Non-rigid Transformations for Musculoskeletal Model

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Abstract
This paper provides describes solution for the fully automatic registration and multi-morphing of surface triangular meshes. It solves the instability problem experienced with non-manifold mesh transformations. A refinement and interpolation of multiple such meshes representing the same object are used to obtain one manifold mesh for later processing. Details can be found in [2].

Categories and Subject Descriptors
I.3.5 [**Computer Graphics**]: Computational Geometry and Object Modeling—*Hierarchy and geometric transformations*

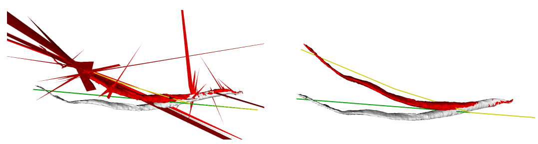
Keywords
registrations, morphing, supermeshes, interpolations, ICP, surface meshes, VTK, spherical parametrisations, deformations

1. Introduction
Non-rigid transformation is a broad term. We should restrict to two specific operations in this paper. The first one is a *registration*. It is used when two or more models of the same object are available and we want to compare them or transfer some of their properties between them. To do this, we have to know which part of source model A corresponds to which part of target model B. In the case of triangular surface meshes, this requires translation of a vertex of one mesh onto the surface of the other one. A vertex-to-vertex mapping is rarely possible with general models so barycentric coordinates can then help to express an exact position anywhere on the surface of a mesh.

A good registration is a necessary condition for a *morphing*. Morphing is a process of interpolation between individual data sets or models. For triangular surface meshes, this actually means interpolation between coordinates and possibly other attributes of individual points on mesh surfaces.

The roadmap [4] highlights importance of both these transformations in the effort for creation of the *Virtual Physiological Human*, a complex model of a human body. Registration should be used to combine results from various measurement of a patient during his or her life. Morphing could then be used to interpolate on time axis and also to fill missing data from database of population samples with measurable attributes such as height, weight, age and others.

We propose an automatic method that performs both registration and morphing for two or more, possibly non-manifold or incomplete, triangular surface meshes. This method was tested in the context of muscle deformation developed in our previous work [1]. As it was found that our deformation filter has problems with non-manifold or unclosed meshes [3], the idea was to use the proposed method to combine multiple surface meshes of various quality representing the same muscle in order to create a new finer mesh that could be used in the deformation filter instead of the original one. Figure 1a demonstrates a successful application of our method.



(a) Original (b) Morphed

Figure 1: Deformation of the original and the processed Sartorius muscle using the deformation filter [3].

2. Proposed method
Our method, which is illustrated in Figure 2, consists of four consequent steps.

The first step is a preprocessing of individual input meshes. It removes all non-manifold artifacts by removing affected cells. Produced holes are then filled and marked.

The second step then picks one of the input mesh as a target mesh and finds rigid transformation to provide approximate alignment of other globally positioned inputs

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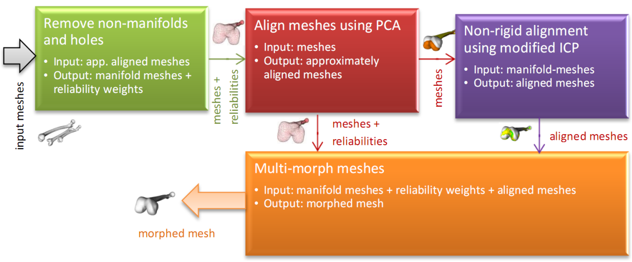
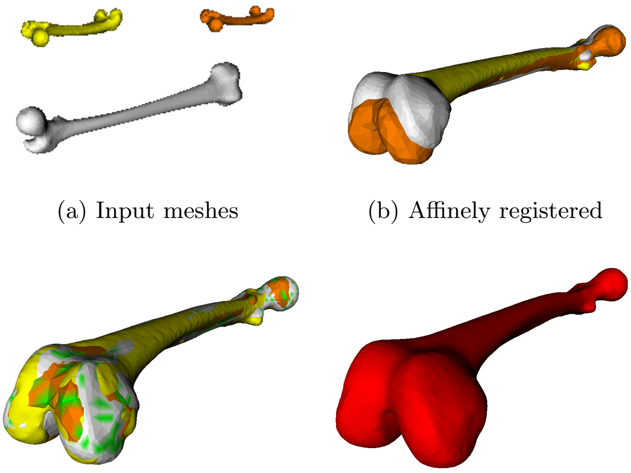


Figure 2: A flow diagram of the method.

(see Figure 3a). It also uses a scaling to minimise space differences of meshes (see Figure 3b).

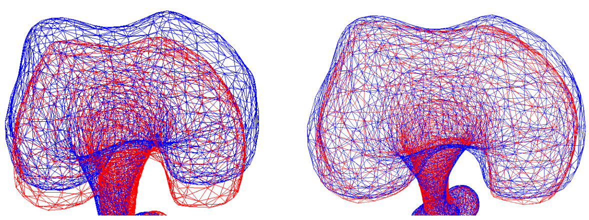


(a) Input meshes (b) Affinely registered

(c) Non-rigidly registered (d) Output of morphing

Figure 3: Phases of the method applied to three models of the Femur bone.

Then the third step can rely on local space solvers to improve this initial alignment and also to expand it into non-rigid registration (see Figure 3c). Techniques that work with small regions on surface of source meshes are used to find the best match on the target mesh. This then produces dictionary of local transformations leading to a deformation of source mesh surfaces. Distances between them and the selected target mesh are minimised this way (see comparison on Figure 4).



(a) Affine (b) Non-rigid

Figure 4: Comparison of two levels of registration of source mesh (red) to target mesh (blue). Bottom head of Femur bone.

The fourth step benefits from this non-rigid precise registration and uses it as a navigation map for multi-morphing of affinely registered input meshes. Individual points of the output mesh are interpolated from their matching points on all input meshes. However, input regions that have been added in the hole filling phase are considered less reliable and their counterparts from unaffected inputs are preferred using weights as interpolation coefficients. These weights have to be spatially smoothened to avoid discontinuities. The final output mesh is then closed manifold triangular mesh (see Figure 3d).

3. Results

Various modifications and approaches for individual method steps were evaluated in experiments with models of human muscles. Both original non-manifold meshes and artificially damaged meshes with severe artifacts including holes, isolated mesh segments and non-manifolds were used. The method successfully fixed all problematic regions and provided robust registration. The non-rigid registration was able to locally align meshes so closely that perpendicular projections of points from one mesh to the other mesh could be used to locate their matches there (see Figure 4).

Morphed meshes were successfully applied to the unmodified deformation filter [3] and effectively increased both its precision and reliability as well as a visual plausibility of outputs (see Figure 1).

Execution times ranging from tens of seconds for inputs with few thousands vertices up to 585 seconds for three meshes with $2 \times 2\,502$ and $42\,502$ vertices were achieved and these are considered acceptable for the intended offline preprocessing application. The longest times were measured in the non-rigid registration phase (typically over 70% of overall time). Many location based queries there could be accelerated using spatial subdivision structures, effectively improving single query complexity from $O(n)$ to $O(\log n)$. Caching of intermediate results was used to enable convenient experimentation with individual phases so that their implementations and parameters could be optimised.

4. Conclusions

This paper provided brief summary of problems, solutions and results discussed in the master thesis [2]. It presented that automatic method for registration and multimorphing of surface meshes was able to process input meshes used in the musculoskeletal modelling project and that it was able to produce morphed meshes improving performance and reliability of the deformation filter used there. Readers are referred to [1] for more details.

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