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A Framework for Motion-Based Mesh Sequence Segmentation

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ABSTRACT

In this paper, we present a complete framework to produce motion-based geometric segmentation of mesh sequences: each segment corresponds to a mesh region that tends either to move rigidly, or to be stretched in a uniform way. We take a sequence of meshes with varying number of vertices as input and match them by pairs. This allows us to find the approximated displacement vector of each vertex of the first frame all along the sequence. Using these displacement vectors, an initial segmentation is performed on the first pair of frames, clustering vertices into static, stretched and rigidly moving regions. This segmentation is then refined after each matching. Our segmentation is computed on the fly, and lets us find the exact frame when each transformation (rotation, translation, stretch) appears. We have validated our method both on dynamic meshes and unconstrained mesh sequences.

Keywords: Mesh Sequence; Mesh Animation; Segmentation; Matching.

1 INTRODUCTION AND RELATED WORK

1.1 Introduction

In computer graphics, segmentation of surface meshes is an important and challenging problem which involves partitioning a mesh into smaller segments of homogeneous characteristics. By doing so, a simplified representation of the mesh is obtained. This representation is more meaningful and easier to analyse. Segmentation plays an important role in diverse applications like texture mapping [LPRM02], compression [KG00], mesh simplification [GWH01] and 3D shape retrieval [Zuc02] among many others. The result of the segmentation required in each case may vary depending on the type of application.

While segmentation of static meshes is a well-known topic (see [Sha08] for a survey), segmentation of mesh sequences is a more recent research field. Here “segmentation” can have two different meanings: *motion-based geometry segmentation* aims at clustering vertices or faces based on their motions while *temporal segmentation* clusters meshes of the sequence (also called *frames*) into meaningful sub-sequences. In this paper, we focus on motion-based geometry segmentation.

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1.2 Related Work

Mesh sequences can be split into two categories. A *dynamic mesh* is a sequence with fixed number of vertices and fixed neighbourhood relationships between vertices. In other words, only the 3D coordinates of the vertices change through time. An *unconstrained mesh sequence* (or *time-varying mesh* or *3D video*) is represented by a sequence of meshes where the number of vertices, as well as the number of faces and connectivity, may vary along the sequence. Typically, dynamic meshes are created from modelers and animation software, while unconstrained mesh sequence are captured from video or computed from (e.g. fluid) simulation.

A few methods for motion-based geometry segmentation of dynamic meshes have been proposed [Len99, AS07]. Some of them ([dATTS08, LWC06]) segment a dynamic mesh into rigid components.

Segmentation of unconstrained sequence meshes is a difficult task since there is no one-to-one mapping between vertices of two successive frames. This mapping has to be explicitly computed for each pair of frames. Cuzzolin et al. [CMK⁺08] and Yamasaki et al. [LTA08] have performed such segmentations for mesh sequences, however the former computes only protrusions (extremities) segmentation while the latter uses an additional skeleton. [SC06] has been designed to solve this problem using voxel clustering, but it suffers from inherent voxelisation problems (low resolution leads to poor results while high resolution leads to high computation time). [KSMH09, JZvK07, MHK⁺08] compute the mapping between any two meshes, but their methods are not designed for sequences so they do not take the temporal coherency into account. Starck et al. [SH07] computes

the matching for distant frames in a sequence, but uses additional video information. Varanasi et al. [VZBH08] tracks the displacement of vertices of the first mesh all along the sequence, but does not provide a matching for all frames.

In this article, we propose a framework (Section 2) to perform a stretched and rigid motion-based geometry segmentation of a mesh sequence, i.e. with varying connectivity and variable number of vertices. A sequence of meshes, without global topological change (the genus of all meshes of the sequence are supposed to be identical), is taken as input. A matching is performed between each pair of meshes (Section 3), which allows to extract the approximated displacement vectors and compute segmentation on the fly (Section 4). A cluster in the resulting segmentation represents a connected region (*patch*) of the 3D object which either moves almost rigidly, or is stretched in a uniform way. Results are discussed in Section 5.

2 PIPELINE OVERVIEW

In this section, we describe the complete pipeline of the segmentation process (see Figure 1). The process can be roughly split, at each time step, into 2 parts:

- matching (Sect.3).
- creation or refinement of the segmentation (Sect.4).

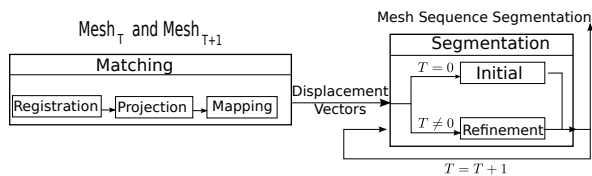


Figure 1: Overall Pipeline of the segmentation.

The algorithm takes as input a sequence of meshes with constant global topology. It registers the first mesh with the second. Displacement vectors between the vertices of the two frames are then computed using the results of the registration.

Based on the displacement vectors, an initial segmentation of the first mesh into (i) stretched (and translated), (ii) static and (iii) rigid regions is computed.

For each pair of successive frames in the sequence, we then apply the same matching process and compute the displacement vectors. The initial segmentation is then refined by analyzing the patches motion.

The segmentation of the sequence corresponds to the segmentation on the last frame, remapped on all frames of the sequence.

3 MATCHING PROCESS

The matching process consists of three successive stages: registration, projection and mapping, which

are described in the following subsections. At the end of the matching process, we have the displacement vectors of the vertices of the first frame all along the sequence and the matching of vertices in frame i with vertices in frame $i + 1$ for $1 \leq i < N$.

3.1 Registration

It takes as input an unconstrained mesh sequence and registers it by pair of frames with the Coherent Point Drift algorithm (CPD) [MSCP07]. CPD is a probabilistic method for non-rigid registration of point sets. This method is robust to noise and outliers. Registration is performed between the vertices of all adjacent frames - vertices in frame F_i are registered with those in frame F_{i+1} for i ranging from 1 to $N-1$ (see Fig 2 for the notation) to obtain registered point sets R_i which are the best alignment of the vertices in F_i with those in F_{i+1} . The number of points in the resulting registered point set R_i is equal to the number of vertices in F_i .

3.2 Projection

Each registered point set R_i obtained from the previous step is projected onto the surface of the subsequent frame F_{i+1} so as to attain a better correspondence between the adjacent frames F_i and F_{i+1} . This projection is performed in the following way:

- For each vertex on the surface of F_{i+1} , its normal vector to the surface of the mesh is estimated.
- For each point α in R_i , the vertex β which is closest to it in F_{i+1} is first searched. For each projected point, the L2 norm with all the nodes on the surface is calculated and the node with the minimum norm is taken as the closest point of that projected point on the surface.
- Finally, every point α in R_i is projected onto the surface of F_{i+1} along the normal vector of the corresponding closest point β on the surface of F_{i+1} . The projected point is denoted by P_i .

Using the above method, every point in F_i is projected onto the surface of F_{i+1} to obtain P_i for i ranging from 1 to $N - 1$. The next step is to find the mapping between the vertices of the two adjacent frames.

3.3 Mapping

For sequences with constant number of vertices throughout the sequence, the correspondence between vertices of adjacent frames is easy to obtain. Every vertex in a frame has a corresponding vertex in the other frames in this case. However, such correspondences are not valid anymore when the number of vertices varies at every frame. In such cases, to establish correspondences between two adjacent frames F_i and F_{i+1} , each point in R_i is considered separately. The vertex β

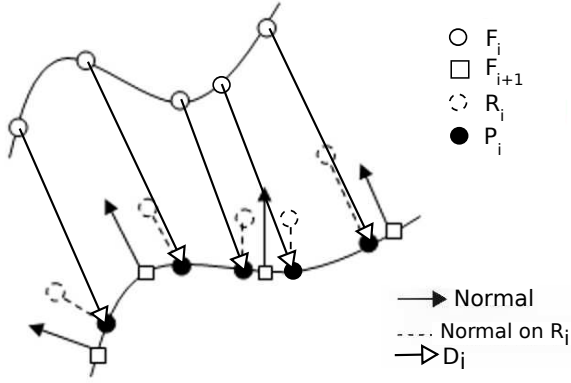


Figure 2: Matching Scheme.

in F_{i+1} which is closest to a point $R_i(\alpha)$ corresponds to the vertex $F_i(\alpha)$. In this way, a unidirectional mapping of all the vertices of F_i with the vertices of F_{i+1} can be computed to obtain F_i^{i+1} , for $i \in [1, N-1]$. Such a mapping is essential if the trajectory of a vertex in a frame has to be followed along the successive frames of the sequence.

Two possible scenarios arise when registering adjacent frames with unequal number of vertices. The first case is when the number of vertices in F_i is greater than the number of vertices in F_{i+1} . In this case, more than one point in F_i may be assigned to a vertex in F_{i+1} . On the other hand, in the case when F_i has fewer vertices than F_{i+1} , some vertices in F_{i+1} may not have any corresponding vertices in F_i . The unidirectional mapping obtained between all adjacent frames can be extended to find the mapping of the vertices in a frame in all the subsequent frames using a recursive procedure. For each vertex α in frame F_i , the index of the corresponding vertex in frame F_j is given by:

$$F_i^j(\alpha) = F_{j-1}^j((F_i^{j-1}(\alpha))) \text{ where } j \geq i \quad (1)$$

The displacement vectors D_i for each vertex in F_i are calculated as follows: $D_i = P_i - F_i$, $i = 1 : N-1$, where the points of P_i are the projected points of F_i on the surface of F_{i+1} . Once these displacement vectors are obtained, the displacement map of each vertex in the first frame can be constructed using the correspondences from the F_i^j arrays. The displacement map is the mapping of vertices in the succeeding frames for each vertex in the first frame, i.e. the displacement map gives the corresponding vertex in any succeeding frame for each vertex in the first frame.

4 SEGMENTATION

4.1 Matching Process and Segmentation

In this section, we present our segmentation method. Our segmentation method relies on correct matching information (i.e. displacement vectors and matching

points). As long as this information is provided, any matching method can be used (not only the one we described in section 3). For instance, we also test our segmentation method using [KSMH09], where the matching is computed on the embedding of the meshes using Laplacian embedding (which “unfold” mesh). Segmentation results using this matching methods are discussed in Sect.5.2.

4.2 Outline

Our segmentation is a motion-based segmentation. We cluster vertices in rigid components, but contrary to previous segmentation methods, we are also able to detect stretch motion. We are using a refinement method:

1. using the first two meshes and the associated displacement vectors, we compute an initial segmentation (section 4.4).
2. for all other frames of the sequence, we refine the previous segmentation by analyzing the current clusters and splitting them if necessary using displacement vectors and vertex matching (section 4.5).

This refinement approach allows us to:

- process long sequences with lots of vertices. We require only two meshes at a time in memory.
- track transformations. We know at which frame a cluster is created and its type of transformation.

The segmentation of the sequence is the segmentation computed on the last frame. This segmentation is then remapped on the whole sequence using the matching information (section 4.6).

4.3 Errors

In the segmentation process, we use a metric denoted as E_T to sort clusters by errors. We use the method proposed by Horn [Hor87] to compute the best possible transformation between two set of points P_i and P_j , where $card(P_i) = card(P_j)$ and points from P_i have direct correspondent in P_j . Horn’s method returns a translation C_T and a rotation C_R such as $P_j = C_R * P_i + C_T$. For (P_i, P_j) , E_T can be defined as either:

- Average error: $AE(P_i, P_j) = \frac{1}{card(P_i)} \sum_{p_i \in P_i} \|C_R p_i + C_T - p_j\|$.
- Max error: $ME(P_i, P_j) = \max_{p_i \in P_i} \|C_R p_i + C_T - p_j\|$.
- Difference error: $DE(P_i, P_j) = AE(P_i, P_j) - ME(P_i, P_j)$.

4.4 Initial segmentation

The initial segmentation is applied on the first mesh F of the sequence. Using the displacement vectors obtained from the matching between the first two frames, we cluster vertices based on three categories, and clustering is applied successively:

1. *static vertices*: these vertices have no motion (clusters of static vertices are denoted as \mathcal{C}_{static}).
2. *stretched vertices*: these vertices are in a stretched region (clusters of uniformly stretched vertices are denoted as $\mathcal{C}_{stretched}$).
3. *rigid vertices*: motion of these vertices can be described by a rigid transformation (clusters of rigid vertices are denoted as \mathcal{C}_{rigid}).

Clusters are computed as follows. Static vertices are defined by displacement vectors whose norms are under a threshold T_{static} , vertices with a norm greater than this threshold and with collinear (and in the same direction) displacement vectors correspond to stretched vertices. They are gathered into connected regions. Rigid vertices are harder to compute. We use a modified version of the method described in [HAWG08]. To cluster them, we define the *extended cluster* \tilde{C}_i of C_i as C_i plus its n closest points (in our experiments, $n = 3$ is sufficient).

The algorithm is:

1. Initialization: each vertex is a cluster.
2. For each cluster, compute the optimal transformation [Hor87] which maps \tilde{C} of first frame to second frame. Points of second frame are reconstructed from points of \tilde{C} and their associated displacement vectors. Take the cluster C_i with the smallest transformation error E_i (defined in section 4.3).
3. For all clusters C_j which intersect \tilde{C}_i , apply the transformation found for C_i to each point of C_j . If the error is under a threshold T_{transf} , merge C_j to C_i . If no merging happens, take the cluster with the smallest error apart from C_i , and do the same. Here the error is defined as the maximum distance between the transformed point of C_j and the displaced point of C_j .
4. Repeat steps 2 and 3 while merging is possible.

As previously outlined, the order in which the clustering is performed is important. The algorithm first computes \mathcal{C}_{static} and $\mathcal{C}_{stretched}$. It then builds a sub-mesh $F_s = F \setminus (\mathcal{C}_{static} \cup \mathcal{C}_{stretched})$. Rigid clusters are computed at the end on F_s , in order to avoid overlapping of rigid regions over static and stretched ones. To avoid small clusters, i.e whose size is inferior to 3% of

the mesh, due to noise or small areas around articulations, we merge them to the neighbouring cluster which minimizes the error as in step 3 of the rigid clustering process.

At the end of the initial segmentation process, the mesh of the first frame is decomposed in clusters of different types based on the displacement vectors between the two first frames. The segmentation is then refined using following frames, after each matching.

4.5 Refinement

The refinement aims at finding new regions which may appear on a new frame. Each cluster is decomposed (if necessary) into sub-clusters. The process starts from the clusters found at the previous step, i.e. the initial segmentation for frame 2, or the previous refinement in the other cases. It also uses the displacement vectors computed during the matching process. The refinement is done in two steps:

- check previous clusters.
- find new clusters.

A quick checkout step is used to avoid to re-create the same cluster. We check that:

- for static clusters, all displacement vectors norms in a cluster are below the threshold T_{static} ;
- for stretched clusters, displacement vectors are still collinear and with the same direction;
- for rigid clusters, the best transformation between the points of cluster C_i at frame F and frame $F + 1$ is valid. This transformation is computed using Horn's method [Hor87] (applied to points reconstructed from the previous frame and from the displacement vectors) If the associated error is above T_{transf} , the transformation is considered as not valid.

All clusters which are still valid are kept unchanged. All other clusters correspond to regions where new transformations are starting. These clusters are decomposed into sub-clusters:

- If the new transformation applies to a whole cluster, this cluster is kept and not decomposed.
- Else, this cluster is decomposed.

This decomposition is similar to the one applied in the initial segmentation: for each cluster C_c of the list, the algorithm computes static vertices, stretched vertices and rigid vertices. As before, static and stretched sub-clusters are computed first and added to the sets of static \mathcal{C}_{static} and stretch $\mathcal{C}_{stretch}$ clusters. $F_s = F \setminus (\mathcal{C}_{static} \cup \mathcal{C}_{stretch})$ is built. Contrary to initial segmentation, the rigid clustering is not applied on F_s , but on $F_s \cap C_c$, to make sure that the transformation applies on C_c . These clusters are added to the set of rigid clusters (See Figure 3).

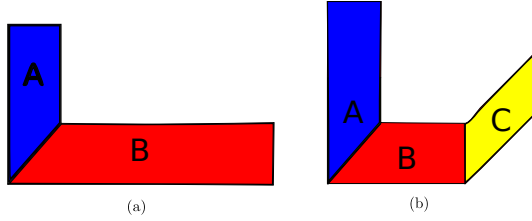


Figure 3: Refinement example: (a) Segmentation at time F . (b) Segmentation at time $F + 1$. Cluster B is refined into sub-cluster B and C because of the rotation.

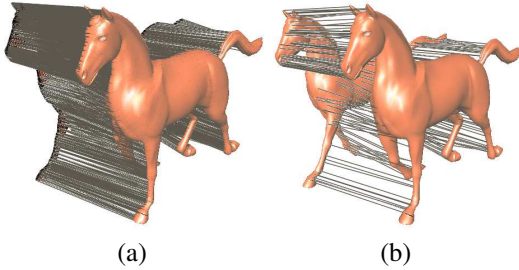


Figure 4: Matching result: (a) Full matching, (b) Partial matching.

4.6 Remapping

Once all frames have been segmented, we report the segmentation of the last frame on the whole sequence using matching information. As some points can be unmatched, when we report the segmentation from one frame to the other, we apply a region growing method to avoid holes in the segmentation. For each unmatched point p_i , we search for the cluster C which contains the maximum number of points in p_i neighbourhood and set p_i in C .

5 RESULTS AND DISCUSSION

5.1 Matching

Matching results are shown in Figure 4 where the correspondences of vertices between different frames of the horse gallop sequence are displayed. The displacement vectors of these corresponding vertices in the succeeding frames are then used in the segmentation process. On a standard personal computer (core 2 duo, 2.33 GHz), matching of one mesh (8199 vertices) with another vertices (7254) takes 13 minutes. The implementation is performed with MATLAB using a fast implementation of the CPD algorithm based on a fast Gaussian transform. In the matching process, the registration of adjacent frames is the major bottleneck as compared to the projection and mapping parts.

5.2 Segmentation

Setting of Thresholds and Errors

To handle noise present on unconstrained mesh sequence, we use the threshold T_{static} . For the decimated horse sequence (see Fig.8), we use a threshold of

1×10^{-4} , the bounding box of the mesh is 12.3177. The threshold T_{transf} corresponds to the motion amplitude tolerated for a cluster on dynamic mesh between two frames. For unconstrained mesh sequence, this threshold should incorporate the slight error of the projected points which contain a small error contrary to models created in a modeler. Segmentation can be refined using different values for T_{transf} : small values produce more clusters as shown in Fig.6. This threshold does not depend on vertex density but depends on the amplitude movement between 2 frames.

In our experiments, the Difference Error should be preferred when dealing with dynamic meshes. Indeed, Difference Error avoids to merge clusters with large errors. Clusters with large errors in dynamic meshes are due to change in transformation. On presence of noise and outliers, the Difference Error is too sensible and Average Error becomes the best error type: large error can result from outliers/noise in clusters. Such cluster should not be discarded if it has few outliers. Fig.5 shows the different errors applied on a dynamic mesh and on a dynamic mesh perturbed with some noise (noise is applied independently on each frame).

Results

Fig.6 shows the result of our algorithm applies to a dynamic mesh compared to [LWC06] and [dATTS08]. As can be seen, our method yields similar results. The main difference with [LWC06] deals with cluster's boundaries: they are not smooth. We do not apply a post-processing stage as boundaries are not clearly defined on an unconstrained mesh sequence (see next section for a discussion on boundaries).

Contrary to previous methods, we handle stretch deformations. We show some results of such clustering on Fig.7. Some parts of the object follow a rigid transformation while others are stretched.

Our algorithm is able to segment unconstrained mesh sequences as shown in Fig.8. Each frame of the horse sequence is randomly decimated, and we segment this sequence. The number of vertices varies from 2624 to 4696. Segmentation is similar to the dynamic one.

Discussion

Our whole process deals with two frames at a time, meaning:

- mesh sequences with a high number of frames and/or vertices can be processed.
- the apparition and the decomposition of each cluster is controlled.

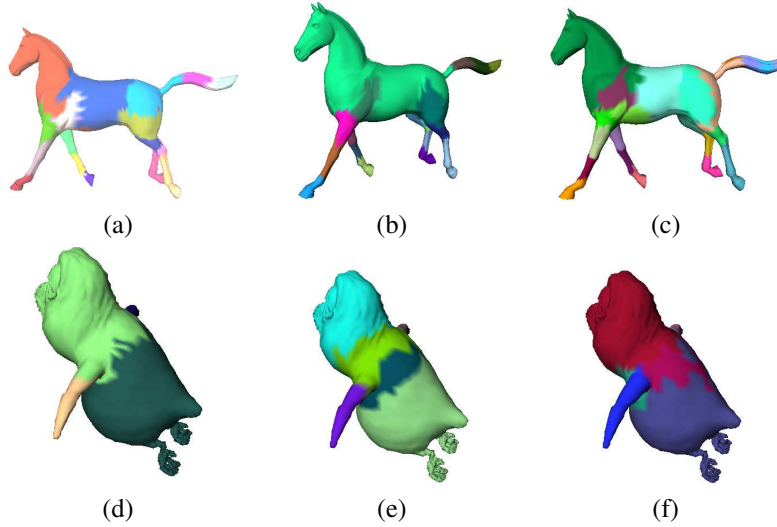


Figure 5: Comparison of error type on segmentation result. (a) Average Error, (b) Difference Error and (c) Max Error on dynamic mesh. (d) Average Error, (e) Difference Error and (f) Max Error on noisy mesh.

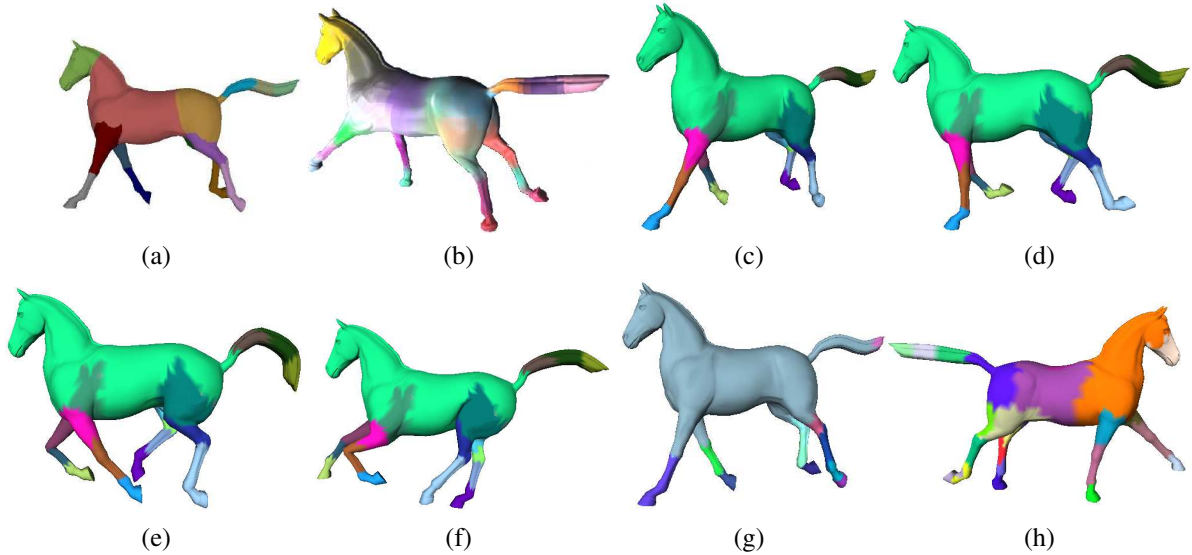


Figure 6: Horse Segmentation: (a) [LWC06], (b) [dATTS08], (c) with our method. (d,e,f) Frames of the sequence. (g) Coarse, $T_{transf} = 0.0015$ and (h) refined, $T_{transf} = 0.0007$ result, to compare with (c), $T_{transf} = 0.0009$.

Boundaries There are two closely related issues on cluster boundaries: they are not smooth and boundaries of clusters on articulation are not necessarily on the middle of the articulation as with other methods. They can be around, a little bit after or before (see Fig.9 for illustration). Clusters are merged while the transformation (see section 4.4) found can be applied, this transformation becomes invalid after/before the boundaries. As we deal with meshes with varying connectivity, boundaries move from one frame to another. As we want to work on these original sequences (i.e with no modification), this is acceptable. Otherwise, a post-processing step can correct this problem by inserting points on boundaries in all frames.

Noise and outliers The presence of some outliers or badly matched points is similar to noise. Usage of aver-

age error merge them with other vertices. The remaining outliers are on their own cluster, and these clusters are small. This means that they are handled by the forced merge of small clusters. However, in presence of many grouped outliers, our algorithm produces incorrect results, as they are clustered together (but the segmentation is coherent with the matching information). It also produces incorrect results when many badly matched points are present: it forces user to select large threshold value. This means that it can produce only a coarse segmentation. In this case the segmentation is correct on the first frame, but it is incorrectly remapped on following frames.

Errors coming from matching and outliers which cause a cluster subdivision at F_i are passed on all

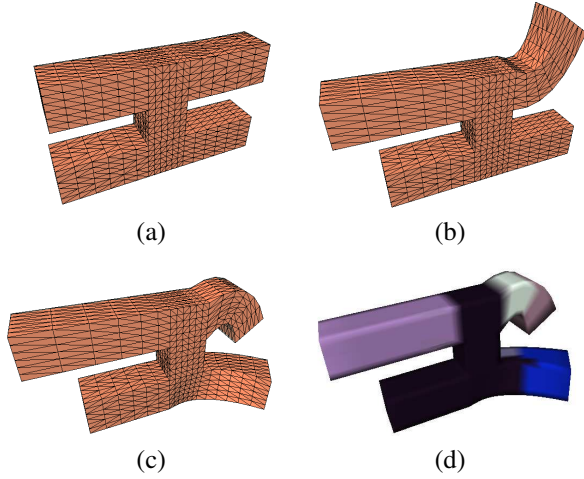


Figure 7: Stretch: (a), (b), (c) frames of the sequence. (d) segmentation.

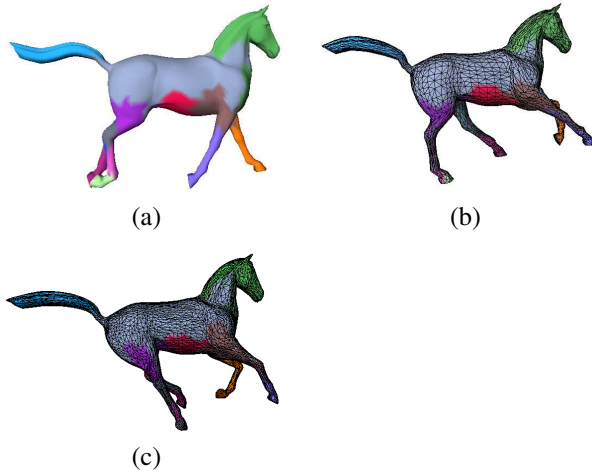


Figure 8: Segmentation on a decimated horse sequence. (a) Result. (b,c) Minimum and maximum number of vertices.

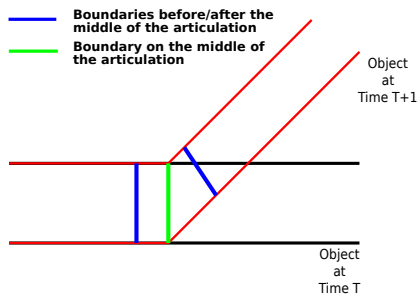


Figure 9: Boundaries on articulation.

following frames. This is due to the nature of our algorithm.

Matching Methods We have chosen to use projected points to obtain the displacement vectors. The consequence is that we have “real” displacement vectors, but with an expensive computation cost. Using an algorithm as in [MHK⁺08], which does not provide projected points, we have to use the matched point to compute the displacement vectors. This implies an error

which is more important than with our method. On a dense mesh, this is not important, as matched points are close to the projected one. However, on sparse meshes, the error can be big enough to either:

- give incorrect result.
- force user to use large T_{transf} (and obtained a coarse segmentation).

Implementation The prototype for the segmentation part is written in C++ using CGAL, while the matching part is written in Matlab.

Future Work The proposed method can be improved in several ways:

- we did not test our method with objects facing global topological changes. We do not see any trouble in handling them: for each pair of successive frames, detect topological changes between them and split clusters concerned by the topological change of the object;
- The algorithm currently works using two successive frames, which means that we can miss slow motions: if the deformation between two frames is too small, the checkout on the refinement process will always be true and the algorithm will not refine the cluster. The threshold T_{transf} limits this problem but working with a small time window (as it can easily fit in memory) can improve this. We have some preliminary results, but the main difficulty consists in automatically detecting the size of this time window. Time window may help to correct invalid cluster subdivision by inspecting following frames.
- Detect new motion type such as twist.

The main objective of our next work is to define a validation framework, using user validation and defining error criteria to validate mesh sequence segmentation [BVLD09, CGF09].

6 CONCLUSION

We have presented a complete framework to segment mesh sequences with varying number of vertices in rigid and stretch components. Our segmentation method works on the fly and allows us to track deformation all along the sequence. Extension to handle objects facing global topological changes, time window to segment slow motion and temporal matching to take advantage of temporal coherency are planned for the near future. This method can be integrated in an automatic production chain, however the threshold needs to be determined manually before. There is no limit to the number of vertices or frames that can be treated by our method, but since errors are passed from frame to frame, long sequence should be splitted into shorter ones.

7 AFFILIATIONS

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A static mesh and mesh sequence repository can be found at <http://www-rech.telecom-lille1.eu/madras/>

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