Interactive Control of Deformable-object Animations through Control Metaphor Pattern Adherence

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Abstract: In this paper we present an adaptive and intuitive methodology for controlling the localized deformations of physically simulated objects using an intuitive pattern-based control interface. To maximize the interactive component presented in this approach we consolidate existing feedback mechanisms in deformable-body control techniques to provide intuitive editing metaphors for stretching, bending, twisting, and compressing simulated objects. The resulting movements created by these control metaphors are validated using imposed behavior evaluation and the effectiveness of this approach is demonstrated through interactively generated compound movements that introduce complex local deformations of objects in existing physical animations.

1 INTRODUCTION

Controlling the behaviors of deformable objects in physically-based simulations is an area within computer animation that has recently received extensive attention. In this field, notable progress has been made in the development of intuitive control techniques that can be used to effectively generate and target deformation behaviors in physical animations. Effective approaches in this domain include goal oriented behaviors derived from optimizations in inverse dynamics (Murray-Smith, 2000) and constraint-based techniques (Witkin and Welch, 1990). These approaches are based on methods that effectively control deformable-object behavior by interpolating between statically defined deformation states. This provides an artist with the ability to generate physically plausible animations of deformable objects by defining this sequence of deformation states. Despite the impressive results that can be achieved using these techniques, there remains a segment within the domain of physically-based animation control that requires the translation of high-level control behaviors into the physical motions of simulated objects to derive realistic deformations. The ability to effectively interpret and map deformation behaviors to a simulated object provides animation artists with a higher level of control over the motions that can be expressed in physical animations. Extending this precise control to localized deformations, realistic motions from deformable models can be obtained (see Figure 1).

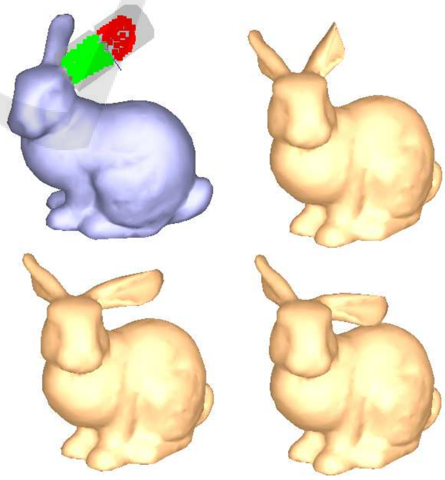

Figure 1: Natural deformation behavior derived from the application of a twist control metaphor. Starting from the rest state (top-left), the application of the twist control metaphor produces a localized deformation (bottom-right).

In this paper we present an approach to utilizing precisely controlled external forces to generate localized deformations in existing animations of both Mass-Spring Systems (MSS) and Finite Element Models (FEM) using high-level control metaphors. Control metaphors introduce an abstraction for high-level deformation patterns that can be imposed on deformable objects to obtain artist directed behaviors. Unlike prior techniques where intermediate motion is not explicitly controlled by an artist, we provide

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a set of controls that allow an artist to continuously interact with the physical state of a simulated object. Specifically, we look at how control metaphors can be used to stretch, bend, twist, and compress localized regions of simulated deformable objects. We then integrate this editing process into an intuitive animation interface that allows for an artist to iteratively refine deformation behaviors through the use of interactive control widgets. The objective of our approach to deformation control is to provide a set of tools that can be effectively used to generate deformations based on predefined control metaphor behaviors and precisely control deformations within existing animations. This tool-set includes real-time simulation recording, the ability to generate dynamic simulation previews, and the introduction of interactive force curves for precise deformation control with motion blending.

The effectiveness of our approach is explored through the application of control metaphors to existing node-based models to generate explicit deformation behaviors. From the resulting animations generated with this proposed method, we illustrate that control metaphors can be used to effectively impose physically plausible localized deformations at any physical time-step within an existing animation. To further illustrate the utility of this proposed technique, we also demonstrate that the subsequent application of control metaphors can be used to define compound localized deformation behaviors.

2 RELATED WORK

Several generalized control techniques in goal oriented optimization (Popović et al., 2000), dynamic key-framing (Hildebrandt et al., 2012), space-time optimization (Barbič et al., 2009), and inverse dynamics (Jeon and Choi, 2007), (Twigg and James, 2008) have been developed to provide effective techniques for generating accurately controlled animations. The common tie between these approaches is that they are directed at the derivation of physically plausible motion defined between statically defined deformation states. Similarly, recent developments in example driven deformations by (Martin et al., 2011) and methods using internal elasticity potentials introduced by (Coros et al., 2012) can be used to direct global deformations form predefined static deformation states or transformation goals. These approaches represent a field of deformation control techniques that utilize constraint-based optimizations that can be used to effectively generate targeted deformation behaviors. However, these approaches lack flexibility in the control of behaviors within intermediate states generated during this optimization process. This can be attributed to the to the difficulties in creating an intuitive connection between artistic intent and optimization control parameters.

To modify the deformation behavior between example or goal states using current techniques, the solution involves the introduction of additional static examples that further refine the description of the desired behavior (Chai and Hodgins, 2007). However the introduction of these additional constraints increases the number of required example deformation states that an artist must provide. Upon doing so, an artist must consider that the accuracy of these input states can significantly affect the physical plausibility of the resulting animation (Arikan and Forsyth, 2002).

In prior rigid-body control techniques based on physical parameter optimization (Popović et al., 2000), these intermediate states can be derived from global transformations. However, providing these additional key-frames for deformable objects represents an additional challenge due to the inherent difficulty in accurately defining static deformation states. This problem is exacerbated for objects with complex topologies or highly-dynamic models such as articulated figures or cloth. While many of these introduced techniques are well suited for generating the intermediate motions between static deformations, an artist is left to provide these initial input states, a non-trivial task. Additionally, the introduction of these new constraints requires a regeneration of all intermediate motions, thus eliminating prior deformation behaviors. This is an undesirable effect if the original deformation behavior was close to the desired result.

Alternative techniques for interactively editing deformable simulations proposed by (Barbič et al., 2012) and (Huang et al., 2011) aim to maintain the original behavioral characteristics of a deformable object within the provided animation. This provides an effective platform for interactively controlling deformations and introduces the ability to alter object behaviors within existing animations.

These contributions substantially improve the interactive editing process used by artists to control object deformations while preserving existing animated behaviors. Our work is related to these contributions and aims to provide an interactive editing environment that can facilitate real-time editing of localized deformations. We propose that generalized high-level control metaphors can be used in cooperation with existing techniques to both generate static deformation states as key-frames, introduce localized deformations in existing animations, and provide tweaks to existing cage-based animation techniques (Joshi et al., 2007), (Ju et al., 2008).

3 METHOD OVERVIEW

The input to our interactive animation system is based on MSS and FEM node-based deformation models as individual rest state objects or as part of an existing physically-driven animation. In both instances the dynamics model driving the deformation behavior is orthogonal to our approach and does not contribute to the requirements of our editing tools. Rather, the only assumptions made about a provided nodal system is that it is composed of n interconnected nodes that define a shell or tetrahedral topology and can be directly integrated into an existing dynamics model. If an animated MSS or FEM model is provided, the animation is discretized into states that correspond to individual time-steps within the underlying dynamics model driving the physical simulation. In using precisely targeted external forces, we can effectively limit the requirement of our approach to dynamics models that support the application of these forces to arbitrary nodes. In our implementation we utilize the VegaFEM physics library (Barbič and Schroeder, 2009) with an implicit Euler integration scheme.

The foundation of our editing approach is based on the development of several components that are required to facilitate this form of force-based editing in an interactive environment. These requirements include (1) reliable local coordinate systems for deformable models to facilitate targeted deformations, (2) the ability to record physical simulations in real-time, (3) the efficient generation of dynamic simulation previews for interactive feedback, and (4) a set of intuitive control metaphors that impose intuitive pattern-based deformation behaviors. We consolidate these components within an interactive editing environment that allows an artist to effectively define new animations and refine the deformation behaviors exhibited by objects within existing animations. In this section we provide the derivation for each of these components and establish how each contributes to this intuitive animation editing framework.

3.1 Local Coordinates

To provide an effective mapping between the implemented control metaphors and the deformable objects upon which they operate, we have introduced a robust technique for estimating local coordinate transformations for deformable-bodies. Building on this development, we introduce the notion of control coordinates that allow metaphors to be directly targeted to localized regions within a deformable object. As these objects are simulated, these coordinate systems maintain the application of a control metaphor to the exact region defined by an artist. This allows us to provide consistency in localized deformations, even for objects that exhibit complex global trajectories. In this section we provide an overview of our method for identifying a unique origin and orthogonal set of vectors that can be used to represent the local coordinate transformation of a deformable-body.

Initially considering the position of a deformable object, we simply select the center of mass C as an accurate representation of the objects global position. To identify the orthogonal set of vectors that will represent the rotation of the deformable object we consider two objectives: (1) the initial orientation should be aligned to the objects geometric definition and (2) the mapping should accurately represent the rotation of the object, even during large scale deformations.

In our approach we have devised a two stage process for identifying this coordinate system. In an initial pre-processing stage we calculate C and the orientation of the coordinate system that best matches the geometric representation of the object through Principle Component Analysis (PCA). As the objects deformation changes during each simulation time-step, we recalculate C and update the orthogonal axes vectors to match the new rotation of the object. The complete derivation of this local coordinate system utilizing PCA and averaged deformable mass distribution is detailed in (Transue, 2014).

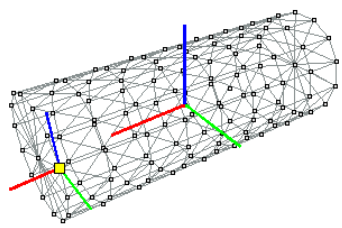

Figure 2: Local and control coordinate systems for a simple deformable object. The selected node of the deformable object represents the origin of the control coordinate system and defines the localized region that will be influenced by the external forces introduced by a control metaphor.

To produce a localized deformation using a control metaphor we must also provide an intuitive way of selecting the affected region. Therefore to attach a control metaphor to a deformable model at a specific location, we employ a simple node selection technique. The selection of an individual node within the object will weld a control metaphor to this node so it can then be used to perform localized deformations. The image in Figure 2 illustrates the selection of an individual node that will define the location of the applied deformation behavior.

3.2 Simulation Recording

The generation of new animations and the support for modifying existing animations requires a complete set of controls for both real-time recording and playback. In our approach we provide the standard set of multimedia controls as part of an interactive time-line that allows an artist to effectively navigate through the collection of frames within the active animation. Providing the ability to use this interactive time-line to scroll through object deformations throughout the recorded animation presents a critical feedback system that allows an artist to closely analyze each deformation state of all animated objects. This presents an artist with the ability to iteratively refine the motion exhibited by the simulated objects until the desired outcome has been reached. In our approach, the ability to refine the deformation behavior using real-time playback allows for a higher level of artistic control when compared to techniques that utilize inverse dynamics to generate a fixed result. This is simply due to the interactive nature of our proposed approach.

3.3 Dynamic Simulation Previews

Unlike optimization techniques that require the use of a secondary deformation state that an artist defines as a dynamic key-frame of the object, our approach does not explicitly define the final position of a deformable object but rather it is generated during the application of the control metaphor. Therefore in using our method an artist does not immediately know how the changes they have imposed on a deformable object will affect the resulting motion of the object. To address this problem we introduce the ability to dynamically generate simulation previews. The image in Figure 3 illustrates the dynamic preview of a falling cloth model before and after a bend metaphor has been applied.

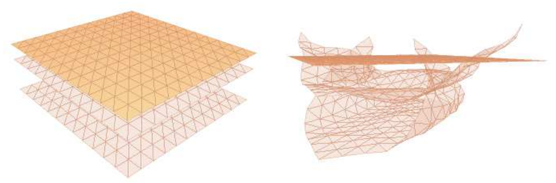

Figure 3: Dynamic preview of a cloth model (for three selected states) as a bend control metaphor is applied. The original animation (left) illustrates the cloth with a uniform decent due to gravity. The application of a bend metaphor (right) provides a realistic animation of the falling cloth.

The generation of a simulation preview does not affect the current animation but illustrates a select number of future states for every object within the animation. This provides an artist with immediate feedback as to how the current configuration of control metaphors applied to various objects will affect both local deformations and global trajectories of all objects within the animation.

4 CONTROL METAPHORS

The fundamental component that we introduce with the proposed method of deformable object control is the notion of high-level control metaphors. These metaphors represent a mapping between a control widget that specifies a motion, pattern, or behavior and the physical implementation of that motion by a simulated object or region within the objects surface. This provides an artist with a generalized and extensible control methodology for introducing localized deformations in animated objects. In this section we introduce the components that formally define a control metaphor and illustrate the flexibility of our proposed technique by demonstrating that these components can be easily interchanged to provide an extensible set of deformation controls.

The implementation of a control metaphor is responsible for providing definitions to the following components: (1) the identification of the control regions that indicate the nodes are influenced by the control, (2) the orientation of the external forces the control produces, (3) the interactive widget that provides a visual representation of the controls behavioral pattern, and (4) the definition of a force curve that defines applied force magnitude over time.

The consolidation of these four components provides the formal basis of the abstract control metaphor definition: given a control metaphor $\mathcal{M}$, the composition of these components into a control metaphor is defined as follows:

$$\mathcal{M} = (\mathcal{R}, \mathcal{O}, \mathcal{V}, \mathcal{F})$$

Where $\mathcal{R}$ represents the discrete set of bounding volumes that identify the regions influenced by this control, the set of normalized vectors $\mathcal{O}$ represents the external force orientations applied to the object in within each region, the set of three-dimensional primitives $\mathcal{V}$ that provides the visual representation of the control, and the scalar list $\mathcal{F}$ represents the force magnitudes that define the application time and duration of the control. Providing a unique definition for component allows for an unbound number of potential control metaphors with this extensible design.

Through the implementation of each component we can derive high-level controls that can easily be configured by an artist to introduce pattern-based deformations (such as bending, twisting, stretching, and

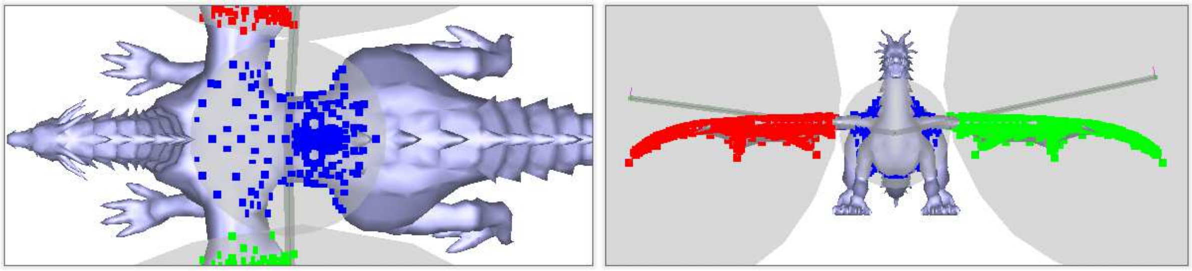

Figure 4: Illustrations (top and front views) of the widget that represents the bend control metaphor as seen within our interactive editing environment. Each sphere identifies one of the control regions that are defined by the bend metaphor.

compression). Additionally, every control metaphor instance contains a unique transformation that defines its relative position and orientation to the geometry of the controlled object. This allows an artist to introduce both global and targeted localized deformations to define new animation or adjust the behaviors of simulated objects within existing animations.

4.1 Control Regions

Control metaphors drive localized deformation patterns based on the set of control regions $\mathcal{R}$ that define which nodes within a simulated object are influenced by the introduced external forces. Specifically, we aim to derive high level control patterns from a collection of primitive regions such that each region $r \in \mathcal{R}$, in part, contributes to the global behavior of the control. From this, we can define the control regions of a pattern-based metaphor as a set of bounding volumes that evaluate a boolean function for the selection of the nodes involved in the deformation.

Depending on the complexity of the desired deformation, a control metaphor may contain several control regions; however to avoid unnecessary complexity in the usability of each control we utilize a limited number of geometric primitives to identify these control regions. If a node resides within any of the control regions within $\mathcal{R}$, it will be highlighted in size and color to indicate its participation within the deformation (see Figure 4). This presents a clean interface that effectively communicates which nodes contained within a simulated model will drive the imposed deformation.

4.2 Force Orientation

The selection of the nodes that will contribute to a localized deformation is interactively defined by the set of artist configured control regions $\mathcal{R}$. Therefore for each control region $r \in \mathcal{R}$, we must define an associated vector field $o \in \mathcal{O}$ that defines the orientations of the external forces applied to each node encapsulated within r. The orientations of the applied external forces provide the defining characteristics of the deformation pattern that will be imposed on the controlled object, and can be defined through a simple force diagram. A control metaphor force diagram simply provides the definition of the spatial configuration of the regions that contain the vector fields that define the orientations of the controls external forces. While the definition of each regions vector field is unbound, uniform vector fields are sufficient for the derivation of most primitive deformation behaviors.

4.3 Visual Representation

To effectively communicate the location and orientation of how a deformation will be applied to a simulated object, we introduce a three-dimensional interactive widget that defines the control regions and structure of the control metaphor. In our approach we provide an interactive widget for each control metaphor that provides an artist with the ability to configure the selection of the effected nodes, the orientation of the applied forces, and the control position of the deformation (Figure 4).

Each interactive widget is represented by a collection of geometric primitives that allow an artist to easily configure the properties of the applied control metaphor. The configuration of these interactive control widgets is obtained by allowing an artist to perform adjustments by selecting the primitive component within the widget and then modifying its parameters (real-time interaction is facilitated though mouse-based gestures). The parameter adjustments that we provide for each control metaphor include the ability to scale and translate each component within the widget. This provides a high-level of flexibility in an artistic control of the provided control metaphors.

4.4 Force Curves

Control metaphors and the associated widgets we have developed provide an intuitive way of effectively imposing a behavioral pattern on a simulated object within an interactive environment; however in the context of physically-based animation several additional parameters must be provided to completely define the resulting deformation. These parameters include the definition of the instance in time when the external forces will be imposed, the duration of this application, and the magnitude of the forces applied to the nodes within each control region of the metaphor. Here we formally introduce the definition of a force curve that provides the required functionality to define all of these properties through a simple interactive curve editor. A force curve f is defined as a discrete set of two-dimensional points that approximate a function that defines the magnitude of the external forces applied through a selected control metaphor. In the instance where multiple control metaphors are applied to an individual object, each maintains its own corresponding force curve. This provides an artist with the ability to create several deformations exhibiting unique characteristics on an individual object.

Time-line Discretization. Force curves approximate a function that defines the magnitude of the external forces required to generate a physical deformation through control metaphors by supplying a scalar value that determines the strength of this deformation. To provide these values in the context of a physical simulation that employs a control metaphor, a force magnitude value must be provided for each simulation time-step. This constraint is implicitly enforced through the approximation of the curve that defines these magnitude values. Let the set $\mathcal{A}$ represent the set of discrete set of points that approximate the force curve f and let (F_{begin}, F_{end}) represent the simulation time-steps that correspond to the application of a control metaphor. The following constraint is then placed on the approximated representation of this force curve: $|\mathcal{A}| = (F_{end} - F_{begin})$. This will guarantee that for each simulation time-step the magnitude of the external forces introduced by a control metaphor is defined.

Curve Control. The implementation of the interactive interface provided to an artist is based on an orthographic projection of a force curve approximated by a Bezier curve. This representation also allows us to provide control points that allow an artist to easily control the shape of the approximated function. An artist can interactively control the position of the end and control points by simply dragging them to the desired location. This provides an accurate method of introduce precise definition of the specific instance an artist would like interject a deformation. An illustration of the curve editor provided within our application is illustrated in Figure 5.

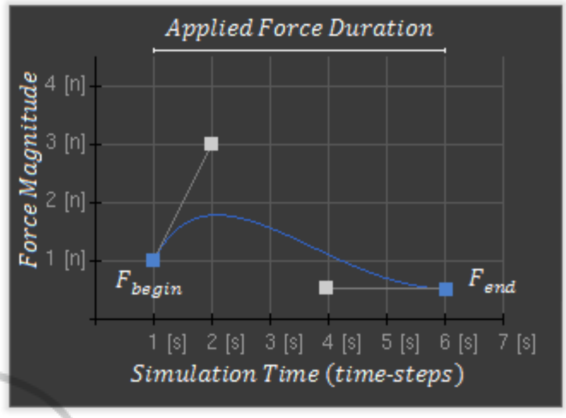

Figure 5: Screenshot of the interactive force curve editor that defines the magnitude of the applied forces over time.

With the proposed curve editing technique, common animation features such as motion blending can be achieved. Motion blending can be achieved through smooth gradients defined within the force curve. These gradients translate to gradual deformations that can be used to blend multiple deformations together smoothly. This also provides an artist with the ability to refine imposed deformations by utilizing multiple control metaphors to derive blended compound deformations.

Force Magnitude-deformation Correlation. The process of determining the magnitude of the applied external forces required to derive the desired deformation is a challenging process. In an effort to assist an artist in the definition of the force curve that will derive the desired behavior we employ dynamic previews. As an artist modifies the force curve to generate a deformation, a dynamic preview can be generated to illustrate the resulting behavior. This provides an interactive feedback loop to an artist to iterate on the motion generated with our approach. Once the desired deformation behavior has been achieved, the simulation can be recorded to make the change to the resulting animation. While this does not resolve the possibility of introducing external forces that generate undesirable or unstable behaviors, it presents an iterative process that allows an artist to visualize and refine the behaviors imposed by our control metaphors.

4.5 Deformation Controls

The definition of each component within this section provides the basis upon which primitive deformation behaviors can be created. The unique set of components defined by a control metaphor can easily be defined to generate commonly required deformation behaviors including bend operations, twisting, stretching, and compression. In this section we provide the formal definition for these primitive pattern-based motions and illustrate how these formalizations demonstrate the desired deformation behaviors on primitive geometric objects.

Stretch Deformation. To derive the behavior imposed by the stretch control metaphor we simply assert that this operation will attempt to separate two regions within an objects geometric definition. These individual regions are separated by a division plane that effectively segments the bounded regions into left and right selection intervals defined within two cylindrical control regions: $\{L_n, R_n\}$. The orientation of the external forces is simply constrained to the X-axis of the controls coordinate system. The node set L_n external force orientation is defined by a negative unit vector along this axis: $\vec{X}^-$, and the orientation of the forces acting upon the node set R_n is defined by a positive unit vector along this axis: $\vec{X}^+$. Given these components we formalize the definition of a generic stretch control metaphor:

$$\mathcal{S} = (\{L_n, R_n\}, \{\vec{X}^-, \vec{X}^+\}, \mathcal{V}, \mathcal{F})$$

The visual component $\mathcal{V}$ of the stretch metaphor is simply defined by the two cylindrical control regions that correspond to the metaphors control regions. To further refine the control provided to an artist, we provide an interactive means of refining the minimum and maximum effect distance from the controls separation plane and allow the radius of these cylindrical regions to be dynamically adjusted. From this formal definition we have also derived the components required for a compression-based deformation. In the application of this control, an artist can simply define a negative force curve which will inverse the orientation of the applied forces, thus compressing the left and right node sets to the origin of the control.

Twist Deformation. The implementation of the twist control metaphor allows for separate regions of a deformable-body, defined by a division plane, to be rotated in opposing directions. The formal definition of this control metaphor closely resembles the stretch control with the exception of of the vector field defined with the cylindrical control regions. Here we define these vector fields as a function of rotation about the controls primary axis where $R(L_n)$ and $R(R_n)$ represent rotation functions operating on the nodes identified within each control region:

$$\mathcal{T} = (\{L_n, R_n\}, \{R^-(L_n), R^+(R_n)\}, \mathcal{V}, \mathcal{F})$$

The visual component of this control metaphor is identical to that of the stretch control and can be interactively customized in the same way by adjusting the nodes contained within the provided control regions. The application of a negative force curve to this control will effectively inverse the rotation functions providing the orientations of the external forces.

Bend Deformation. Considering the implementation of a pivot-based bend deformation control, we define three separate control regions, each containing an associated (uniform) force orientation vector field. The Joint-Bend-Force (pivot force), denoted O, defines the direction of the force that opposes the Left- ($\vec{L_{bf}}$) and Right- ($\vec{R_{bf}}$) Bend-Forces to impose a bend deformation based on the selected nodes contained within the controlled object. The opposing deformations created by the imposed external forces combined with the provided offset creates the desired deformation behavior at the center of this control metaphor. An illustration of the spherical control regions and force orientations for this control is presented in Figure 6.

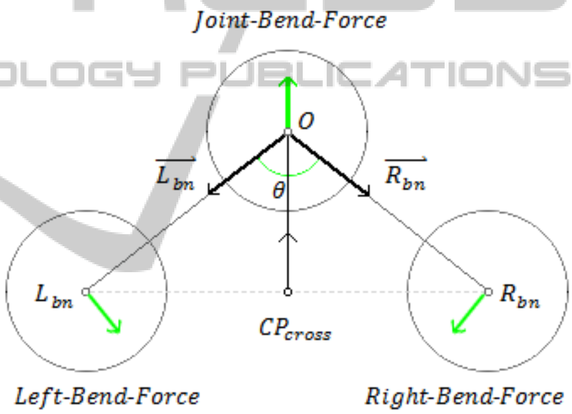

Figure 6: Force diagram illustrating the orientations of the external forces that are applied within each of the three control regions used to generate a pivot-based bend deformation.

From this force diagram and the provided set of spherical control regions, the formal definition of this pivot-based bend control metaphor can be derived:

$$\mathcal{B} = (\{O, L_{bn}, R_{bn}\}, \{\vec{O}, \vec{L_{bf}}, \vec{R_{bf}}\}, \mathcal{V}, \mathcal{F})$$

The visual component $\mathcal{V}$ is composed of three sphere-based control regions identified in the controls force diagram. To provide the ability to further refine the configuration of this control metaphor, we provide a customizable joint-angle θ that defines the angle between the L_{bn} and R_{bn} node sets and allow the radius of each control region to be adjusted. Additionally, we provide the ability to extend the distance between each of the control regions to adjust the length of the resulting bend deformation.

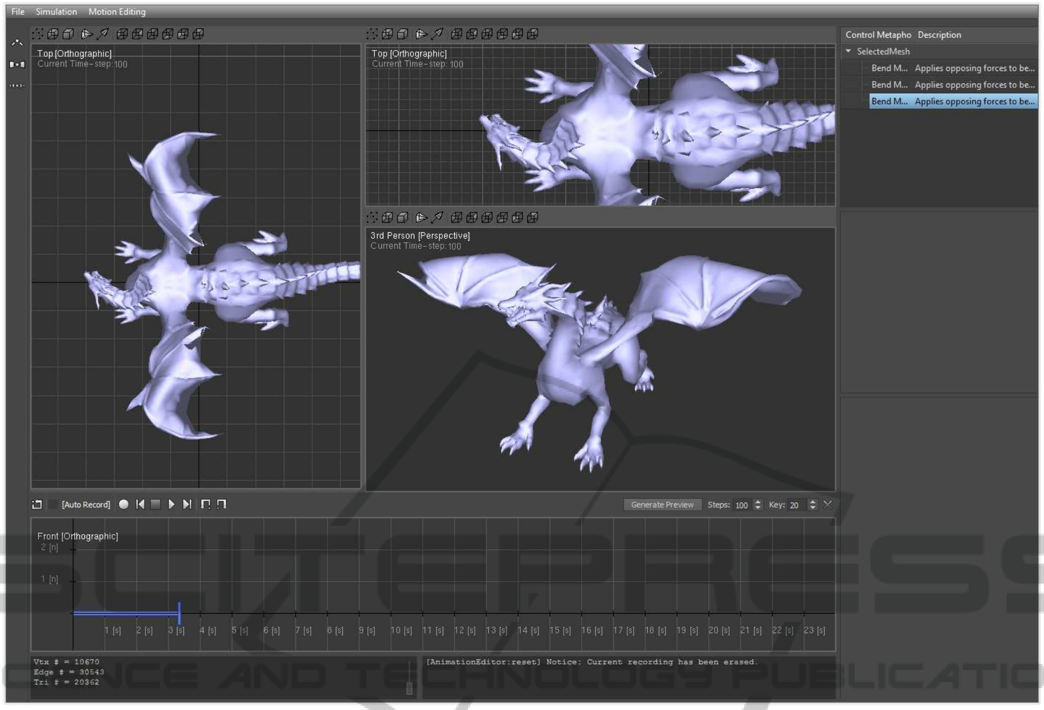

Figure 7: Screenshot of our interactive animation editing environment with media controls, time-line, and loaded scene containing a high-resolution deformable dragon. Three bend metaphors have been applied to achieve the displayed deformations.

5 EDITING ENVIRONMENT

To facilitate the generation of new animations within an interactive editing environment, our approach relies on the animation studio software we have created to facilitate the required functionalities listed in Section 3. This editing environment provides the core functionality required to view, generate, and record physically-based animations. The ability to interactively introduce control metaphors and edit deformation behaviors is facilitated through the main studio interface of our animation editing application.

This implementation provides the ability to animate multiple objects within a scene, facilitates interactive deformation views, and manages configuration of multiple control metaphors per simulated object. The image in Figure 7 provides a screen-shot of our application with a loaded animation. This interactive interface is defined by three main components: (1) the main scene viewports that allow an artist to effectively view the deformation behaviors imposed by the selected control metaphors, (2) the animation time-line which allows for the recorded animation to be dynamically viewed, and (3) the list of control metaphors applied to the currently selected object.

The resulting deformations that we have obtained were generated using our approach facilitated through this provided editing interface. In the next section look at several demonstrations of the localized pattern-based deformations introduced by our proposed control metaphors configured and employed within this interactive editing environment.

6 RESULTS

To clearly demonstrate the utility and flexibility of our approach we provide several illustrations of primitive pattern-based motions, localized surface control, and compound deformations obtained through the application of multiple control metaphors. We show how each of the introduced control metaphors can contribute to a flexible animation tool-set that can allow artists the create new animations of deformable models and refine the behaviors of simulated objects within existing animations.

The implementations of our pattern-based control metaphors introduce a basic set of deformation operations that provide the required foundation for creating complex animations of deformable models. These results are based on the primitive deformation operations such as compression, bending, and twisting. Here we demonstrate the resulting deformations that can be obtained using these controls individually.

Compression Deformation Result. A compression deformation can be derived by applying a stretch control metaphor with a negative force curve. The image in Figure 8 illustrates how this metaphor can effectively compress a tessellated cylindrical model.

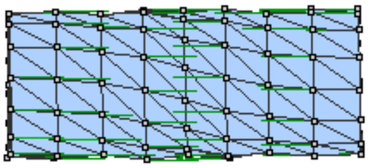

Figure 8: Resulting application of a control metaphor imposing a compression behavior. The orange lines indicate both the orientation and magnitude of the applied forces.

While the desired compression is obtained, we note the slight twist to the topology of the models surface. This effect is due to the uneven selection of the nodes involved in this deformation. We discuss the potential deformation side-effects that can be created from misaligned control metaphors in Section 7.4.

Bend Deformation Result. The application of a bend control metaphor to a cylindrical model provides the expected results when applied to the length of the object. The image in Figure 9 illustrates the effectiveness of this control metaphor in this instance. However, when performing a global deformation with a bend metaphor, we ensure that the selected control regions are balanced with respect to the bend pivot.

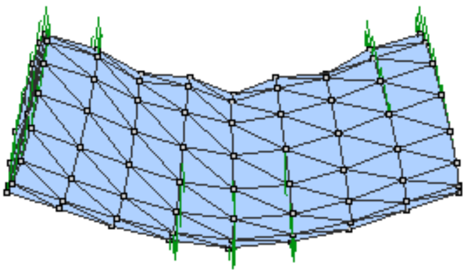

Figure 9: Global pivot-based bend deformation.

The success rate of applying this control metaphor to an object to derive a global deformation is based on the material stiffness coefficients that define the elasticity of the model. When the bend control metaphor is applied to a rigid model, an uneven distribution of forces will incur an unintended torque on the object.

Localized Deformations. Control metaphors can effectively introduce localized deformations based on the control coordinate system we have created to provide an artist with the ability to target a region within a deformable model. The two examples illustrated in Figure 10 illustrate these targeted deformations.

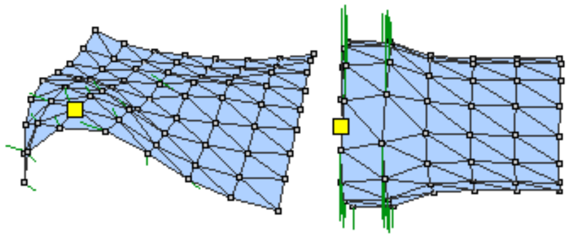

Figure 10: Twist (left) and stretch (right) control metaphors applied to models to derive localized (to the position of the enlarged node) deformation behaviors.

Compound Deformations. The process of applying multiple control metaphors to an individual deformable model provides the ability to derive complex secondary behaviors within the topology of the model. The illustration of the two control metaphors applied to the Stanford bunny mesh in Figure 11 represents an application of two control metaphors used to derive a compound deformation.

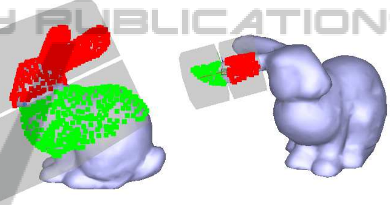

Figure 11: Control metaphor compound deformation. The twist metaphor turns the rabbits head (left) and a bend metaphor controls the rabbits ear (right).

The resulting deformation (see Figure 12) imposed by the application of both control metaphors induces a naturally blended motion between both operations. A more complex compound deformation utilizing three control metaphors is provided in Figure 13.

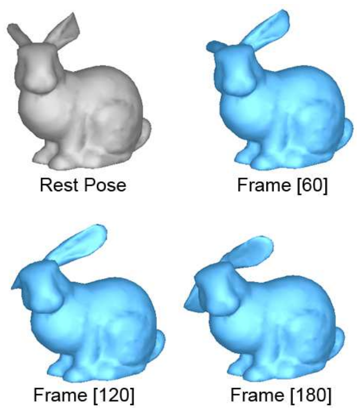

Figure 12: Compound deformation result created from the control metaphors illustrated in Figure 11 (throughout 180 simulation time-steps).

Figure 13: Compound deformations of a dragon raising its wings and rotating its head. The imposed deformations are created from the localized application of four control metaphors. The animated result is displayed left to right.

7 EVALUATION AND DISCUSSION

The evaluation of an artists ability to effectively formalize and translate the result of a desired localized behavior to an object within a physical simulation is a challenging task. The applicability of the provided set of control metaphors depends on several critical factors including: (1) the artist's ability to effectively identify a node that represents the desired location of the deformation, (2) the selection of an appropriate predefined control metaphor, and (3) the process of properly configuring the provided control widget to derive to desired behavior. To objectively evaluate the effectiveness of our approach, we analyze the integration of our force-based metaphor technique into the existing set of deformable object control methodologies introduced in Section 2. In this section we define how our approach is framed to borrow key concepts from these existing methods and identify how our technique can contribute to an artists ability to effectively generate localized deformation behaviors within existing animations. Additionally, we also consider drawbacks imposed by the set of reoccurring problems (such as deformation oscillations and induced torque) that are introduced when utilizing external forces to drive deformation behaviors.

7.1 Inverse-dynamics

Inverse dynamics is an animation technique that provides an artist with a high-level of control of an objects deformation states. The ability to define the exact state that will be achieved by a deformable object provides an artist with a powerful tool that can be used to effectively produce targeted animations. This technique effectively reduces the time required to generate a targeted animation of deformable object by simply interpolating dynamic key-frames. This is achieved by calculating the forces required to match the constraints imposed by the dynamic state of the object for each key-frame during the animation. However, utilizing a set of key-frames that define static states of a deformable body as the input to a dynamic system presents a large challenge to an artist: derive a set of complex dynamic states for an object undergoing an deformation such that the interpolated behavior will represent a realistic and physically plausible motion.

While the task of defining the dynamic states of an object (node position, velocity, etc.) may be achievable for models with a simple geometric composition, objects with complex deformation states such as cloth will present an artist with the challenging task of deriving the intermediate states of this deformation. Manually obtaining this state with a high level of fidelity for these complex objects is extremely challenging and generally requires an additional tool-set (such as cage-based controls) to assist in this process. Furthermore, even if the definitions of these dynamic states are given, we are not guaranteed that the resulting motion provided by the interpolation process will represent a fluid or natural behavior. This will lead an artist to the process of iteratively refining the included dynamic key-frames to obtain the desired behavior.

This is where we emphasize the ability of our technique to generate physically plausible behaviors based on high-level deformation patterns. The motion naturally inspired by the application of external forces can provide a resulting deformation behavior with a high level of fidelity that can be used to define a dynamic key-frame. Additionally, our technique can be used to address unrealistic motions that may be generated through the inverse-dynamics interpolation process. This can be achieved by introducing a control metaphor that acts upon the object within the existing animation refine the resulting behavior. Therefore the our method of creating localized deformations complements this approach and can be used to improve the quality of the generated animations.

7.2 Cage-based Control

Cage-based deformation control introduces the ability to manipulate complex model topologies by utilizing a reduced set of representative nodes that form an inflated cage around a deformable object. The nodes of this superimposed cage can then be explicitly controlled by an artist to implicitly direct the deformations of the complex underlying surface. The primary concept introduced by cage-based deformation control techniques is that they greatly reduce the level of control presented to an artist, thus the complexity of the deformation editing process is greatly reduced.

This form of deformation control is generally utilized as the solution to deriving physical plausible dynamic key-frames. However, this process does not address the generation of physically-based motions over time. This solution to deformation control must rely on other techniques (such as an inverse-dynamics approach or rest-shape adaptation) to derive the intermediate motion states required for an animation. This is due to the fact that the key contribution from this technique is a representative functional mapping between the nodes of the superimposed cage and the nodes within the controlled deformable body.

This mapping however, provides an effective means of imposing a high-level behavior on a complex deformable model. We borrow the application of this concept and extend it to represent dynamic behaviors imposed by our high-level control metaphors. Therefore we can effectively provide a higher level of control to an artist to accurately convey the behavior of the intended deformation. The control regions defined within each control metaphor define the bounded region that acts as dynamic cages that closely adhere to the global trajectory of the simulated object. This forms the basis of our control technique for translating high-level deformation patterns to the underlying representative geometry.

7.3 Rest-shape Adaptations

The development the technique pioneered by (Coros et al., 2012) that utilizes internal elastic potential between static deformation states to derive motion from internal forces, introduces an effective means of animating deformable objects through example- and goal-oriented objectives. This technique effectively eliminates reoccurring problems with external force-based techniques (such as oscillations and induced torque) and also introduces the notion of the animated object developing a *persona* due to the intrinsic derivation of internal forces, making them seem lifelike.

The lifelike effect introduced by this technique however may not be desirable in all instances. In the development of our force-based technique, we propose a more generalized method of applying deformations to simulated objects. Through the subsequent application of localized deformations using control metaphors, our approach can approximate lifelike movements of deformable objects (as shown in Figure 13); however the incurred artistic labor is more extensive than that required by this rest-shape adaptation technique. In our approach, multiple control metaphors are required.

7.4 Metaphor Alignment

The correct application of a control metaphor depends on the intended result desired by an artist imposing the behavior. To adhere to the original intent of the control metaphor, it must be properly aligned with the geometry of the simulated object it will deform. Even with the simplified form of interactive control widgets provided to the user, the applied external forces can fail to produce the intended deformation.

Control metaphors are subject to several conditions that must be met for the desired behavior to be achieved. This indicates that there are several factors that can contribute to an invalid configuration of the applied control metaphor that may lead to an undesirable or unstable deformation behavior. These factors include: misaligned control widgets, an inadequate external force magnitude, and the incorrect parameter configuration for the applied control metaphor. The image in Figure 14 illustrates an instance where a bend metaphor has not been properly aligned to the underlying geometry of the simulated object. Specifically, we note the lack of the selected nodes with two of the provided control regions. Therefore, the only external forces that will be applied to this object reside within the joint set of this metaphor. The resulting deformation will not match the intended result provided by this metaphor due to the misaligned widget configuration.

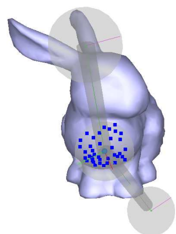

Figure 14: Invalid alignment of an applied bend metaphor where only one set of nodes is properly identified. This will result in an incorrect deformation behavior due to the incorrect widget orientation.

The implications of these requirements however are not without their own merits. The flexibility provided to an artist through the selection of the localized region, the orientation of the control, and configuration of the parameters specific to the applied control, can produce unwanted deformations; however this also provides freedom to an artist to use the provided tool-set in alternative ways. As shown in the example deformation in Figure (dragon result), the head of the dragon can be turned using a bend deformation rather than a twist control metaphor.

8 CONCLUSION

In this paper we have presented an effective way to impose pattern-based deformations on simulated MSS- or FEM-based deformable models. We have illustrated that the targeted application of the proposed high-level control metaphors can effectively generate physically plausible deformations in new animations and can be used to modify the behavior of objects within existing animations.

In this results of this paper we have demonstrated that in using the method of controlling targeted deformations we have introduced, localized deformations can effectively be imposed on simulated objects and we preserve an artists ability to iteratively refine the resulting behavior. We have also defined the outline of the interactive editing environment that was used to create these desired deformations. Additionally, through the subsequent application of the primitive control metaphors introduced in our approach, we have demonstrated that compound behaviors can be effectively generated to create complex animations. Our deformation control technique has also been compared to other leading approaches and we have discussed the potential contributions and problems associated with this approach.

While this technique contains the commonly reoccurring challenges associated with the application of external forces, the resulting deformation behaviors provide physically plausible results that can be used to effective generate realistic animations.

9 FUTURE WORK

The accurate control of deformable objects in simulated environments for the generation of physically plausible animations continues to present a challenging task. In this work we have identified a generalized method for imposing pattern-based deformation behaviors on simulated objects; yet several of the prominent reoccurring problems with the application of external forces remain, including oscillations, imposed torque, and unbound force magnitudes.

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