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Harmonic Guidance for Surface Deformation

Rhaleb Zayer, Christian Rössl, Zachi Karni and Hans-Peter Seidel

Max-Planck-Institut für Informatik, Saarbrücken, Germany

Abstract

We present an interactive method for applying deformations to a surface mesh while preserving its global shape and local properties. Two surface editing scenarios are discussed, which conceptually differ in the specification of deformations: Either interpolation constraints are imposed explicitly, e.g., by dragging a subset of vertices, or, deformation of a reference surface is mimicked.

The contribution of this paper is a novel approach for interpolation of local deformations over the manifold and for efficiently establishing correspondence to a reference surface from only few pairs of markers. As a general tool for both scenarios, a harmonic field is constructed to guide the interpolation of constraints and to find correspondence required for deformation transfer. We show that our approach fits nicely in a unified mathematical framework, where the same type of linear operator is applied in all phases, and how this approach can be used to create an intuitive and interactive editing tool.

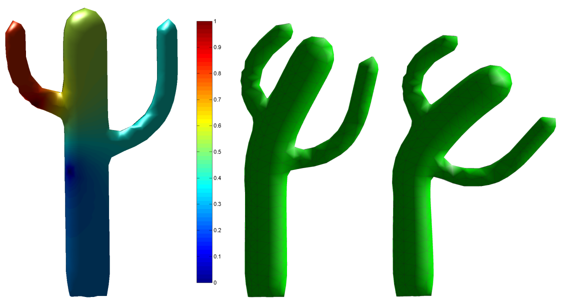

Figure 1: *A simple edit: The visualized harmonic field is used as guidance for bending the cactus (left). Here, the field is defined by one source (red) at the tip of the left arm and one sink (blue) below the middle of the trunk. The result is shown in the center image. Notice the different propagation of the rotation compared to the edit on the right, where three sources on all arms were chosen (without picture).*

1. Introduction

One of the most governing representations of 3D objects adopted by the Computer Graphics community is the 2-manifold mesh. In recent years, many Digital Geometry Processing algorithms operating on such mesh structures were developed. These methods generally deform the surface geometry and/or alter the mesh connectivity.

In many applications it is important to preserve the local shape properties under global changes of the surface mesh. The best-known example is probably surface editing: A user selects and drags a subset of vertices to a new location in space, and within a region of influence the shape should follow this manipulation in a natural way. This means that the overall shape follows the specified global deformation while geometric details like, e.g., folds and wrinkles, are locally deformed in a way that their characteristic appearance persists. To be useful in practice, such editing tool must be intuitive and provide interactive response.

In this paper, we describe interactive surface deformation tools based on a linear framework. We identify the propagation of local transformations over the surface as a key technique, which is the first contribution of the paper: This interpolation plays a vital role because it ensures that the overall deformation looks natural, and that the required geometric detail is preserved. We establish smooth harmonic scalar fields over the mesh to guide this process.

In addition, we consider a different surface editing scenario: deformation transfer. Here, manipulation of a reference model is transfered and applied on a target model, e.g., copying an animation sequence of an object to another similar object. Instead of the explicit specification of complex deformation, the user provides only a small number of corresponding markers on the two models. These are used for establishing correspondence which essentially guides the transfer of local deformations. As a result, the target object mimics the global deformations of the reference object.

As basic technique, we apply harmonic fields, this time for efficiently finding correspondence. We show that this second contribution fits nicely in the overall framework, despite the conceptual difference of this second surface deformation scenario. Harmonic guidance provides a natural and efficient tool for interactive and intuitive surface deformation: the required scalar fields provide inherent smoothness, and they are constructed at virtually no extra cost. This is because all required computational ingredients are available in form of the linear reconstruction operator, necessary for applying the deformations.

2. Related work

We are aware that the design and deformation of smooth surfaces is a well-studied problem, and a multitude of approaches exist. In the following, we focus on deformation preserving the local detail of a shape which is modified on a global scale.

Multi-resolution techniques are well-known and probably represent the most prominent approach to this problem, e.g., for surface modeling [ZSS97, KCVS98, GSS99, BK04]. Shape information is decomposed encoding geometric detail relative to local frames [FB88], which are defined with respect to a smooth base surface. After deformation of the smooth base, the local frames are implicitly adapted (i.e., rotated) and detail is reintegrated into the reconstruction.

Alternative methods for various kinds of surface editing rely on a relative representation [Ale03] which captures local shape detail, namely Laplacian coordinates. However, the inherent lack of rotation and scale invariance of the linear operator requires local transformation of the differential coordinates. To account for this, local rotations are estimated either from normal averaging over an initial reconstruction [LSC*04], or from embedding a simultaneous least-squares optimization for linear approximants to rotations and isotropic scales in the linear reconstruction operator [SLC*04].

Here, we note that both of the latter approaches, multi-resolution methods and differential coordinates, transform (rotate) their respective shape detail information such that the reconstruction consistently preserves local detail while the overall shape follows the global deformation. We can interpret this transformation as updating the mappings of local regions from the source to the target shape – hence, as finding meaningful local deformations. Furthermore, we mention the most recent [LSLC05] proposing an alternative family of rotation-invariant coordinates.

In fact, the recent work of [YZX*04] applies this notion directly: Generalizing the concept of Poisson image editing [PGB03], local deformations [Bar84] are specified and then propagated over the surface mesh. The resulting deformation field and additional conditions capturing smoothness (including continuity) and local shape detail yield a linear system whose solution defines the desired target shape.

So far, we discussed deformation for direct, interactive surface editing. Deformation transfer [SP04] is a different metaphor applied to mimic a reference deformation of one triangulated shape on another one. Here, local deformations of a target are sampled from the deformation of a reference surface; given a corresponding deformation field, a linear operator is used for reconstruction similar as for the above. This process is steered by pairs of corresponding markers, which are used to establish meaningful correspondence between the overall shapes using an iterated closest point algorithm to deform the target into the initial reference geometry.

Sumner and Popović [SP04] point out that no bijective mapping is necessary for establishing meaningful correspondence, in fact, a many-to-many mapping is generally obtained. While this seems sufficient for deformation transfer, we remark that there exist techniques to construct constrained bijective maps between surfaces [KS04, SAPH04], which provide a computationally more expensive alternative.

In addition to explicit shape manipulation, we mention free form deformation methods [SP86, Coq90] which achieve surface deformation by warping the surrounding 3-space. This space-warp can possibly be defined using (local) rotational constraints [LKG*03] or weight functions parameterized with respect to geodesic distances on the surface [BK03] for improving the propagation of constraints. In the context of deformation transfer, as-rigid-as possible shape interpolation [ACL00] defines a piecewise linear space-warp over a triangulated domain, corresponding to deformation of the boundary.

Finally, we note that the advantageous properties of harmonic fields have been used most recently for quadrilateral remeshing [DKG05].

3. Overview and contributions

We construct harmonic fields over a manifold and apply them to guide local deformations for surface editing and to establish correspondence for deformation transfer. We show that both problems can be addressed by a unified mathematical framework, where the same linear operator is applied in all stages: decomposition, propagation of local deformations, correspondence, and detail preserving shape reconstruction.

The aim of this work is not to present a completely new shape deformation technique. Instead, we propose our novel interpolation as a natural ingredient to [YZX*04], which provides a basic mesh editing framework. Here, the propagation of local deformations is an essential stage for surface manipulation, as the linear reconstruction operator alone cannot account for local rotations and scaling. To achieve fair and efficient propagation, we propose harmonic fields, which are smooth scalar functions in the manifold (Sec. 5). We believe that this construction is natural, we show that it is efficient. Also, we remark that it avoids an approximation of – generally non-smooth – geodesic distance fields for (uniform, linear, or Gaussian) blending.

Deformation transfer requires an additional phase for establishing correspondence between reference and target shape. We propose to use harmonic fields in a novel approach: Inspired by the notion of barycentric coordinates, we establish a family of – not necessarily independent – coordinate functions over the manifold. The partition of unity property of these coordinates provides a convex combination setting, which is used to match corresponding pairs of triangles (Sec. 6).

Our method is very different from the iterative deformation process in [SP04]. Working entirely in the 2D manifold, it does not depend on absolute coordinates which makes it less sensitive to the initial alignment of the shapes, in general a prerequisite for such iterated closest point algorithms. Also, we are not applying a non-linear optimization process, and in particular no user parameters are required for appropriate blending of an energy functional.

Our results confirm that we find good correspondence efficiently using relatively few markers, hence little user interaction. Again, we apply only additional back-substitution, using the same linear operator as within all phases of the whole deformation process.

Finally, we show as an additional contribution, that reasonable transfer can be achieved differently and even more efficiently by harmonic guided interpolation of deformations at the markers (Sec. 7).

4. General differential setting

In the following sections, we will consider the steady-state elliptic equation

$$\nabla^2 u = f\,, \tag{1}$$

with appropriate boundary conditions. If $f \equiv 0$, this is well-known as the (Dirichlet problem for the) *Laplace equation*. For a non-null function f, this setting is called the *Poisson equation*.

We consider piecewise linear functions over triangulated manifolds, which can be scalar fields or multi-dimensional vector fields. The discretization of this setting is well-known and leads to a sparse linear system

$$Lu = b, \tag{2}$$

where the matrix L represents the discrete Laplace-Beltrami operator matrix (see, e.g., [PP93, MDSB02]).

Equation (1) and the associated linear system (2) are the basic tool applied throughout this work. The same system will be solved for different right hand sides, in the sense of either the Laplace equation or the Poisson equation. This means effectively, that the matrix L is decomposed only once and subsequent solutions are obtained from back-substitution alone.

5. Surface editing along harmonic fields

For intuitive surface editing, the user interacts only with a small number of vertices, while the system automatically places all other vertices within the selected region of interest in a natural, detail preserving way. Hence, the editing tool acts on a submesh of interest, whose vertices are classified as fixed, edited, or free. The last class includes the majority of vertices, whose new positions are to be determined. Fixed vertices just stay in place and impose boundary constraints. Edited vertices are positioned by the user, and the relocation of a region of such vertices defines a deformation. Alternatively, a deformation can be directly prescribed for the vertex, e.g., for twisting.

In this section, assume that the same deformation is defined for all edited vertices, i.e., a single rigid mesh region is repositioned, as is the case for the majority of manipulations. In Sec. 7, we show how multiple local deformations can be interpolated simultaneously.

Given this local deformation for the edited vertices, it should be interpolated in a natural way over the whole (ROI) manifold, in order to compute the global shape edit. We achieve this by using harmonic fields for deformation guidance.

A harmonic function h satisfies the Laplace equation $\nabla^2 h = 0$. For discrete scalar harmonic fields, we prescribe the value 1 as boundary conditions for the edited vertices acting as sources, and 0 for fixed vertices, which we denote sinks. Solving for $Lh = 0$, with respect to these boundary conditions, the resulting harmonic functions smoothly blend between 0 and 1 with no local extrema other than sources and sinks. As before, L denotes the discrete Laplace-Beltrami operator. Due to the chosen discretization the gradient flow of the fields respects the intrinsic surface geometry, and it is independent of the particular tessellation of the surface. Figure 1 (left) visualizes a harmonic field over a simple surface mesh using a color table.

We decompose the local deformation into scaling and rotation, the last represented by unit quaternions. At each vertex, the value of the harmonic field is used to blend between the source deformation with the identity fixed at sinks. The result is a smooth deformation field over the manifold.

For the reconstruction of the globally edited surface from this deformation field we follow the approach in [YZX*04] based on solving the discrete Poisson equation (see also

[PGB03]). By sampling the deformation field at the barycenters of the triangles, we obtain a piecewise constant field, i.e., deformations per triangle. Then each triangle is deformed separately, which yields a deformed but fragmented, discontinuous mesh. For integration of the right hand side of the Poisson equation, we compute the gradients for the deformed triangles. The divergence of this gradient field is summed at vertices shared between triangles according to the original mesh connectivity, yielding the right hand side vector b. The solution of the associated Poisson equation $Lx = b$ provides the new vertex positions x.

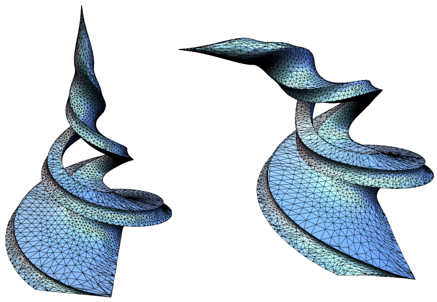

Figure 2: *Edit of the twirl object with sharp features.*

We note that in contrast to [LSC*04, SLC*04] L represents the Laplacian matrix without any changes, in particular all constraints are incorporated into the right hand side.

6. Deformation transfer guided by harmonic fields

The main goal of this section is to present an approach for finding correspondence between two surfaces. This correspondence is vital for deformation transfer, a tool for mimicking deformation of the reference on the target shape [ACP03, SP04]. Certainly, meaningful correspondence can only be achieved if there exists a semantic correlation between shapes, like between several models of four-legged animals.

To establish correspondence, the user marks few pairs of corresponding points on the reference and target surfaces. This interaction establishes the semantic correlation between models and will guide the whole process. Hence, it is essential to carefully select markers such that good coverage of the reference deformation is obtained. At the same time, the number of markers should be kept low to minimize interaction. So the usual procedure is a corrective loop, where the user iteratively specifies new markers or to updates old ones, and recomputes the deformation transfer until satisfying results are achieved. For this reason, efficiency for finding correspondence and its quality directly account for user-friendly interaction.

The correspondence maps each triangle of the target mesh to one face of the reference. Note that we do not understand correspondence as a bijective mapping and do not solve a cross-parameterization problem [KS04, SAPH04], which in general applies constraint non-linear optimization.

In fact, for deformation transfer a non-bijective mapping is sufficient as stated by Sumner and Popović [SP04] and verified by our experiments (see also Figure 4). However, it is vital for the mapping that it respects semantic correspondence, and that it is independent of the tessellation or resolution of the model. Furthermore, it should be established efficiently to allow quick response for fine tuning. Based on such mapping, we decide on match or mismatch between target and reference triangles, for matches local deformations are transferred.

We use harmonic fields to guide the correspondence. Motivated by the notion of shape functions for linear triangles[†], we propose a generalization to manifold meshes. Given a triangle, we can associate with it three functions with values 1 at one vertex and 0 at the two opposite vertices. These shape functions define a set of basis functions over the triangle, well-known as the barycentric coordinates, which can be used for linear interpolation over the triangle. We aspire to establish a generalization of such characterization to manifold meshes, usable for deformation transfer.

Given a set of markers $\{m_1, \ldots, m_k\}$, we associate with it a family of "shape functions" defined over a mesh. For each marker m_i, we define one harmonic field h_i with Dirichlet boundary conditions by setting its value to 1 at m_i and to 0 at all other markers m_j, $i \neq j$. This family of functions defines an k-dimensional vector field over the entire manifold, assigning each vertex a vector $(h_1, \ldots, h_k)$.

This family is in general not independent and does not necessarily form a basis. However, we remark that they satisfy the partition of unity property $\sum_{1 \leq i \leq k} h_i \equiv 1$. This property is of interest for our approach as it guarantees well-behaved and bounded coordinate functions h_i. We exploit this fact for finding correspondence.

For two surface meshes with clear semantic correspondence and a set of correspondence markers, we expect that the harmonic fields will be similar and hence correspond. Our experiments verify this observation. Correspondence between triangles is then achieved by matching the vector field of each target triangle (given by the barycentric average) to a triangle of the reference mesh which yields the closest field value. Here, we define closeness in terms of the 2-norm of h. We remark that due to our experiments this can be reduced to taking into account only the n maximal vector components for each value of h, where $3 \leq n \leq k$. This way we transfer local deformations to the target from matching reference triangles. Analog to editing, the solution of the

† Formally, shape functions for triangular Lagrangian finite elements of degree 1.

Figure 3: *Left: The head of the cow is rotated and scaled. Right: Head and fin of the (top) turtle are bent.*

Poisson equation provides the new target mesh, which mimics the deformed reference shape.

7. Harmonic interpolation for editing and deformation transfer

In this section, we show how to interpolate multiple deformations simultaneously, which can be regarded as blending between several sources, each of which propagates a different deformation. We remark that this can be directly applied to the editing setting of Sec. 5. Here, we discuss the interpolation in another context: we explore the possibility of direct deformation transfer without establishing any correspondence other than the markers. In other words, local deformations of the reference surface are sampled at the markers. On the target surface, they are used as constraints for harmonic interpolation.

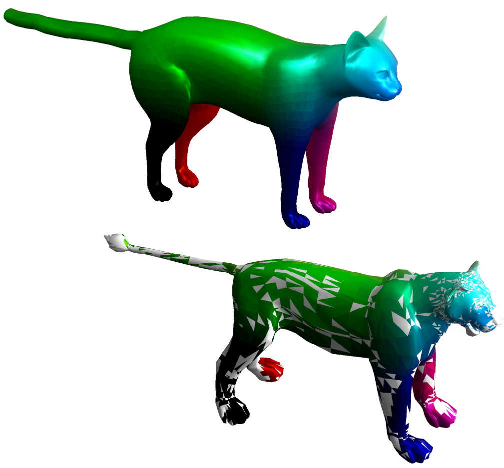

Figure 4: *Illustration of a non-bijective correspondence map: The cat as target surface is color coded. For deformation transfer from the lion, the cat triangles are mapped onto the lion, shown in the bottom visualization using the same color code. Indeed the lion is not fully covered, however, the good match in colors indicates a meaningful transfer of deformations, i.e., the left front legs correspond, etc.*

Given correspondence between marked triangles on the reference and target surface, we can compute the deformation on each of these triangles, using a virtual tetrahedron as in [SP04]. The deformations are converted into unit quaternion form. The four components of the quaternion (plus a scaling component if required, see Figure 3 (b)) are considered as separate scalar fields in the manifold. We consider the propagation of the deformations over the surface as establishing harmonic functions, i.e., we find a solution to the Laplace equation, which satisfies all given deformations independently in every component. Once the solution is obtained, the Poisson scheme is used to apply the deformation.

Despite the simplicity of this approach, it works surprisingly well, it is extremely efficient, and it provides a natural propagation at no extra cost. However, the approach is limited by its nature: First, all local deformations which are obtained from the interpolation are within the convex hull of the given deformations at the markers. The scheme cannot synthesize deformations in between, which have not been captured. Second, the interpolation assumes a smooth variation of deformations relative to the surface domain. It cannot predict and react on strong variations of the target surface, which are not reflected in the reference. Hence, if the two surfaces locally differ too much, the interpolated deformations may not be meaningful. Of course, both issues can be addressed by placing additional markers, in particular near geometric detail.

8. Results and discussion

Figures 1, 2, 3 5, and 6 show several edits of models with varying complexity and shape detail. The linear framework enables edits at interactive rates. The Laplacian matrices are decomposed only once after a region of influence is selected, the factors can be reused for efficient back-substitution for reconstruction after every single change of the deformation. The time for decomposition and initial solution when editing the entire Happy Buddha model at a resolution 220K triangles is in the order of few seconds on current hardware.

Surface deformation is a very broad topic, and we believe there is no single solution to the variety of editing problems anticipating the needs and desires of modelers and designers. So obviously, the proposed methods within this work

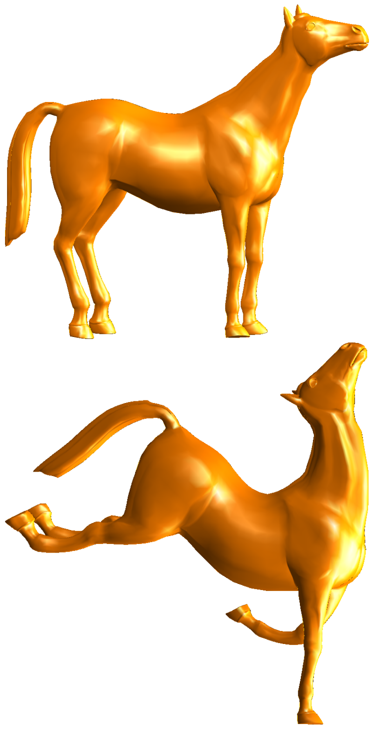

Figure 5: *An exaggerated edit of the reference horse model.*

are limited and target only some specific problems. While the method is in general robust to triangle foldovers, there are no guarantees on mesh self-contact and penetration.

Figure 7 shows the transfer of the lion poses to the cat, correspondence was established using 68 markers for the upper left pair of models. (The correspondence map is illustrated in Figure 4.) The models are taken from [SP04], but we reverse their transfer: the reference deformation sequence was given for the lion, in fact, we are using their output of their algorithm as input. We consider this as a hard but fair test for our correspondence computation, and the ideal result would be to recover the original manually animated cat sequence. The results confirm that our mapping is good. Certainly, artifacts in the input reproduced but rarely amplified. The deformed cat gets close to the original sequence, we observe most problems with the deformation of the tail and inevitable surface self-intersections. We emphasize that the correspondence was established only from the solution of a linear system, in particular, no non-linear optimization was applied.

Figure 8 shows a similar test: using 120 markers, the deformation sequence is transferred back onto the original horse model only by harmonic interpolation. For each pair of images, the left one shows the manually animated model (from [SP04]), while the right one shows the original horse deformed according to the result of the interpolation. In an ideal setting, the second one should reproduce the first one. The results show, that this is nearly the case, and it confirms the harmonic interpolation of local deformations in general. Certainly, for the plain harmonic interpolation method more markers are needed for achieving good results.

Comparing Figure 7 and 8 and the approaches of Sec. 6 and 7, respectively, we observe that for the first approach approximately the same number of markers as for [SP04] is sufficient while we require no additional user parameters and only applications of the linear operator and simple searches over the harmonic coordinates in contrast to non-linear minimization. However, this process is still not quite interactive. Our second approach using harmonic interpolation requires more markers in general. It eliminates matching and hence greatly reduces computational cost, which are independent of the number of markers. In brief, our two approach balance number of markers versus more efficiency and interactiveness.

Discussing limitations, we would like to emphasize that the matching relies heavily on the semantic similarity of the models at hand. In fact the method would not yield convincing results for models with different semantics (e.g., very short legs versus very long legs). The number of markers used in our method is of the same order of magnitude as the ones used in [SP04]. We note that it is possible to establish a matching with less markers especially when dealing with very simple poses, however, the current number of markers is reasonable given that poses of the cat and lion are rather extreme.

Furthermore, a judicious placement of markers in order to better capture deformations can always reduce the number of needed markers. On the other hand for the harmonic interpolation usually more markers are needed as the solution tends to have a slight "rubbery" behavior especially around the joints (see Fig. 8). This is in part due to the elliptic nature of the interpolation, so more markers are needed around the joints in order to maintain a good approximation of the the deformations. However, in practical applications one might prefer this interactive approach using more markers which can be added and readjusted on the fly yielding immediate response.

9. Conclusions

We presented a surface deformation framework for shape editing and deformation transfer. As a central tool we apply harmonic fields to guide the deformations, i.e., to interpolation of local deformations over the manifold and to establish correspondence for deformation transfer. Our unified approach is elegant and natural: the same mathematical building blocks, solving the discrete Laplace and Poisson equations, are applied in all stages. Inherent smoothness is provided, and non-linear minimization of energy functionals is avoided. In fact, use of linear operators render the ap-

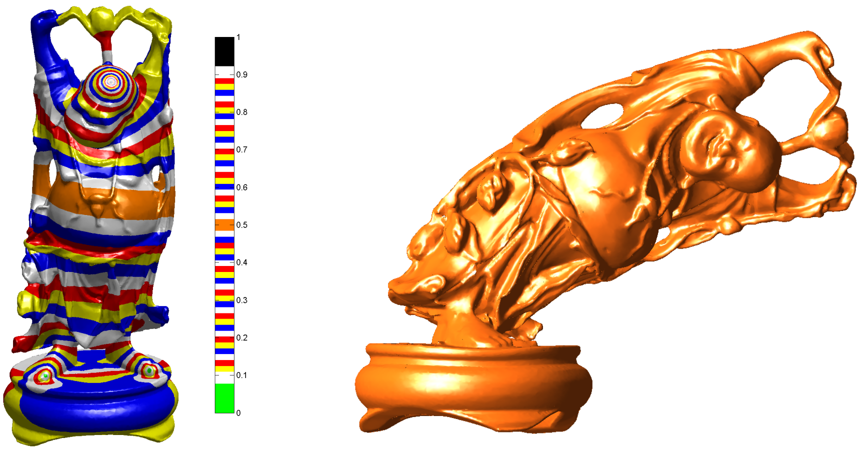

Figure 6: *The harmonic field on the Happy Buddha model, visualized left, guides the bending and twisting edit. This is the largest mesh used with* 220*K triangles, two sinks at the feet and one source on the head were applied.*

proach efficient, the same sparse linear system is solved multiple times per problem instance. Hence, only a single matrix decomposition is required. Our results confirm effectiveness and efficiency of the approach.

Harmonic fields offer a nice framework for surface editing and they proved to yield promising results in surface resampling [DKG05]. We see potential use for them in other areas of computer graphics such as mesh segmentation and motion planning.

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Figure 7: *Harmonic guided deformation transfer from the lion onto the cat (top left pair). The lion sequence is the result of [SP04]. We use it as input and transfer the deformations back onto the cat model (see also Sec. 8).*

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Figure 8: *Testing the harmonic interpolation. Left: Horse animation taken from [SP04]. Right: Result of interpolated deformation transfer applied on the original horse (Fig. 6, see also Sec. 8).*

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