Efficient 3D Shape Acquisition and Registration Using Hybrid Scanning Data

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Abstract

We consider efficient 3D shape acquisition and surface registration using dissimilar laser range scanners. Most previous solutions do not use global shape information for optimal local surface registration. In this paper, we exploit the fundamental 3D scanning "trade-off" between the coverage of the global shape structure and numerous local surface patches to construct a hybrid laser scanning system provided that it can acquire both global and local shape information. The scanned low-resolution global shape data supplies the global shape structural prior for registering the high-resolution local 3D surface patches. Local surface patches can thus be optimally registered requiring less overlapping and thus reducing redundancy. To verify the feasibility of this system, we have implemented a prototype based on two laser range scanners, a hand-held one for the coarse global low-resolution model and a second stationary high-resolution line scanning system. This prototype system was evaluated for various real 3D models. Based on geometric data alone without using texture information, the results show that the proposed hybrid 3D scanning approach outperforms previous approaches in the presence of noise and outliers. The approach can be further applied to other practical 3D shape applications.

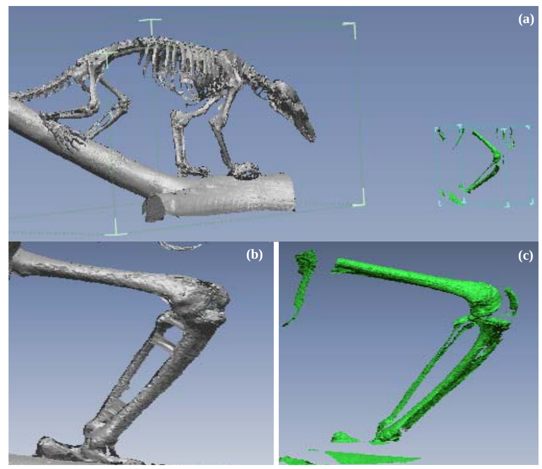

Figure 1. (a) A scanned low-resolution complete 3D shape model. (b) Zoom in (a). (c) A scanned high-resolution local surface patch.

1. Introduction

3D shape acquisition and surface registration is important in computer graphics, vision, and related fields. Although recently some 3D acquisition techniques like structured light, coded light, time-of-flight, Moire interferometry, and triangulation-based laser range scanners have been gradually developed, efficient and high-quality 3D acquisition and surface registration is still a hard problem.

Generally, 3D shape laser measuring techniques can be classified into two groups according to the measuring mechanism and scanning hardware. One type of high-precision laser scanning system includes a camera system and a laser beam or a laser plane. The 3D shape is recovered using triangulation based on the intersection of the illuminating laser beam and the rays projected back to the camera. During each scanning process, the scanning system is stationary and the focal length of the camera system is adjusted according to the scanning facades. Therefore, one needs to rotate and translate the 3D object to cover the entire 3D shape. Such range scanning systems can often achieve high-resolution scanning patches of the 3D object, e.g., Fig. 1(c). An alternative type of hand-held laser scanner is light and movable. The position and orientation of such laser device is computed on-line using different mechanisms such as electromagnetic sensors, or optical LED tracker, etc. Therefore, the hand-held laser scanner can easily acquire a relatively low-resolution global shape model within a continuous scanning period, e.g., Fig. 1(a)(b).

However, to acquire a complete 3D shape model, most surface registration methods use only those scanned local surface patches. In these cases, it is not easy to get high-quality 3D shape models due to difficulties of registration and lack of global shape information. These problems can be listed as follows. (i) Typically, local areas of the surface appear in several different scans. It is hard to select the most suitable scanned local surface patch from many scans and discard the other scans. (ii) With the extraction and voting of local features without global measure criteria, small alignment errors for local patches may accumulate to large distortion [13, 15, 18]. (iii) It is difficult to find naturally global shape geometric prior information which can optimally adjusts local surface registration. For example, Fig. 2 shows some registration error using only numerous local surface patches without global shape geometric prior information.

To solve these difficulties, a considerable amount of research has been dedicated to 3D surface registration from different sides such as rigid pairwise local-surface registration, rigid global surface registration and nonrigid surface registration. A classical method for rigid pairwise local-surface registration is the Iterative Closest Points method (ICP) [3, 4, 7]. A similar method named free-form surface registration with adaptive threshold is also independently proposed by [26]. Later on, a sampling based ICP method has been proposed [12] for improving local-patch alignment using constraints of rigid transformation. Rigid global surface registration methods have been proposed for simultaneously registering all local scans in rigid transformation [7]. In this case, since some registration errors are easily accumulated through the alignment of local patches, other methods focus on reducing the errors, e.g., closed-form methods [2, 16], parallelizable pairwise alignment [19], and so on. Nonrigid surface registration methods can be considered as an extension of the Thin-Plate-Splines (TPS) [5] method, e.g., non-rigid-shape with rigid-component warping [14], vertex affine transformation [1], extended TPS [9], and surface interpenetration measure based genetic algorithm [21].

Furthermore, most 3D surface registration methods use certain assumptions. For example, the ICP algorithm needs a good initial alignment [3, 4]. On the other hand, certain measure criteria are also used for local feature extraction [11, 23] due to high-dimensional feature voting spaces. Certain global measure criteria are used for unifying the registration solution [17]. However, in practice, due to the large space of possible 3D shape deformations, transformations, and complexities of noises, registration of local surface patches tend to be local redundance and global uncertainty. From sequentially scanned local patches, it is also hard to find global shape information which keeps the consistency of local surface registration and the fidelity of the recovered global shape.

In this paper, the goal of our hybrid laser scanning system is to aid local surface registration using global shape information. The suggested new data acquisition system uses hybrid scanned data sets from a stationary and a hand-held non-stationary laser scanner. The approach are described in the following. Firstly, in order to obtain the required information, we define the fundamental 3D scanning trade-off between the coverage of the global shape model per scanned patch and numerous local surface patches. In place of many small local patches, we can work with a global scan together with fewer local scans. Secondly, the local scans are registered not only pairwise but also simultaneously with respect to the global shape model. In this way, different types of registration errors and distortions are minimized. In our system, using geometric shape information alone, we extract geometric feature points [11] using raw data which can largely preserve the original shape information. Furthermore, we formulate the surface registration problem in an adaptive regularization energy function. This leads to a linearly constrained non-linear optimization problem which can be solved very efficiently.

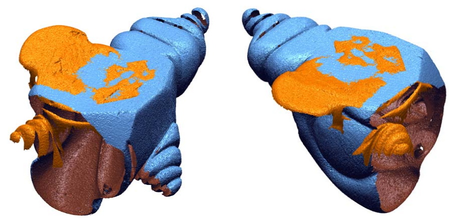

Figure 2. $a|b$**. Registered and merged patches are shown in blur(outside) and brown (inside). The patch (orange) is registered at the wrong position. It should close the hole at the bottom of the model.**

Finally, this approach is simple and robust in the presence of noise and outliers. Experiments show that the prototype hybrid scanning approach outperforms previous approaches. Our approach can efficiently achieve high-quality 3D shape acquisition and surface registration.

2. A 3D Shape Scanning Trade-off

Since most 3D acquisition and reconstruction systems can only reconstruct or acquire certain 3D patches (e.g., outdoor scenes, indoor objects), it is still difficult to achieve a complete high-quality 3D shape. Even for laser scanner 3D acquisition systems, a trade-off between local geometric surface patches and the global shape structure is still crucial for achieving efficient and high-quality surface matching and registration. For example, the alignment of the scanned local surface patches should not influence the final shape fidelity. It is important to align the local surface patches correctly without certain distortions. However, with a growing number of overlapping of local surface patches, the accuracy of local geometry might be improved but the accumulated distortion and error can be also increased. To optimize the result, we need certain global shape structure information to optimally adjust and control the registration of numerous local surface patches.

The relationship among the coverage of per patch, resolution of scanned patches and the number of scans of an object is illustrated by the solid curve in Fig.3. Since there are a lot of overlaps and scanning noises among scanned local surface patches, the curve is not straight. These curves are mainly determined by the characteristics of the given scanned objects, e.g., size of the object, geometric complexity, and so on. Different objects might have different number of scanned local patches to cover a global shape model. That is, if a 3D shape object has more scanned local surface patches, each of these local surface patches might have high-resolution but lower coverage of the global shape structure. On the other hand, the higher coverage of a global 3D shape model can supply more geometric structure features and global shape geometric information.

Instead of relying on one type of scanned local data patches, we propose to use two very different scanning data for 3D shape acquisition and surface registration, e.g., high-resolution local surface patches together with a low-resolution global shape structure model. The hybrid stationary and non-stationary hand-held laser scanning system for one object is illustrated by two dots in Fig.3. As we shall see, these two type of 3D laser scanners complement each other by supplying high-resolution local surface patches and low-resolution well-structured global shape models.

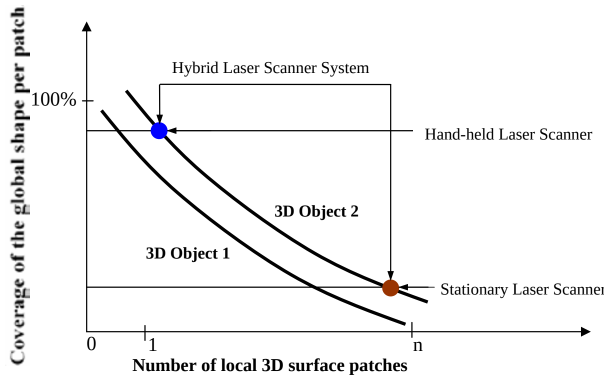

Figure 3. The trade-off between the number of scanned local surface patches and the coverage of the global shape structure. More high-resolution local surface scans cause more difficulties on surface registration.

3. Surface Registration using Hybrid Data

Based on the analysis of the hybrid scanning data, our proposed approach needs to process not only pairwise rigid local surface alignment but also local-to-global non-rigid surface registration using the global geometric shape prior.

Therefore, we propose a new approach to align the local surface patches in a local-to-global manner using the hybrid data. The diagram of the proposed approach is shown in Fig. 4. In this diagram, pairwise local surface are aligned in the rigid ICP method so that we can keep more fidelity of those aligned local surface patches. Simultaneously, each local surface is non-rigid adjusted using a global nonrigid TPS bending algorithm.

3.1. Rigid Local Surface Registration

When we register many local surfaces, we use the ICP algorithm. The ICP algorithm for registering two point sets was introduced by [4, 7]. Basically, this algorithm iteratively performs two operations until convergence. The first operation consists of finding the closest point in one point set for each point in the other set. In the second operation, the minimal distance between the two point sets is estimated using only the corresponding point pairs. To improve the performance of the classical ICP method, a lot of extensions of the method have been developed. A comprehensive analysis of these extensions to the original ICP algorithm is summarized by Rusinkiewicz et al. [20].

To apply the ICP algorithm for large amounts of scanning data, two fundamental questions need to solved for achieving more robust local surface registration. Similar to most non-linear minimization algorithms, the first question is how to construct an initial alignment for any given point sets that can ensure a correct global convergence. The second question is how to construct an efficient mechanism that can adaptively sample points from all scanned local patches to have an efficient registration with respect to the correct global minimum. Traditionally, it is hard to solve these two questions using only numerous scanned local surface patches. In most cases, this initialization can be obtained by using knowledge about the position of the 3D sensors or by user input. If it is not possible, more complicated techniques like principal component analysis with a constrained exhaustive search [8] become necessary.

Using hybrid scanning data, the complexity of searching a good initial alignment is simplified. The scanned low-resolution global shape model supplies accurate initial global feature points. Also, the low-resolution global shape is directly used to learn a probability distribution. This probabilistic distribution supplies an adaptive weight for refining pairwise local surface alignment using the ICP algorithm.

3.2. Non-rigid Global Surface Registration

We use the thin-plate-spline (TPS) method for global registration by mapping each local feature point onto its global position. The TPS method [10] has been introduced

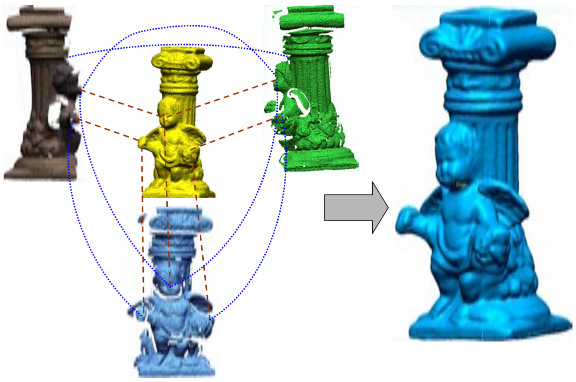

Figure 4. Left: high resolution local surface patches (brown, green, blue) and the low resolution global shape model in the middle. Local surface correspondence (blue lines) and related features in the optimal global positions (brown lines) via iterative local-to-global nonrigid adjustment.

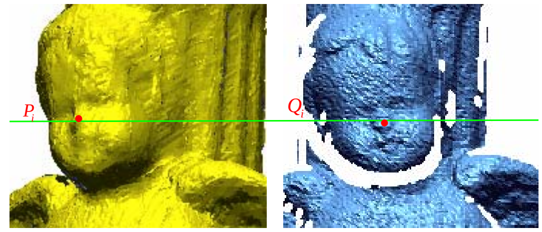

Figure 5. $a|b$ **(a) Low-resolution shape model and 1D profile. (b) A high-resolution local surface patch and related feature position.**

to 3D geometric deformation processing [5]. The TPS has an elegant algebra expressing the dependence of the physical bending energy of a thin plate on point constraints. For interpolating a surface over a fixed set of nodes in plane, the bending energy is a quadratic form in the heights assigned to the surface. To apply the algorithm, we should firstly consider a bending energy which is a non-rigid, globally smooth function including affine and non-affine warping components. Especially, the non-affine warping component means that the sum of squares of all second order partial derivatives is minimized. Such functionality can be used for surface warping in 3D spaces and it is easily computable. On the other hand, the role of this bending function is similar to the approach of Laplacian-based mesh deformation [6].

To process it, the TPS is normally formulated in a regularization energy functional according to [10, 24, 25] without interpolating. In this regularization energy function, only one regularization parameter λ need to be considered for warping. This means that the warping strength depends on the regularization parameter λ. Here, the spline will not be interpolated, but for any fixed regularization parameter λ, there is a unique minimum for this regularization function. While λ is close to zero, we get exact alignment of corresponding surface vertices. If λ is zero, interpolation is exact and as it approaches infinity, the resulting TPS surface is reduced to a least squares fitted plane, i.e.,"bending energy" of a plane is 0.

Using the hybrid scanning data, the low-resolution global shape model supplies geometric feature points prior as the global feature positions. When the global features are positioned, all local scans need to be warped to align them. We compute the warp that maps all the feature points on each scan to their global positions, shown in Fig. 4. After we warp the registered surfaces to the entire scan using the TPS algorithm, we can improve the resolution of 3D shapes using non-rigid aligned local surface patches or merge hybrid data to improve the quality of 3D shapes.

Since we need to have precise local-to-global nonrigid alignments using the low-resolution global geometric prior, for this reason, we must rely on accurate local-to-global correspondences. However, automatically accurate correspondence of local-to-global feature points on complicated 3D models need to be further investigated.

3.3. Workflow and Implementation

When dealing with hybrid scanning data sets consisting of hundreds of high-resolution local surface scans, it is not practical to perform supervised pairwise registrations aligning each scan with other partially overlapping scans.

Using hybrid scanning data, a low-resolution global shape model supplies a suitable initial alignment in two steps. (1) One manually specifies for each patch three points and their corresponding points on the global model. (2) the ICP algorithm refines this placement of the patches using extracted feature points of the patches and the global model. Then the patches are registered incrementally to each other in a growing process. After each such registration the merged patches are registered with the global model in a non-rigid way. The low-resolution global shape model supports a probability distribution of feature positions. This distribution is used as an adaptive weight for automatic refining pairwise local surface alignment. In case of an incorrect merging of a patch the registration of the merged patch with the global model yields a poor quality. This can be detected automatically and then interactively corrected. For example, the large alignment errors in Fig. 6 can be corrected using global shape feature positions.

We consider several implementation aspects, including the search for closest points, choice of parameters, and efficiency. The efficiency of the our approach depends on several factors. For searching nearest neighbors we apply

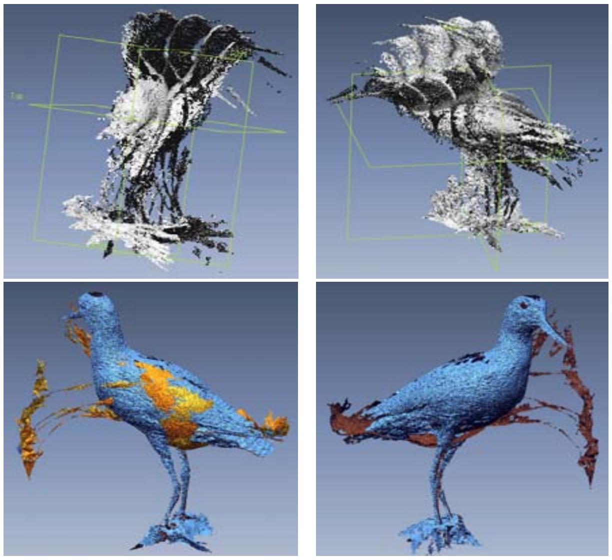

Figure 6. $\frac{a|b}{c|d}$ **Surface registration errors using only local surface patches appears even with manual initial alignment without using global shape model. (a)(b) Local surface patches. (c)(d) Registration results.**

k-d trees for speed up the searching[22, 26]. Parameters must be chosen that govern when a registration is considered satisfactory. In our case, the regularization parameter λ during the global nonrigid-shape alignment is small, e.g., $\lambda = 10^{-9\sim-10}$. The non-rigid global surface alignment and refinement is adjusted with weak bending energy according to global shape feature positions.

4. Experimental Results and Discussions

Experiments are carried out to systematically evaluate and demonstrate the effectiveness of the suggested hybrid scanning system in terms of acquiring local detail scans and estimating uncertainty and confidence in various regions of the scanned objects with different genus complexities.

4.1. Hybrid Scanning System and Data

We use a stationary scanner and a hand-held laser scanner to construct such a hybrid scanning system, shown in Fig. 7. The stationary laser scanner on the tripod is a Minolta VIVID-900 scanner with an accuracy 0.16-0.22 mm which can scan object size between 0.1-1 m within a distance of 0.6-2.5 m. To optimize the scanning results, the right lens has to be chosen based on the distance between the object and the laser scanner, and the size of the object. The hand-held laser scanner is a “Polhemus FastSCAN” with an accuracy 0.75-1 mm which is a on-line 3D generating scanner via a transmitter and a receiver, connected

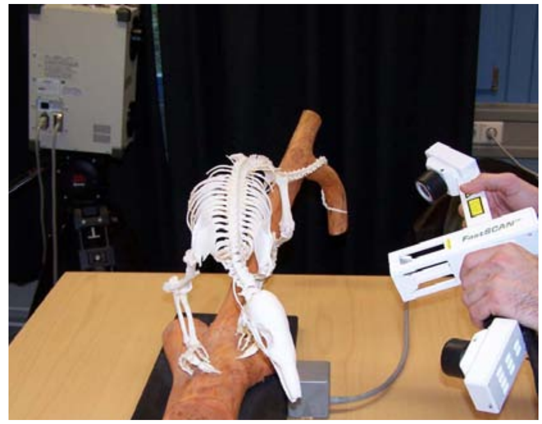

Figure 7. Tripod stationary scanner (background) and the hand-held scanner (right).

to a processing unit in an magnetic field. It has a relatively low-resolution but we obtain a scanned global shape model in one scanning process.

To test the efficiency of the hybrid laser scanner system, several 3D shape models of different size, surface material, geometric complexity, and geometric structure were chosen in order to validate the efficiency and accuracy of the proposed approach. Fig. 1 shows a skeleton of an anteater (approximately 0.80 m long). For such complex objects a large number of high-resolution patches are required, in this case 370 scans. One such high-resolution patch is shown in Fig. 1(c), and a low-resolution global shape model is shown in Fig. 1(a) and (b). The result of the acquired 3D shape model using hybrid data is presented in Fig. 12.

Fig. 8 shows a bird and a swan model. The bird has real bird feathers and, thus, it is very hard to scan with high quality. Moreover, the legs of the bird are dark, absorbing the laser beam of the stationary laser scanner, as shown in Fig. 8 (b). The hand-held scanner more complete scanning data due to its different mechanism, shown in Fig. 8 (a). Compared to the bird model and the anteater model, the swan model is easier to scan due to its simpler material and geometric structure.

4.2. Comparison of Methods

The traditional approach for surface reconstruction from laser scans is to register and align local patches of the same (fine) resolution. Features for registration can be selected manually when the automatic feature extraction and surface alignment fails. Our approach is based on the use of hybrid scanning data, i.e., the high-resolution local surface patches are not only matched each other but also are registered on the low-resolution global shape model. All scanned local patches are aligned to the global shape model.

Through our experiments, the noise distribution of 3D

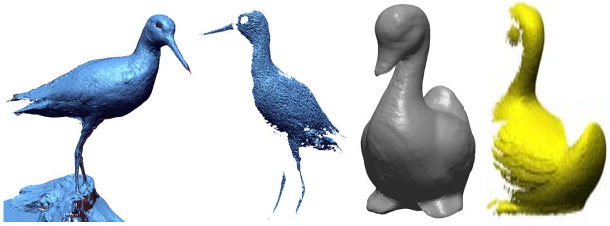

Figure 8. $a|b|c|d$**. Low-resolution global shape (a)(c), high-resolution local patches (b)(d).**

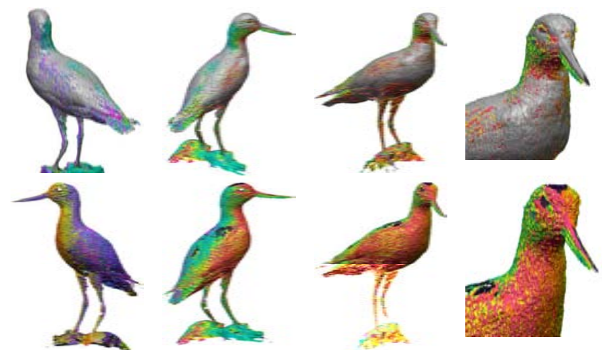

Figure 13. $\frac{a|b|c|d}{e|f|g|h}$**. (a)(b)(c)(d) Results of registering, merging hybrid data. (e)(f)(g)(h) Results of registering, without merging hybrid data. Patches are color coded.**

scanning data is observed not additive Gaussian noise but rather a more complicated distribution including the influences of CCD camera, laser beams and object movements. Certain smoothing and denoising pre-processes of local surface patches will heavily influent the accuracy of feature extraction and surface registration. Therefore, In our experiments the original scan data have been used, without any prefiltering for noise reduction and smoothing.

Firstly, we show some results using only local surface patches. Fig. 6 shows registration errors. Even with a lot of human supervision, the model still has a lot of errors. This result is largely improved using hybrid scanning data, shown in Fig. 13. Secondly, we show some improved 3D surface registration results using hybrid scanning data, shown in Fig. 9. Fig. 9(a) shows a section of the low-resolution complete shape model of the anteater, (b) shows the improved shape model using several high-resolution local surface patches, aligned on this low-resolution shape model. (c) shows the improved shape model in one color.

Fig. 10 compares results of the classic and the hybrid registration approaches. Fig. 10 (b)(c)(d), obtained by registering only high-resolution patches shows gaps and distortions in the model. Since the surface registration starts from one side, accumulated global distortion appears at the other side. Fig. 10 (f–h) shows the results using the hybrid method. The local surface patches fit together. Although, some small distortions still appear due to some gaps in the low-resolution scanning data, shown in Fig. 10 (e), the resulting model is very close to the original object. In Fig. 11, we can see the similar performance.

Some more results show the robust performance of using hybrid data. For example, Fig. 13 show that we can achieve encouraging 3D shape acquisition and surface registration result for a difficult scanning object, e.g., the bird with real feathers and thin dark colored legs and mouth. Fig. 13(a–d) show well-recovered 3D shape registering and merging of the hybrid scanning data while Fig. 13(e–h) shows that holes result when not merging hand-held scanning data.

Overall, the advantages of our approach can be listed as: it provides information for global optimization, reduces the number of required scanning patches, easily fills holes, eliminates accumulated alignment errors, and is robust to noise and outliers.

5. Conclusions and Future Work

We have presented an efficient approach for complex 3D shape acquisition and high-quality surface registration using hybrid scanning data. The method makes use of a natural global shape coverage when registering numerous local high-resolution surface patches. It is robust to outliers of scans and can deal with some reflections, missing object parts, and may compensate occlusion of objects in high-resolution scans.

Our experiments show that the joint utilization of global and local geometric shape information, together with an efficient adaptive registration method, makes it easy to reliably and efficiently reconstruct 3D shapes using only geometric information, without the need of other more information. We believe that our proposed method can be applied for 3D shape or outdoor 3D scene acquisition and registration in various research domains.

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References

[1] P. Alliez, D. Cohen-Steiner, O. Devillers, B. Levy, and M. Desbrun. Anisotropic polygonal remeshing. In *In Proc. of ACM SIGGRAPH 03*, pages 485–493, 2003.

[2] R. Benjemaa and F. Schmitt. A solution for the registration of multiple 3D point sets using unit quaternions. In *ECCV*, 1998.

[3] R. Bergevin, M. Soucy, H. Gagnon, and D. Laurendeau. Towards a general multi-view registration technique. *IEEE Trans. on PAMI*, 18(5):540–547, 1996.

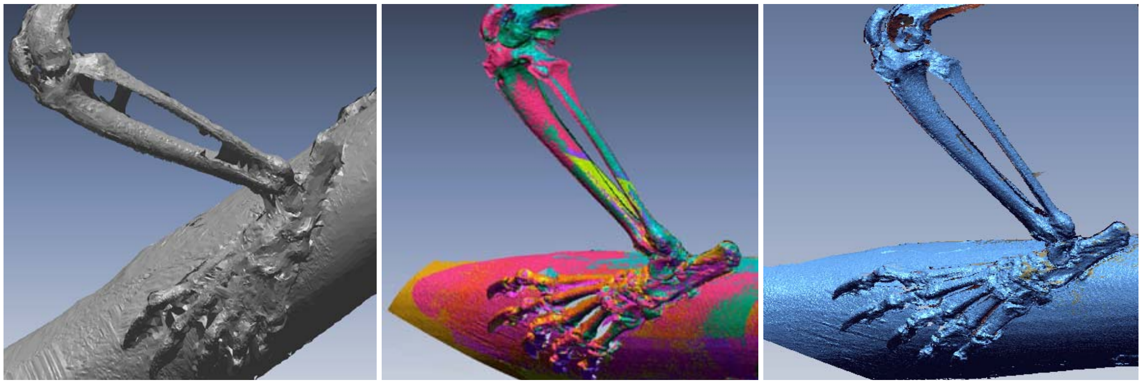

Figure 9. $a|b|c$**. Registration of high-resolution local surface patches to low-resolution global shape model. (a) Low-resolution 3D shape model from the hand-held scanner. (b)(c) Registration results using high-resolution 3D surface patches together with the low-resolution 3D shape model (a).**

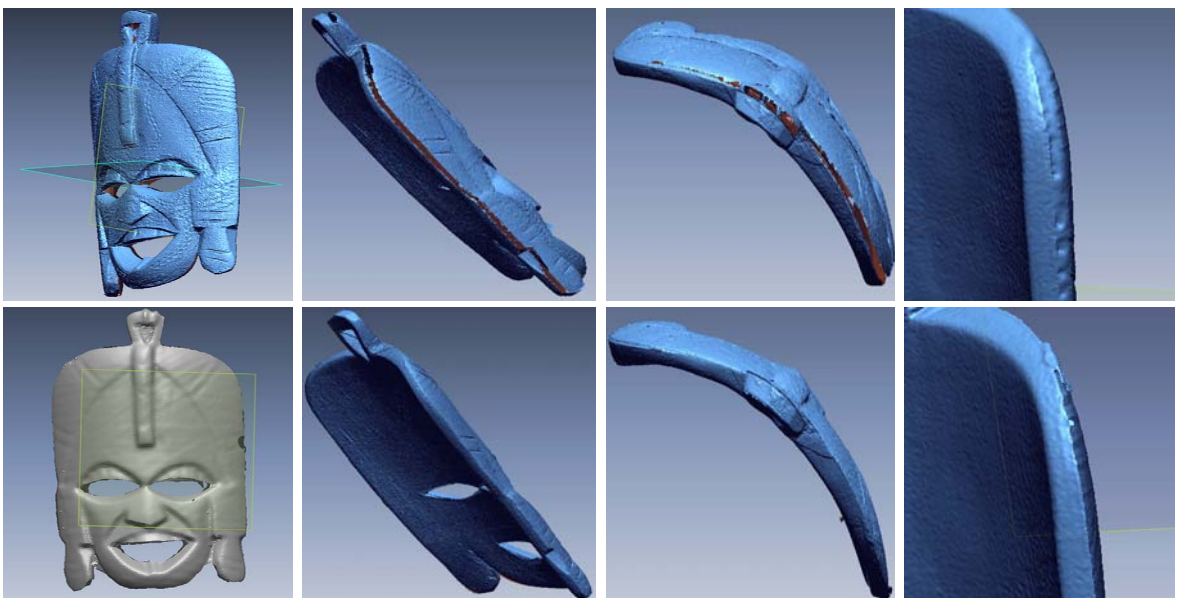

Figure 10. $\frac{a|b|c|d}{e|f|g|h}$**. Top row shows registration using only high-resolution patches: a high-resolution patch (a) and resulting registration errors (brown colored holes) (b–d). Bottom row shows registration with the hybrid method: the low-resolution global shape model (a) and high-quality registration using hybrid scanning data (f–h).**

[4] P. Besl and N. McKay. A method for registration of 3D shapes. *IEEE Trans. on PAMI*, 14(2):239–256, 1992.

[5] F. L. Bookstein. Principal warps: Thin-plate splines and the decomposition of deformations. *IEEE Trans. on PAMI*, 11(6):567–585, 1989.

[6] M. Botsch and O. Sorkine. On linear variational surface deformation methods. *IEEE Transactions on Visualization and Computer Graphics*, 14(1):213–230, 2008.

[7] Y. Chen and G. Medioni. Object modelling by registration of multiple range images. *Image and Vision Computing*, pages 145–155, 1992.

[8] Y. Chen and G. Medioni. Ransac-based darces: A new approach to fast automatic registration of partially overlapping range images. *IEEE on PAMI*, pages 1229–1234, 1999.

[9] H. Chui and A. Rangarajan. A new algorithm for non-rigid point matching. In *CVPR*, pages 44–51, 2000.

[10] J. Duchon. Splines minimizing rotation-invariant seminorms in sobolev spaces. In *Constructive Theory of Functions of Several Variables*, pages 85–100. Springer-Verlag, 1977.

[11] N. Gelfand, L. J. Guibas, L. Guibas, and H. Pottmann. Robust global registration. In *Eurographics Symposium on Geometry Processing*, 2005.

[12] N. Gelfand, L. Ikemoto, S. Rusinkiewics, and M. Levoy. Geometrically stable sampling for the ICP algorithm. In *3DIM*, 2003.

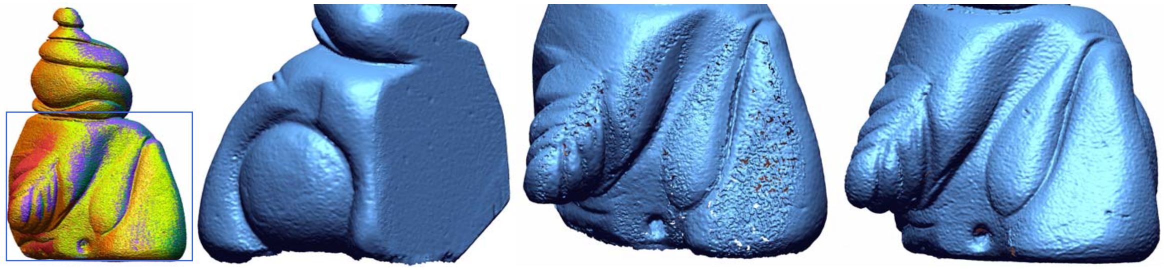

Figure 11. $a|b|c|d$**. (a) A 3D shape model. When registering high-resolution patches one side of the object registers well (b), while the other side has large distortions (c). Registration with hybrid data produces a better result (d).**

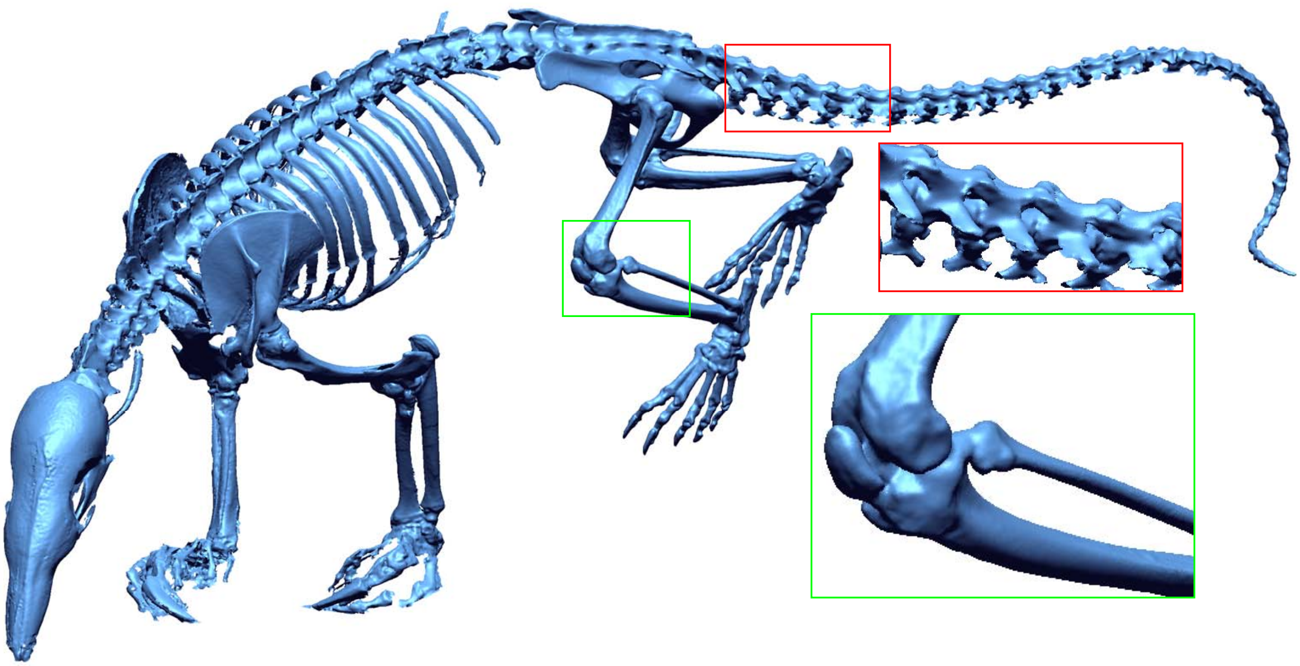

Figure 12. Acquired 3D shape model for an anteater skeleton using the hybrid data

[13] W. E. L. Grimson and T. Lozano-Perez. Localizing overlapping parts by searching the interpretation tree. *PAMI*, 9(4):469–482, 1984.

[14] D. Hähnel, S. Thrun, and W. Burgard. An extension of the ICP algorithm for modeling nonrigid objects with mobile robots. *IJCAI*, 2003.

[15] M. Levoy, K. Pulli, B. Curless, S. Rusinkiewicz, D. Koller, and etc. The digital Michelangelo project: 3d scanning of large statues. *SIGGRAPH*, pages 24–28, 2000.

[16] X. Li and I. Guskov. Multiscale features for approximate alignment of point-based surfaces. In *Symposium on Geometry Processing*, 2005.

[17] X. Pennec and J.-P. Thirion. A framework for uncertainty and validation of 3d registration methods based on points and frames. *IJCV*, 25:203–229, 1997.

[18] H. Pottmann, Q.-X. HuangG, Y.-L. Yang, and S.-M. Hu. Geometry and convergence analysis of algorithms for registration of 3d shapes. *IJCV*, 67(3):277–296, 2006.

[19] K. Pulli. Multiview registration for large data sets. In *3DIM*.

[20] S. Rusinkiewicz and M. Levoy. Efficient variants of the ICP algorithm. In *3rd 3DIM*, 2001.

[21] L. Silva, O. Bellon, and K. Boyer. *Robust Range Image Registration Using Genetic Algorithms and the Surface Interpenetration Measure*, volume 60. World Scientific, 2005.

[22] R. Szeliski and S. Lavallee. Matching 3-D anatomical surfaces with non-rigid deformations using octree-splines. *IJCV*, 18(2):171–186, 1996.

[23] G. Taubin. Estimation of planar curves, surfaces, and nonplanar space curves defined by implicit equations with applications to edge and range image segmentation. *IEEE Trans. PAMI*, 13:1115–1138, 1991.

[24] A. Tikhonov and V. Arsenin. *Solution of Ill-Posed Problems*. Wiley, Winston, 1977.

[25] G. Wahba. *Spline Models for Observational Data*, volume 59. SIAM, 1990.

[26] Z. Zhang. Iterative point matching for registration of free form curves and surfaces. *IJCV*, 13(2):119–152, 1994.