A match and merge method for 3D modeling from range images

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Abstract: This paper presents a new method for combining several range images to create a complete virtual model of an object. It considers the problem of unpositioned range images, which must be registered before their fusion into the final model. The proposed method relies on a modeling which preserves the topology of the range images and introduces a new view fusion algorithm that is coupled with registration. The successful operation of a modeling system that implements this method, illustrated by some examples, speaks for its applicability and practical efficiency.

1. Introduction

Application like virtual museums, reverse engineering or industrial inspection generally need virtual models that are very close to their real counterpart. Range scanners now provide a simple and fast way to capture 3D data but most of them suffer from the same problem: as data is measured from a single point of view, only a part of the object surface can be scanned at a time. Consequently, acquisitions from several viewpoints must be performed and these views must then be combined to create the final model.

Typically, the modeling process can be divided into three phases. The surface of the object is first measured from several viewpoints. Then, in a second step named registration, the resulting views are aligned, in order to retrieve their relative position with regard to the object. Finally, the different views are fused into a unique mesh that covers the entire object.

The registration is straightforward if the scanner-to-object relative position is known for each view but when this does not apply, one must rely on the intrinsic properties of the surfaces like geometry, orientation or color to register them. This paper considers such an approach.

Several authors investigated that problem: Besl [1] proposed an automatic surface registration algorithm called ICP. It uses two sets of data points as an input and registers them by minimizing their mean square coupling distance. In the original algorithm, one set must be a subpart of the other, which is not the case in the present application where each surface contains data not present in the other. Turk [12] proposed a modified version to take that fact into account. Finally, Schütz [10] proposed to also consider color and surface orientation in the ICP matching algorithm for a better matching.

Once the surfaces are matched, they must be fused together in order to eliminate redundant data and to create a unique mesh. The methods that have been proposed to integrate 3D views mainly differ in how they treat redundant data. They can be separated into two groups: partial erosion of surfaces and complete retriangulation of the surface points. Several authors [7, 12] erode the overlapping surfaces until the overlap disappears. The two surface meshes are then recombined at their frontiers in order to have one unique mesh for the union of the two surfaces. Other authors [2, 8, 11] discard the mesh information from the triangulated views, if calculated at all, and retriangulate the overlapping zone or even the complete point set.

This paper proposes a novel match and merge method, which relies on a modeling that preserves the range image topology all along the reconstruction and introduces a new fusion algorithm that is coupled with registration. Topology preservation is an advantage because range images provided by scanners can be easily triangulated. It permits to avoid later triangulation and it also permits to create models from textured views.

The new fusion algorithm, unlike other works where the fusion is a totally separated task (involving 2D projection or similar complex algorithms), couples fusion with registration and takes full advantage of the available mesh correspondence to treat overlapping areas. This link between registration and fusion permits to create a simple and effective view fusion algorithm.

A basic description of the modeling system can be found in section 2. Following sections focus on the description of the registration and fusion algorithms that implement the new match and merge method. Finally, models obtained by the presented method with various objects are shown.

2. System Architecture

A general diagram of the modeling system is presented in figure 1. Of course, the input of the system is the object to be scanned. The view digitizing block captures range images with the help of a range scanner and creates virtual views from them. These virtual views are then combined in the view integration block, which outputs the expected virtual model. A more detailed description of both blocks follows.

2.1 View Digitizing

The main goal of view digitizing is to acquire the 3D data for each view and to present them in a virtual view format that preserves the topology of the scanned surfaces. Three main parts compose the view digitizing block: Data acquisition, hole filling and view triangulation. The output is a triangulated mesh which is possibly colored or associated to a texture map [4].

2.2 View Integration

The integration process is iterative, a new virtual view being added to the virtual model under construction at each step.

The view integration block is subdivided into another two blocks: view registration and mesh fusion. During view registration, the relative positioning between the new view and the virtual model is found. During mesh fusion, the new view and the virtual model are fused into a single mesh. As we said before, view registration and mesh fusion are linked together in the sense that the fusion algorithm takes advantage of the correspondence established during registration.

Both registration and mesh fusion are now described in detail in section 3 and 4.

3. View Registration

Any additional view which is to be added to the virtual model has to be registered first with the virtual model. The registration that performs this task proceeds in two distinctive steps: rough positioning and fine positioning; rough positioning being solved by an interactive pose estimation task and fine positioning being solved by an automatic matching task.

3.1 Interactive pose estimation

Human perception easily identifies corresponding surface parts for any object type and shape. Therefore, the user can easily enter a hint by means of an interactive interface. Fig. 2 shows an example of two roughly aligned surfaces used as starting configuration for the automatic matching.

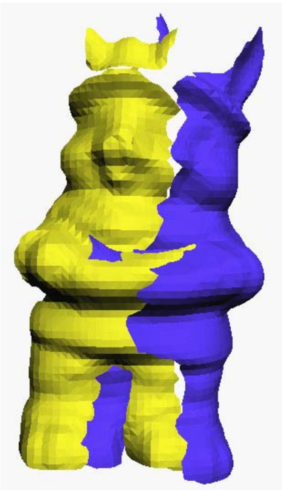

Figure 2: *Roughly aligned views*

3.2 Automatic Matching

Besl proposed an algorithm called ICP for performing automatic surface registration [1]. This algorithm registers two surfaces starting from an initial pose estimate. The algorithm proceeds iteratively. First, it pairs every point of one surface called P with the closest point of an other surface called X. These pairs of closest points are used to calculate the rigid transformation (**R**, **t**), which minimizes their mean square coupling distance or error. The surface P is then translated and rotated by the resulting transformation and the algorithm starts again with the closest point coupling. This algorithm has been shown to converge but not necessarily towards the optimal solution. A good starting configuration is preliminary to a successful convergence. However, the range of successful starting configurations is rather large (see [3] and Fig. 2) and does not constraint the operator too much when entering a pose estimate.

In the original algorithm one surface is a subpart of the other which is not the case in our application where each surface contains data not present in the other. The ICP algorithm needs therefore to be modified as proposed by Turk [12]. Closest points which are too far apart are not considered to be corresponding points and are not coupled. The calculated closest points couplings are therefore weighted as follows:

given $\mathbf{x}_k \in \mathrm{X}$ and $\mathbf{p}_k \in \mathrm{P}$

$$w_k = \begin{cases} 1 & d_k < (c \cdot s \cdot r)^2 \\ 0 & else \end{cases} \qquad \text{Eq. 3.1}$$

with $d_k = \|\mathbf{p}_k - \mathbf{x}_k\|^2$ and $k \in [1, \ldots, N_p]$

which results in the modified error minimization

$$e(\mathbf{R}, \mathbf{t}) = \frac{1}{W} \sum_{N_p} w_k \|\mathbf{R}\mathbf{p}_k + \mathbf{t} - \mathbf{x}_k\|^2 \qquad \text{Eq. 3.2}$$

$\forall$pairs of $(\mathbf{p}_k, \mathbf{x}_k)$ and $W = \sum_{N_p} w_k$

This modification assigns the weight zero to invalid couplings as shown in Fig. 3. The decision threshold for a valid coupling square distance is set to the product $(c \cdot s \cdot r)^2$ where s equals the sampling distance and r equals the reduction rate. The constant c allows to control the convergence and the precision of the matching.

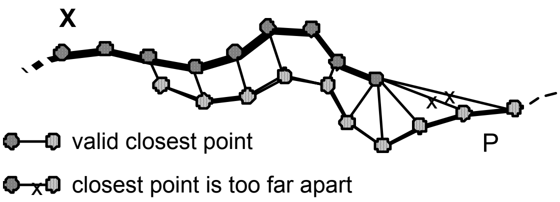

Figure 3: *Closest point couplings for two surfaces*

Schütz [10] proposed to also consider color and surface orientation in this matching algorithm. It permits to have a better coupling, especially when both surfaces are quite symmetric because pure geometry is generally not sufficient in that case.

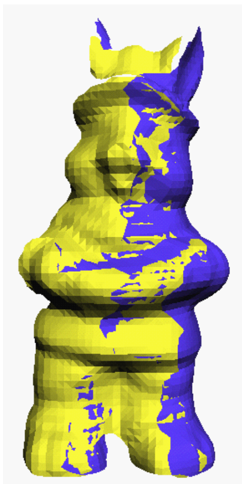

Figure 4: *Fully registered surfaces*

Experiments on several objects showed that the modified ICP algorithm converges quickly. As mentioned before, the two surfaces should have enough common data points. 30 to 50 % of common surface has been observed to be a good amount. Fig. 4 shows the same surfaces as in Fig. 2 after the execution of the automatic matching.

In order to verify the registration quality and to stop the iteration a pertinent measure is needed. The minimization error e corresponding to the mean of the square distances is a measure generally used to qualify the matching. Another statistical measure which has been used successfully to qualify matched surfaces [9] is the deviation of the square distances indicating the matching regularity. Both values should be as low as possible. But, this may lead to a solution where only very few points are coupled. In order to avoid such cases, matchings with a high number of coupled points on the surface P are selected, as proposed by Krebs [6]. The percentage of coupled points on P together with the mean and the deviation are printed for every iteration of the automatic matching and allow the operator to continuously evaluate the matching.

4. View Fusion

Once a view has been registered with the partial model, both meshes need to be fused together to create a unique mesh. The new view fusion algorithm operates on triangle meshes and proceeds by erosion. As said in the introduction, it takes advantage of the correspondence established during registration to eliminate redundant surfaces and to triangulate the resulting gap.

More precisely, this mesh fusion algorithm is characterized by the following steps:

1) **overlap detection:** The valid couplings $(\mathbf{p}_k, \mathbf{x}_k)$ from the previous automatic matching are used to easily identify the parts of surface P which overlap surface X where P and X are defined as in the previous section.
2) **overlap erosion:** The overlap part of surface P is eroded.
3) **frontier detection:** A gap separates the surface X and the eroded surface P. The frontier on P is calculated during the overlap erosion where a closest point search detects the start of the frontier on X.
4) **gap filling:** The gap enclosed by the two frontiers is filled with triangles with an algorithm similar to the one proposed by Pito [7]. The filling algorithm works in 3D space and does not need any projections into tangential planes which increases its reliability.

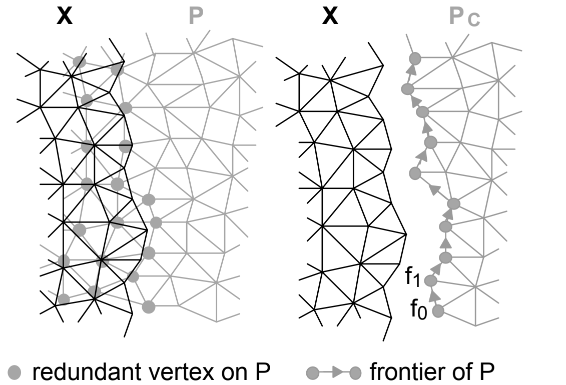

Figure 5: *Erosion of the redundant zone and frontier detection*

The details of the algorithm are discussed below and illustrated by examples in the figures 5 and 6.

The following deterioration of the gap filling algorithm have to be avoided. First, if the frontiers of the two surfaces diverge which results in a large gap or second if the bridge triangle normal is negative indicating a filling in the wrong direction. In these cases new candidates are calculated, the filling process is initialized with the next edge from the edge list or the filling is stopped.

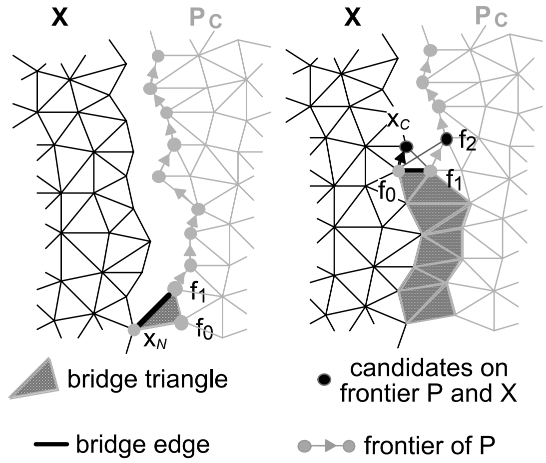

Figure 6: *Gap filling initialization and iteration procedure*

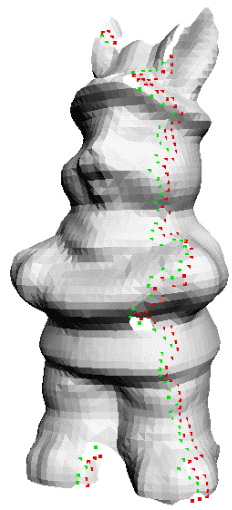

Figure 7: *Fusion result*

5. Results

The presented method has been integrated in a complete modeling system that associates various range scanners and a modeling environment running on a SGI workstation. Two structured light scanners based on projectors by ABW were used. These scanners are based on space coding principle and use projected stripes and triangulation. They vary in size and resolution: their resolution is about 0.5mm and 0.07mm and the maximum size of the object to be scanned is respectively about 400mm and 50mm. The modeling environment is programmed in C/C++, using the Open Inventor library to manage 3D data. Views and models are implemented in indexed face set lists containing triangles, for use by the display routines and the data manipulation algorithms. The use of a common data structure reduces memory overhead and keeps data conversion routines at a minimum.

Object modeling by the proposed method is illustrated by two examples. The first one is a texture mapped model of a clay rabbit. This model was built using a decimation of the vertices and a texture. It permits to reduce the amount of data and to create a realistic looking model. The resolution of this model is about 2mm. It was reconstructed using 8 views and contains about 4000 vertices and 7800 faces. This result is a typical example of a multimedia type model, which requires a good appearance and low data size but where high geometric precision is not necessary.

The second example is a reconstruction of a watch frame. The resolution of this model is about 0.15mm. It contains 60000 vertices and 115000 faces and required about 20 views. This is an example of model that can be used in industrial application like reverse engineering. In such case, high resolution is required to have a good precision.

These examples show that the presented algorithm can be used to create realistic looking as well as precise virtual models of real objects.

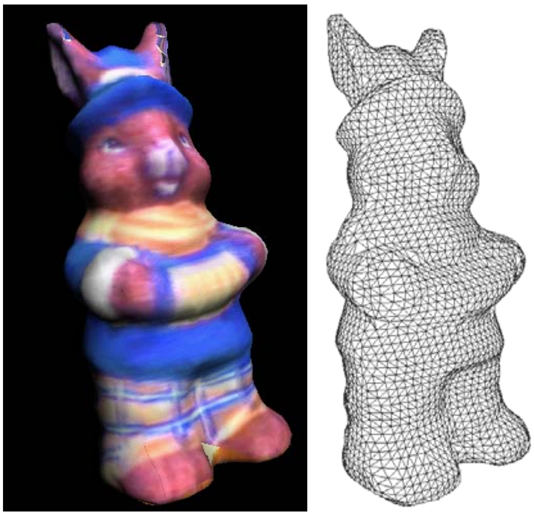

Figure 8: Textured model of a clay rabbit

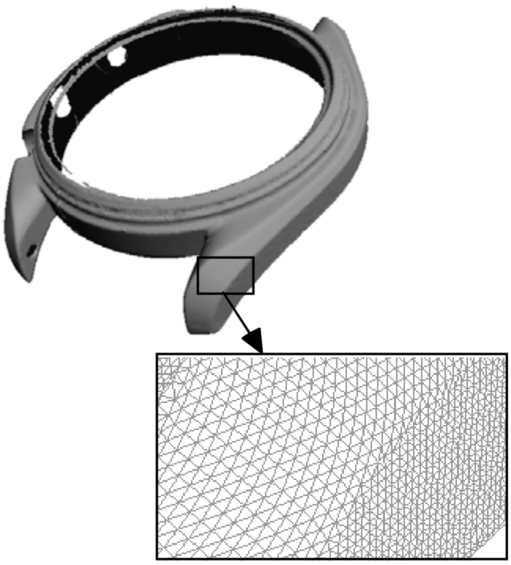

Figure 9: High resolution model of a watch frame

6. Conclusion

A modeling method with a new fusion algorithm is presented in this paper. It combines several range images to create a complete virtual model of an object. It considers triangulated views from unpositioned range images. The relative positioning of the views, or registration, is based on the intrinsic characteristics of the surfaces only. The view fusion algorithm is coupled with registration, taking advantage of the neighborhood correspondence established during the automatic registration process. It keeps most of the existing view triangulation, removing redundant surfaces and linking remaining meshes together.

A full system using this method was built around a range scanner based on structured lightning. Several objects have been scanned and results proved this simple algorithm to be effective, be it for precise, high resolution models or for realistic looking, textured models.

7. References

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