norm of the translation vector is smaller than a threshold.

In order to validate this result, the overlapping percentage between both views is computed. First, as the computation of the overlapping region is hard consuming, an approximation is applied. Hence, the 3D bounding box of both surfaces is computed. Then, the overlapping is analyzed in 2D by projecting both bounding boxes on the planes X-Y, X-Z and Y-Z. Then, the percentage of overlapping area is computed by means of the overlapping of the bounding boxes in such planes. If this overlapping percentage is higher than a threshold (50% in our case), a loop is considered between these views. Second, in order to speed up the process and assuming that the real overlapping area is not necessary but just a percentage, an approximative but very fast computation is proposed. Hence, a nxn matrix is defined whose elements are increase by 1 if they belong to any box, and unset to 0 otherwise. Then, an approximation of the overlapping area is obtained by counting the number of 2 divided to the area formed by both boxes.

4.3 Cycle minimization

When a cycle is found, a multi-view minimization must be applied to decrement the propagation errors. In order to take into account all the views of the cycle, corresponding pairs are simultaneously searched for in all views. For each view i, the translation vector with respects to the other views j is computed. If the distance is small enough to guarantee an overlapping region, point-to-plane correspondences are searched for, obtaining two sets of points P_{ik} and P_{jk}, where P_{ik} and P_{jk} are the points from the view i and j, respectively. Then, the function f to minimize is the following:

$$f = \sum_{i=1}^{N-1} \sum_{j=2}^{N} \sum_{k=1}^{N_p} P_{ik} - (T_i^o \times)^{-1} T_j^o \times P_{jk} \qquad (2)$$

where N is the number of views in the cycle, N_p is the number of point correspondences between views i and j and T_i^o is the transformation matrix than aligns view i with respect to the first view in the cycle. This function is minimized by using Levenberg-Marquardt algorithm.

5 RESULTS AND DISCUSSION

In order to test our approach, real images are acquired with the 3D sensor developed in our laboratory (Matabosch et al., 2006). The goal of this sensor is to acquire 3D surfaces by means of a on-the-self camera and a stripe laser composed of 19 slits. The set-up lets us to acquire views from moving objects or acquire consecutive views while the sensor is manually displaced around the object, without any prior information about the pose.

As the goal of the experiments is to evaluate the accuracy of the registration process, the sensor is placed on a XYZ-translation table (see Figure 3). In this experiment the object of Figure 5a is used and 27 consecutive views are acquired.

Determining the transformation matrix that relates the coordinate system of the sensor with respects to the coordinate system of the table, the motion between consecutive views can be computed and compared to the motion obtained by the registration process.

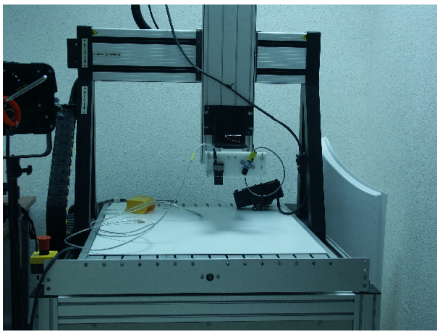

Figure 3: Set-up used in the experiments

Both translation and rotation errors are represented in Figure 4. Translation errors are obtained as the discrepancy between the real translation (given by XYZ-Table) and the estimated one (obtained by registration). Rotation errors can be analysed by comparing the angle between both real and estimated rotation axis and the discrepancy between the norm of both axis of rotation. Figure 4 shows that our method is suitable to reduce the propagation error in the presence of cycles. Although Sharp's method obtains better results at the end of the cycle (view 21), the error is worse distribute inside the view with respect to our approach. After this view, the error increases because no other cycle is found.

The complete reconstruction is shown in Figure 5, where an integration algorithm is applied to obtain a continuous surface without redundant information. The algorithm used is based on the Volumetric Integration method of Curless (Curless and Levoy, 1996).

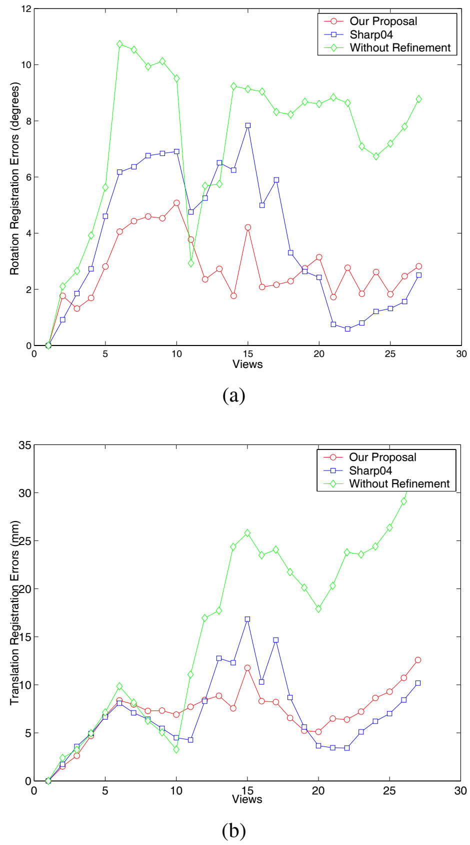

Figure 4: Evolution of the registration errors: a) Rotation Errors; b) Translation Errors

6 CONCLUSIONS

In this paper, a survey of registration techniques is presented discussing the pros and cons among them. Furthermore, as most part of registration algorithms do not solve the problem of error propagation, some approaches are discussed and a new proposal is presented.

Our proposal is based on minimizing the registration errors between all views contained in a loop. A loop is detected by computing the translation vector between views. Then, in order to prove that a real loop exists, the overlapping between the first and the last view in the loop is computed. An approximation of the overlapping area is computed by means of the projections onto planes X-Y, X-Z and Y-Z with the aim of reducing the computing time.

When a loop is found, global error is minimized by using a multi-view registration algorithm based on Levenberg-Marquardt and point-to-plane correspondences.

Results show that errors are less important compared to the ones obtained by using traditional Pair-wise approach. Furthermore, as only views of the same cycle are simultaneously minimized, our approach obtains better accuracy in less computing time compared to a classic multi-view.

These experiments also show than our method obtain better results than the proposal of Sharp. This is because our proposal minimize the global registration error whereas Sharp's algorithm

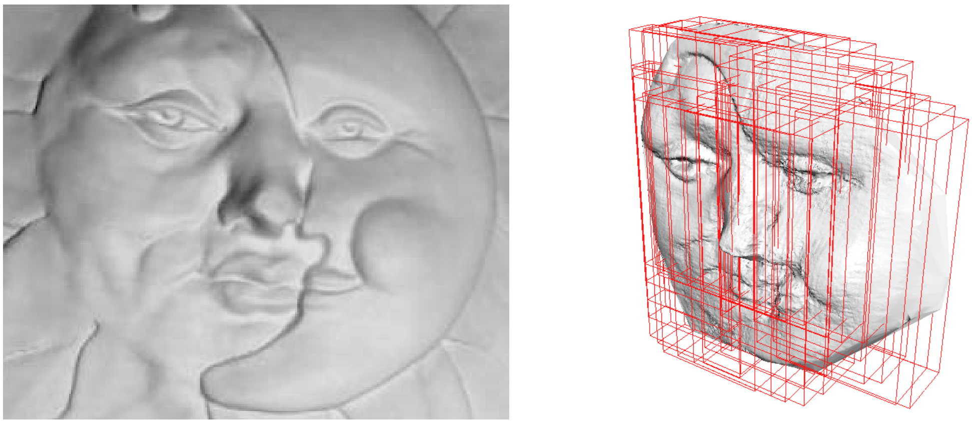

Figure 5: Complete registration of a real object: a) Picture of the object b) Final registration including bounding boxes of all 27 views acquired to obtain the final model

only force that the error between initial and final view of the cycle must be zero, then the error is distributed through the views of the cycle. On the other hand, this distribution does not require significant computation, obtaining final results in less time than our proposal.

Experimental results are done with real objects, obtaining both visual and quantitative good results.

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