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Sepulveda

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(54) **CHARACTER DEFORMATION PIPELINE FOR COMPUTER-GENERATED ANIMATION**

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(51) **Int. Cl.**
G06T 13/00 (2006.01)

(52) **U.S. Cl.** **345/473**; 345/419; 345/420

(58) **Field of Classification Search** ..... None
See application file for complete search history.

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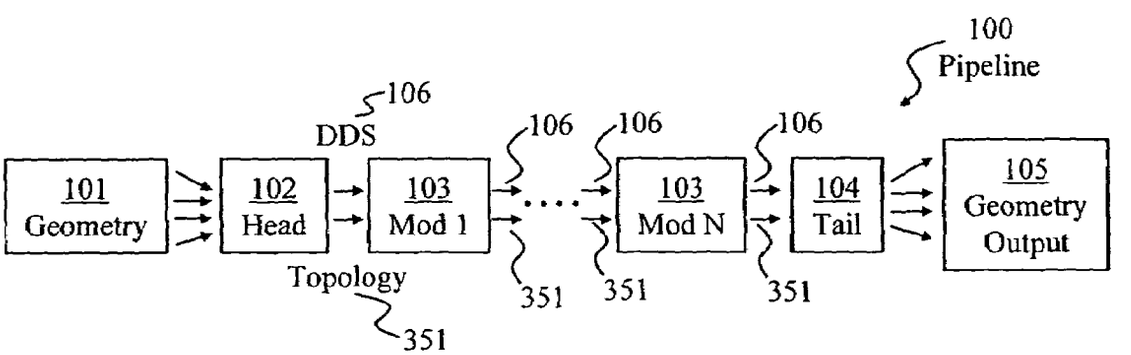
(57) **ABSTRACT**

A deformation system for animation abstracts the notion of per-point deformation to create a pipeline, including a number of deformation modules capable of handling animation of geometry (such as characters), dynamics (such as simulations) and/or effects (such as particle systems). Deformation pipelines are defined, that work as templates capable of deforming and animating families of similar characters. Support is provided for various binding modes, including sequential, parallel, blend, and hierarchical, so as to facilitate several techniques for combining deformations.

93 Claims, 16 Drawing Sheets



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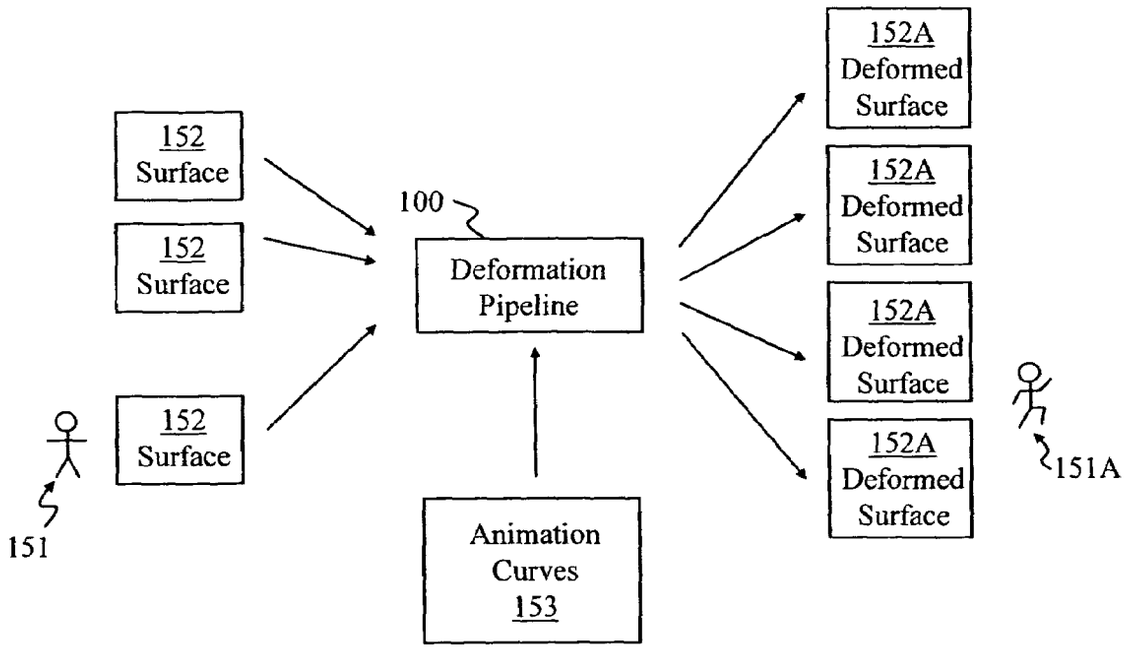

152
Surface
152
Surface
152
Surface
151
100
Deformation
Pipeline
Animation
Curves
153
152A
Deformed
Surface
152A
Deformed
Surface
152A
Deformed
Surface
152A
Deformed
Surface
151A

FIG. 1

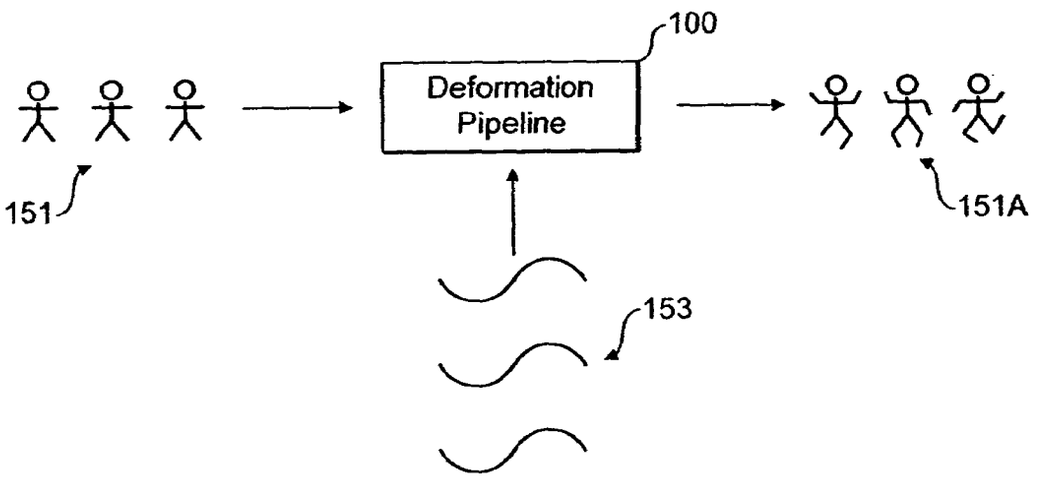

100
Deformation
Pipeline
151
151A
153

FIG. 2

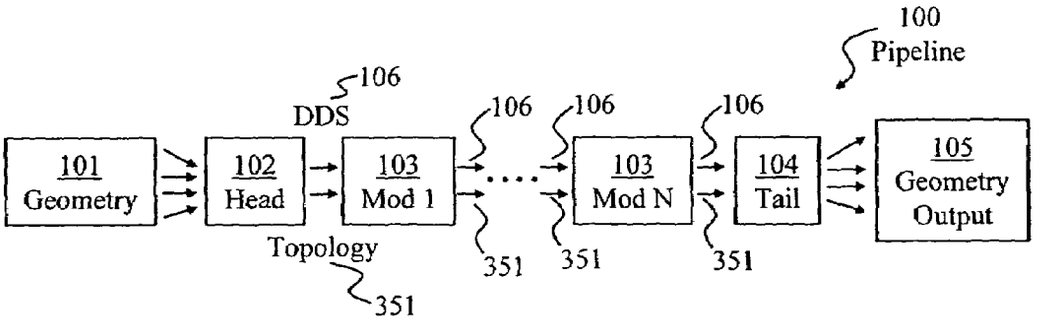


FIG. 3

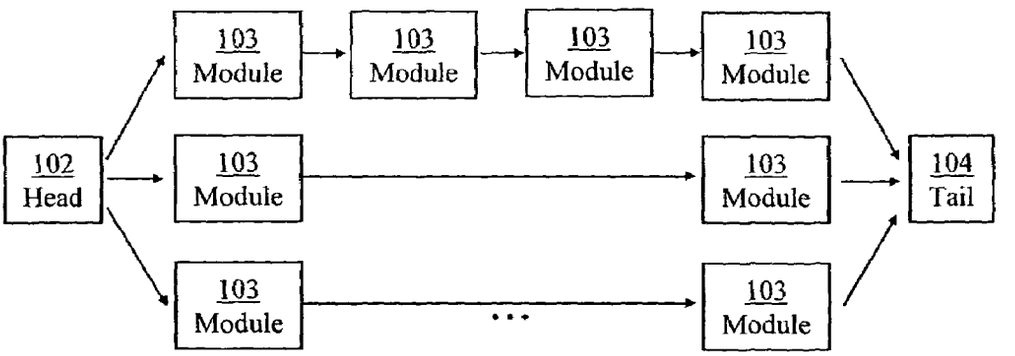


FIG. 4

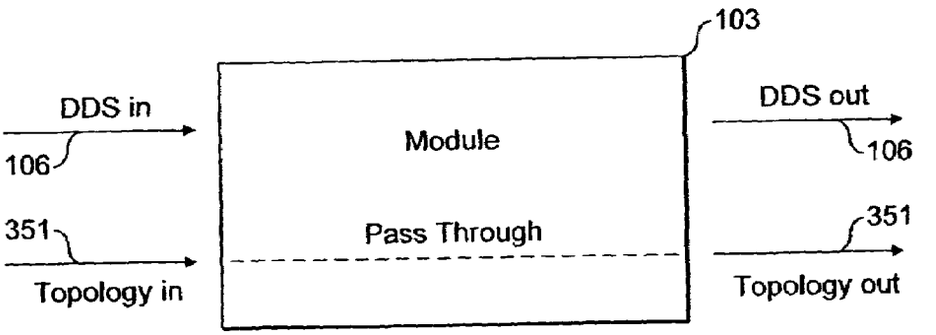


FIG. 5

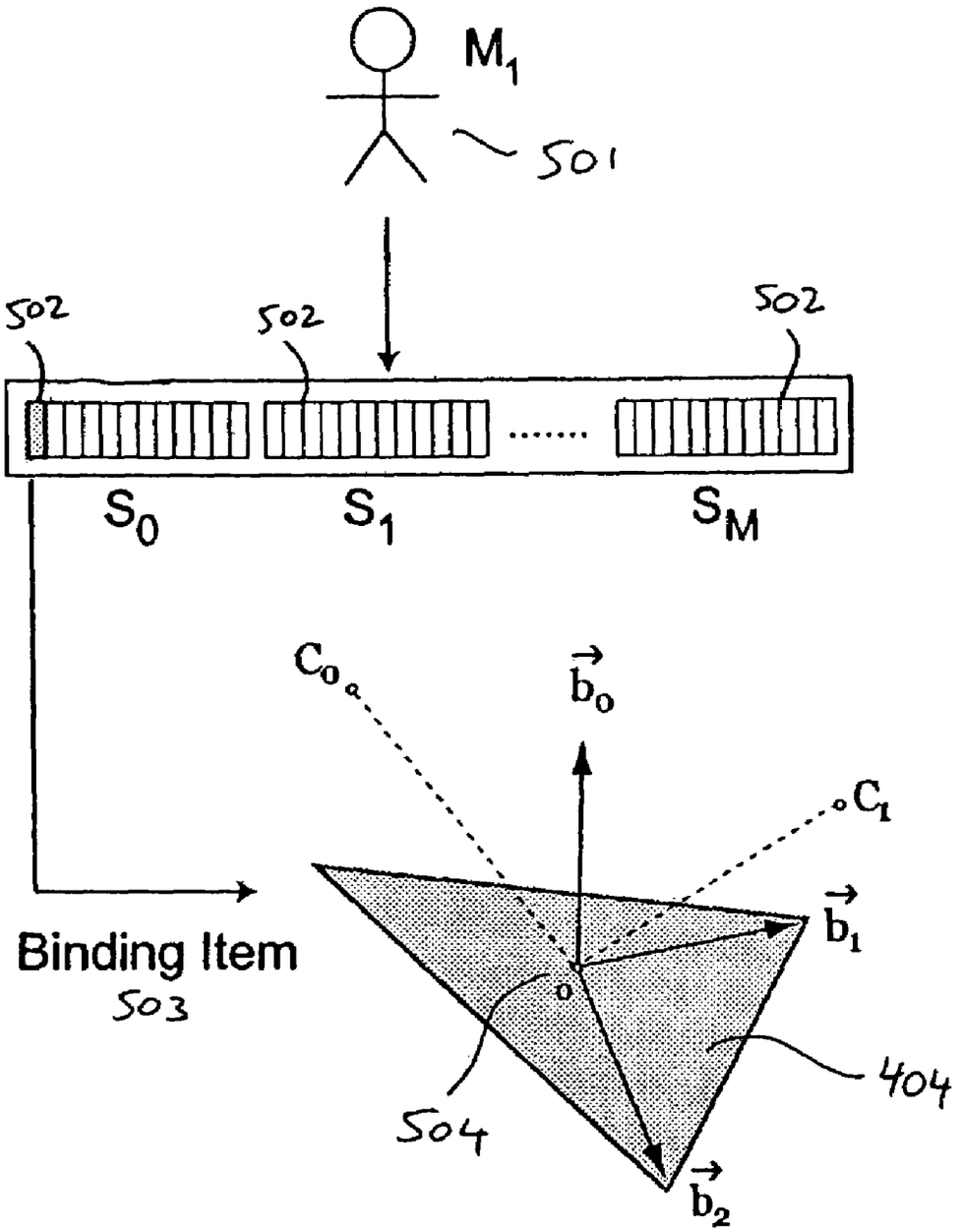

M1
501
502
502
502
S0
S1
SM
C0
b0
C1
b1
o
Binding Item
503
504
404
b2

FIG. 6

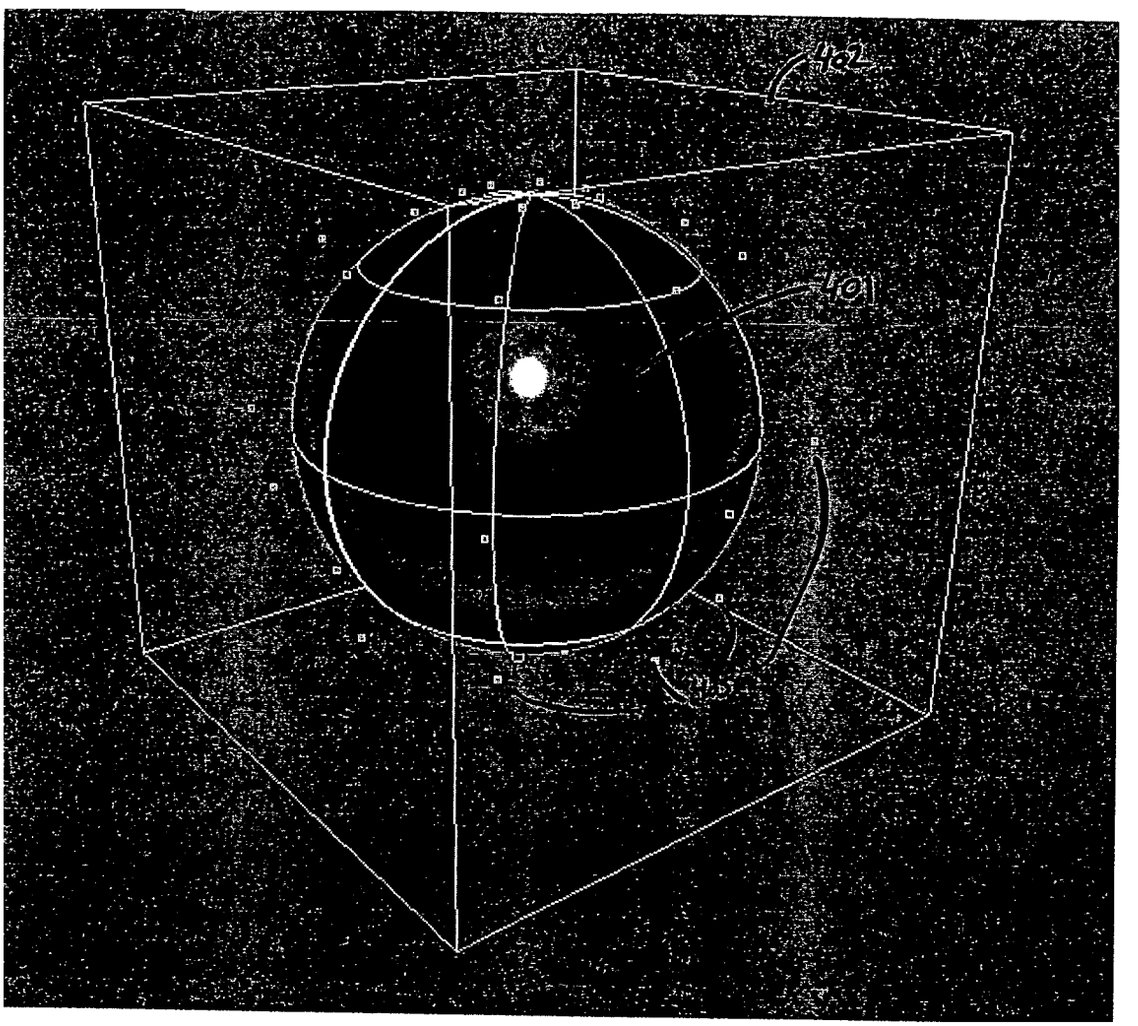


FIG. 7A

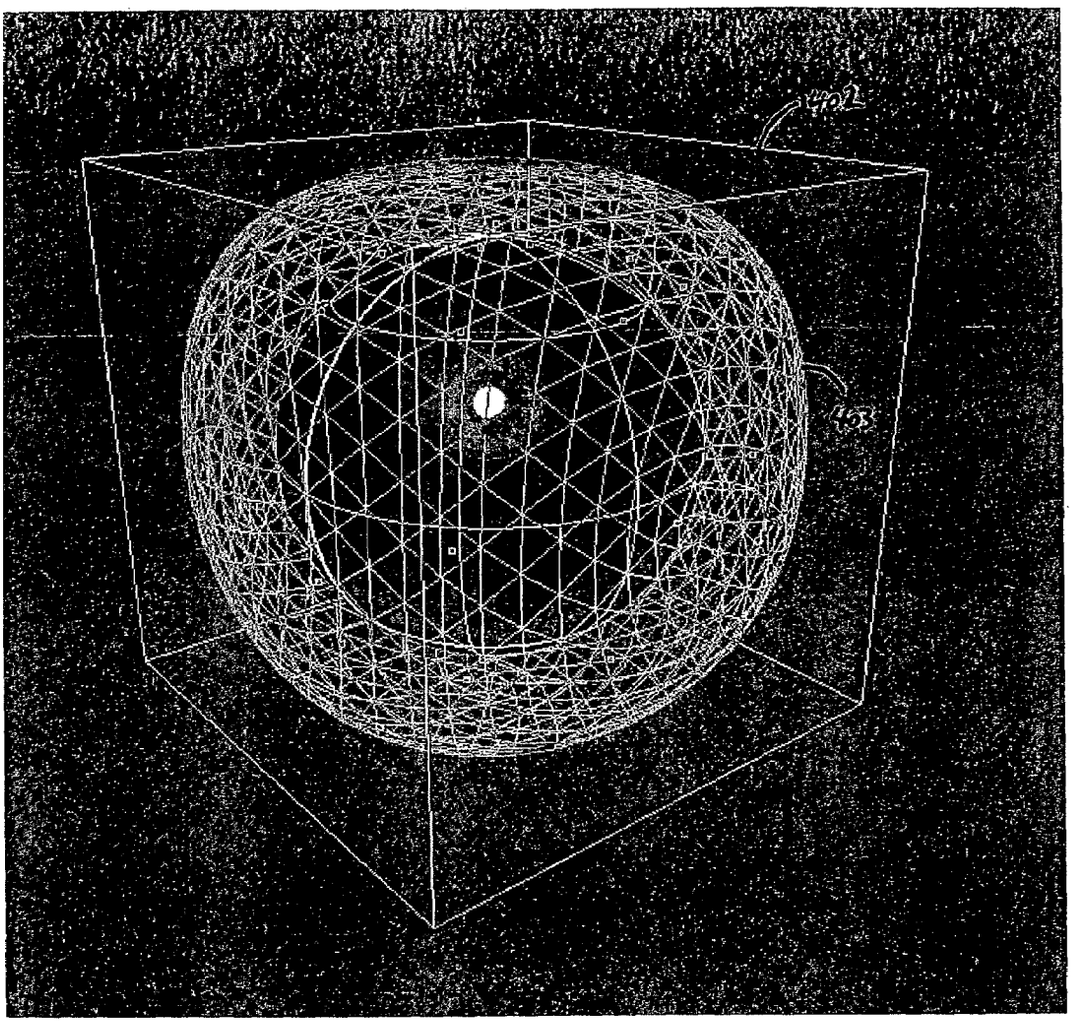


FIG. 7B

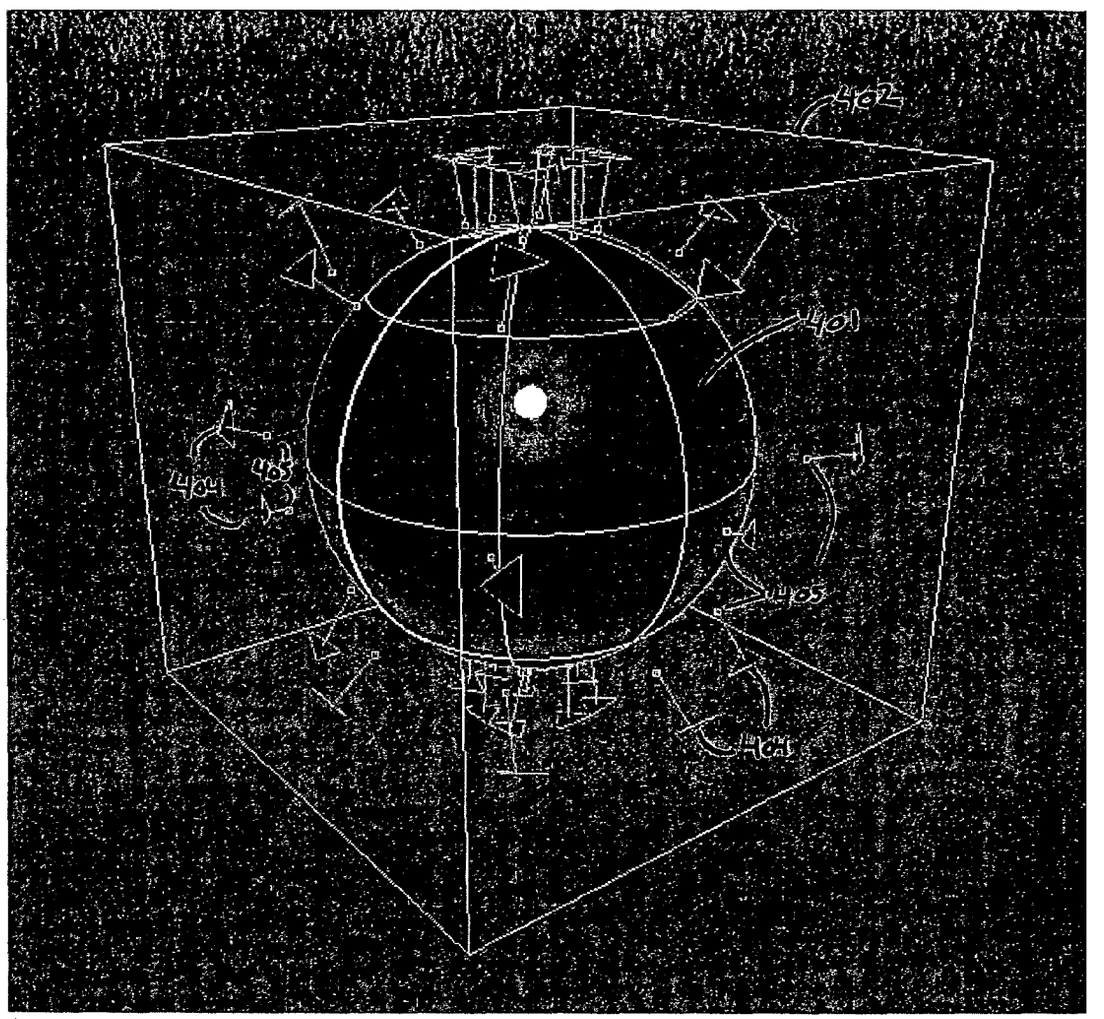


FIG. 7C

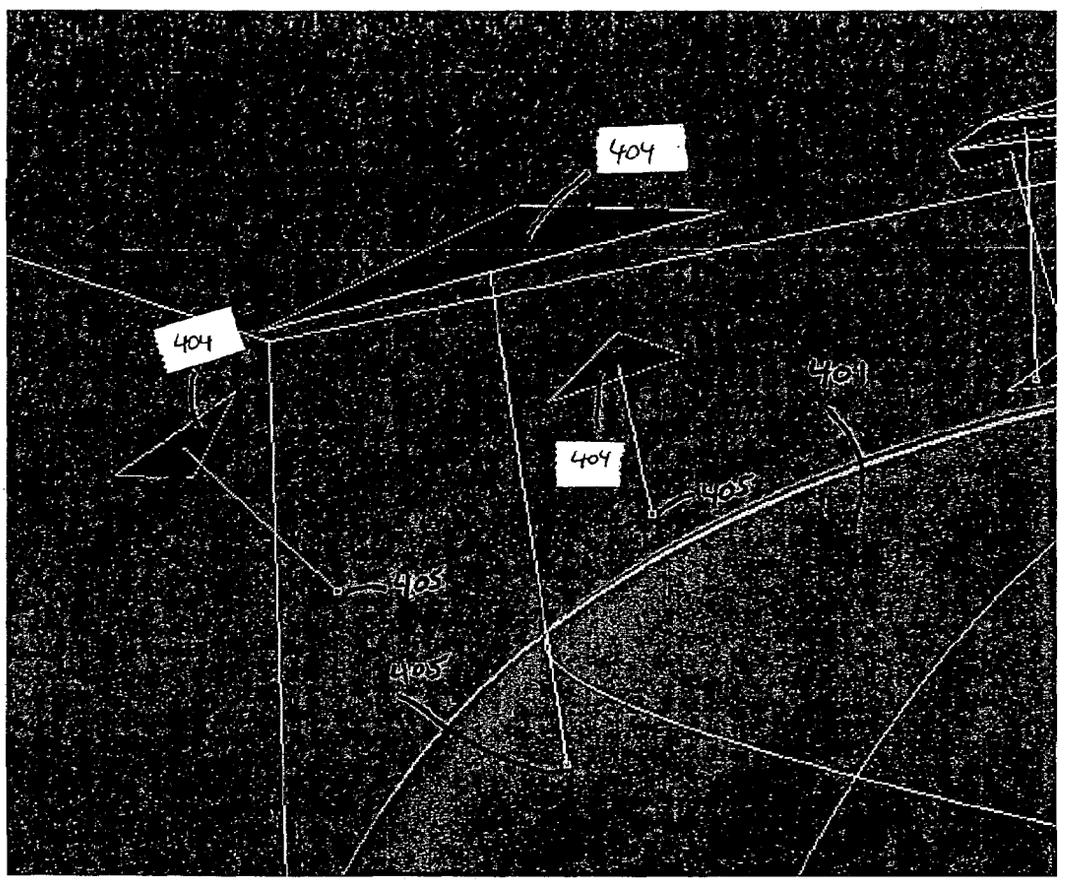


FIG. 7D

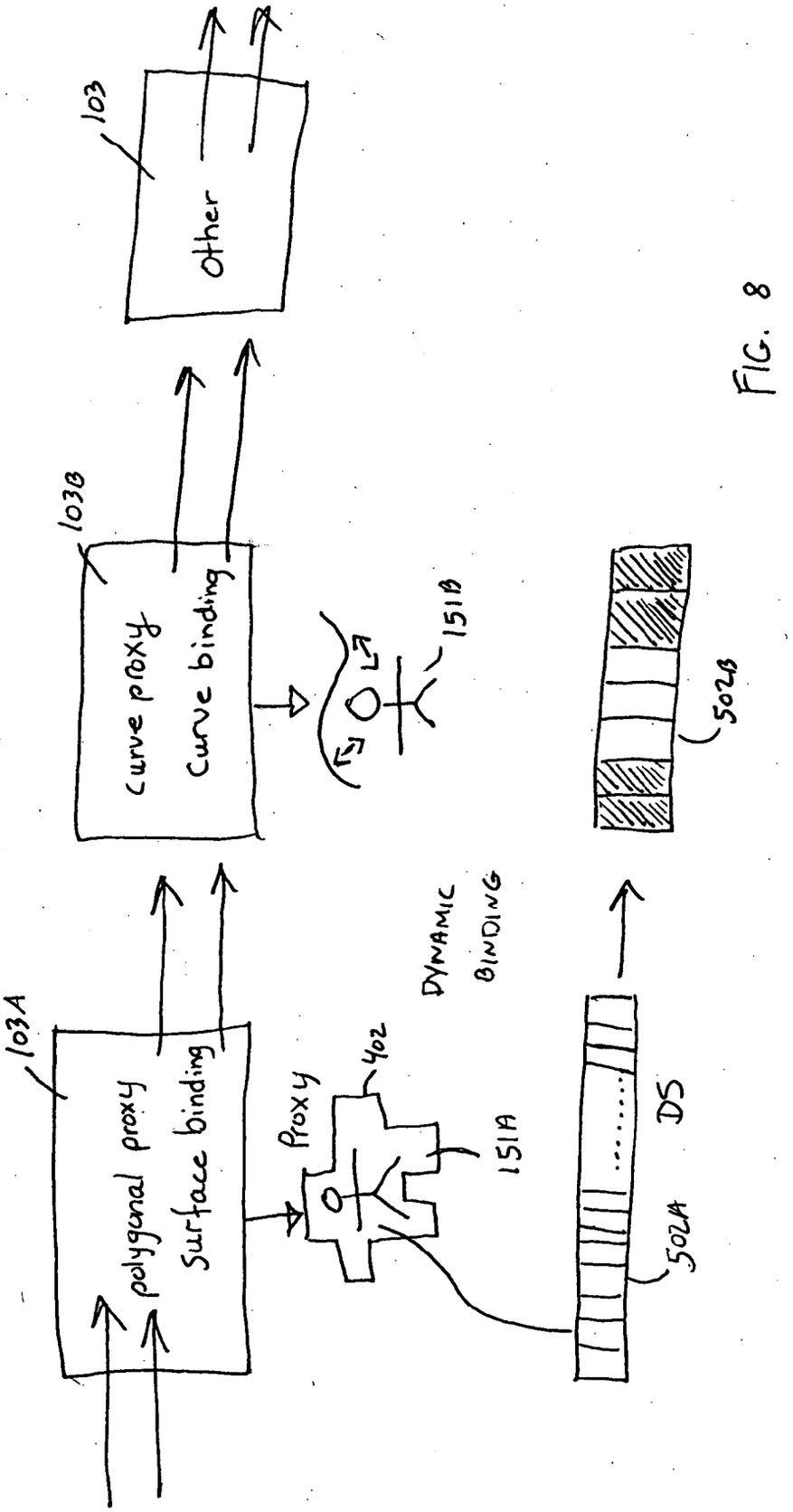

103
Other
103B
Curve proxy
Curve binding
151B
502B
103A
polygonal proxy
Surface binding
Proxy
402
DYNAMIC
BINDING
151A
502A
DS

FIG. 8

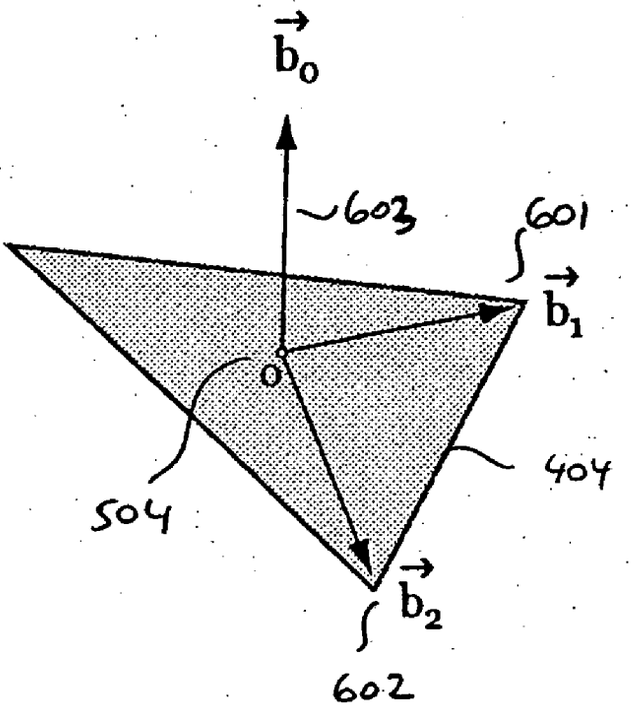
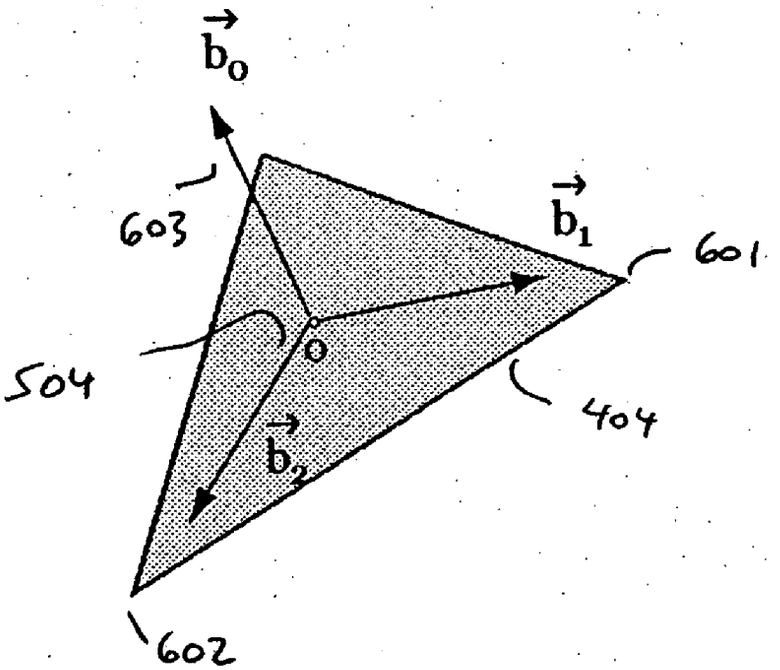

$\vec{b}_0$
603
601
$\vec{b}_1$
o
504
404
$\vec{b}_2$
602

FIG. 9A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o
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602

FIG. 9B

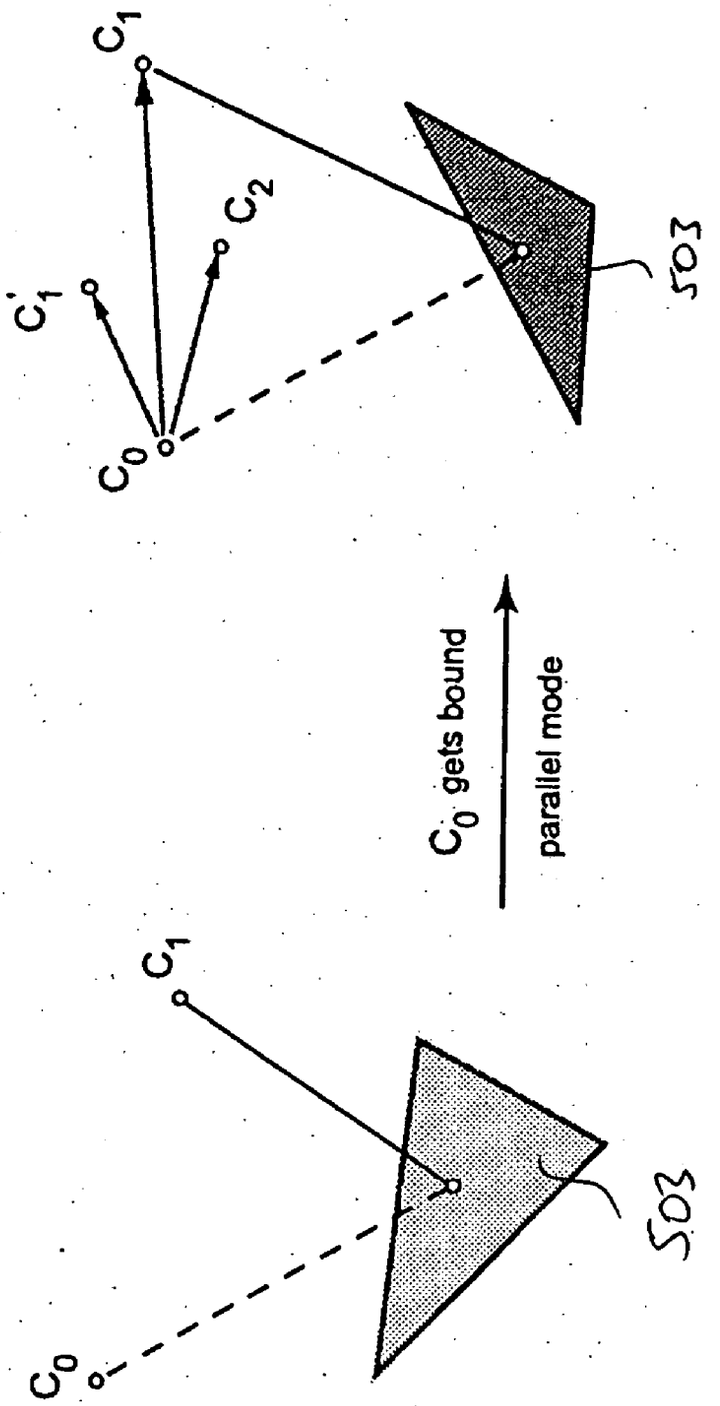
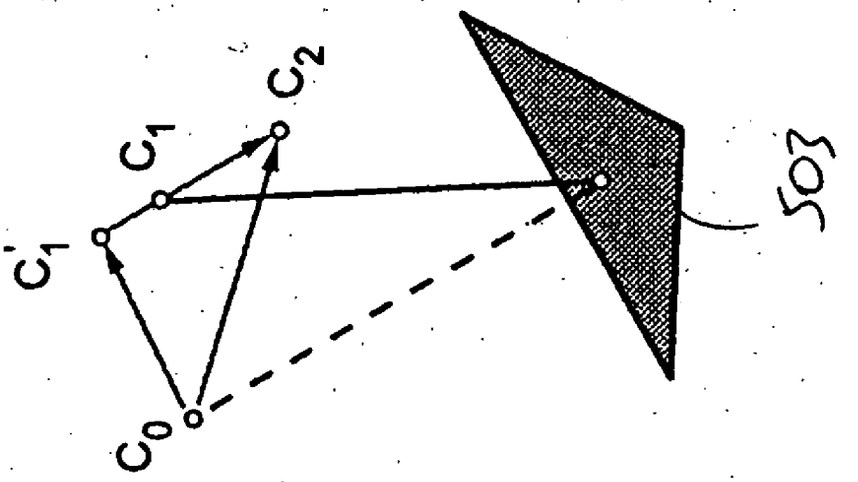
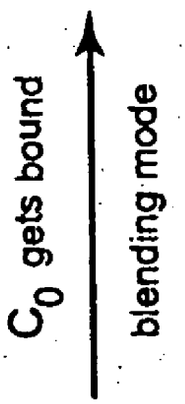


FIG 10A





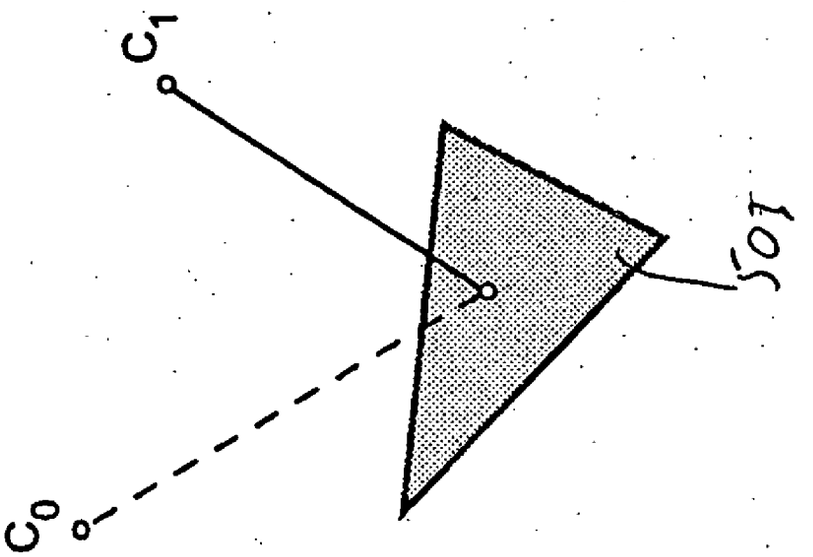


FIG. 10B

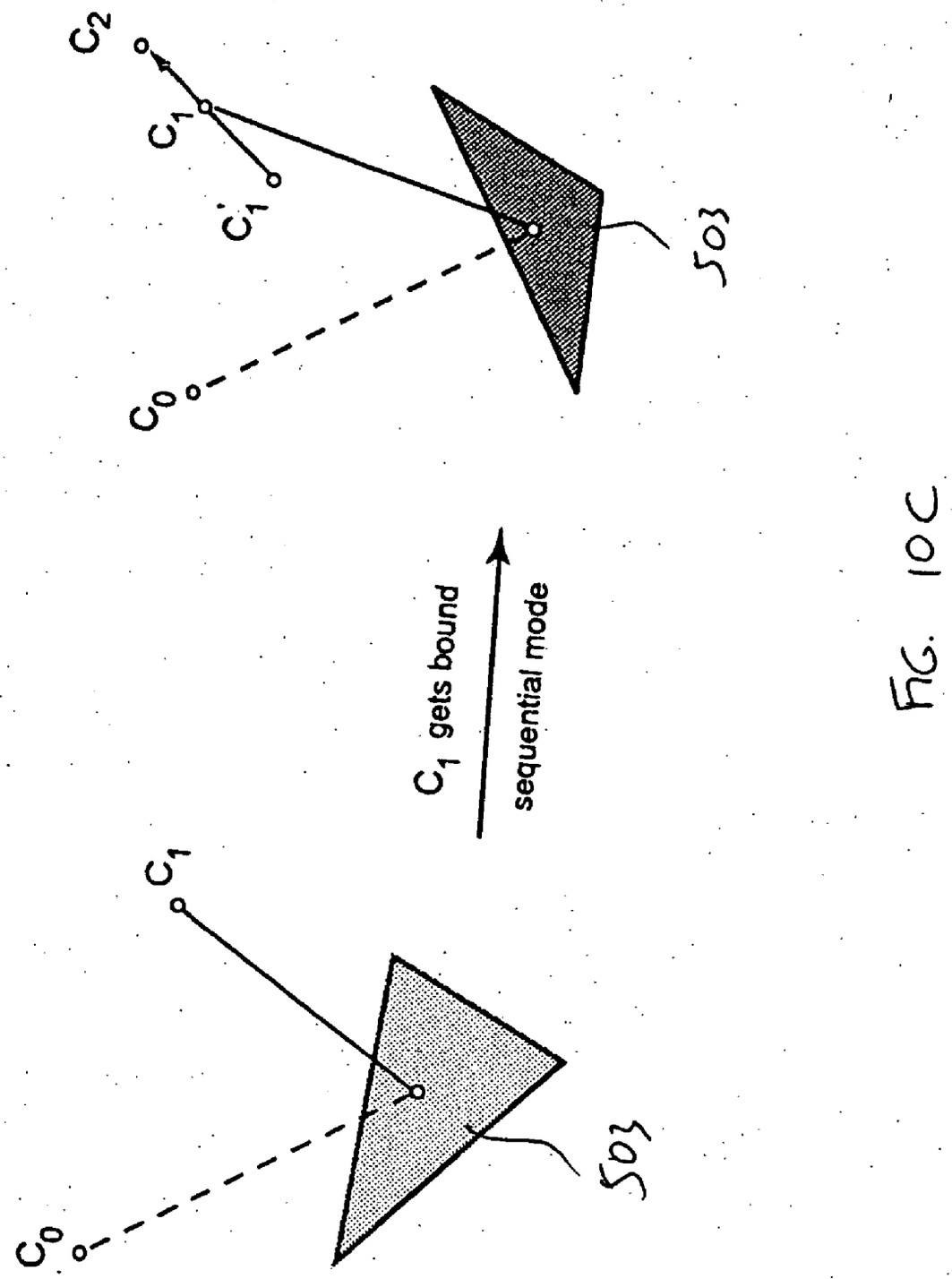


FIG. 10C

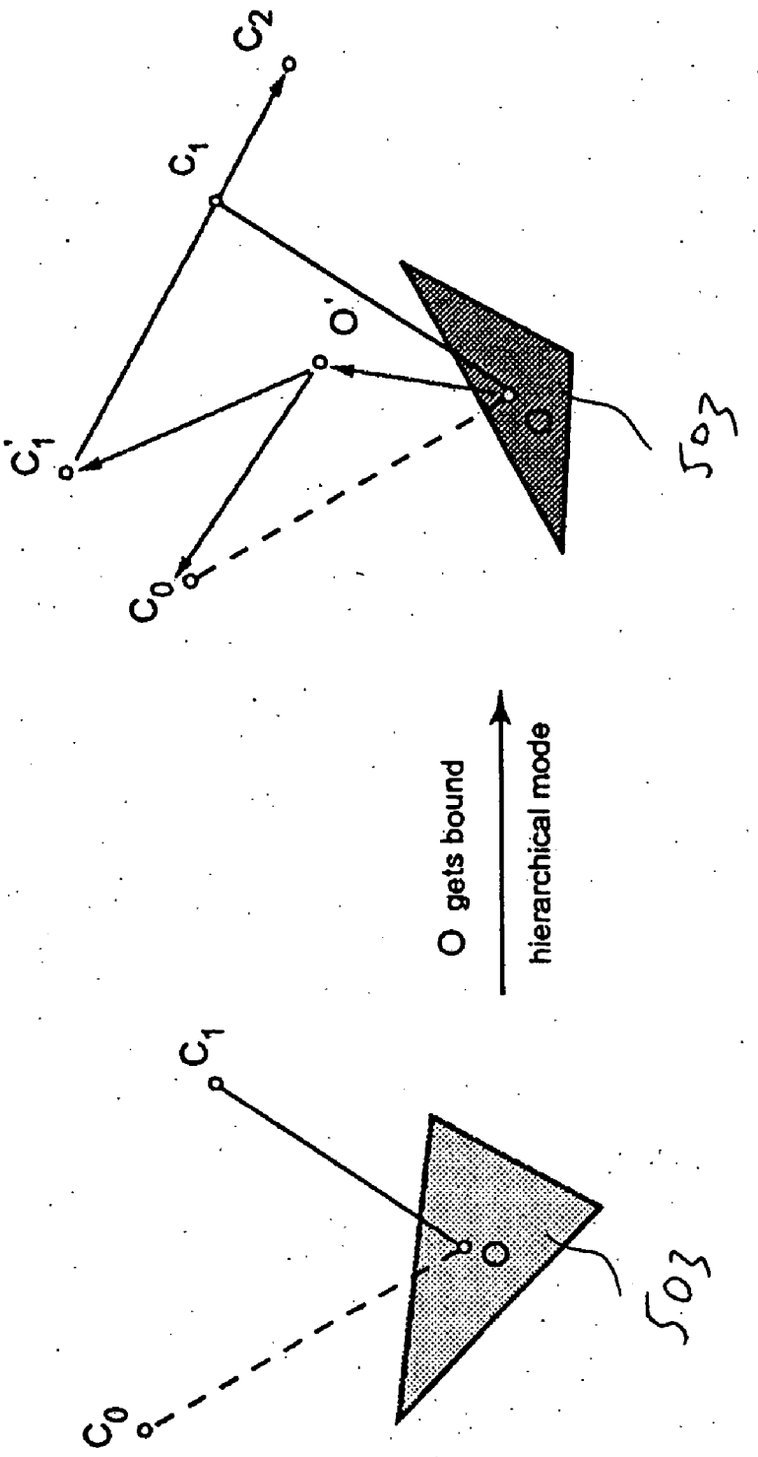
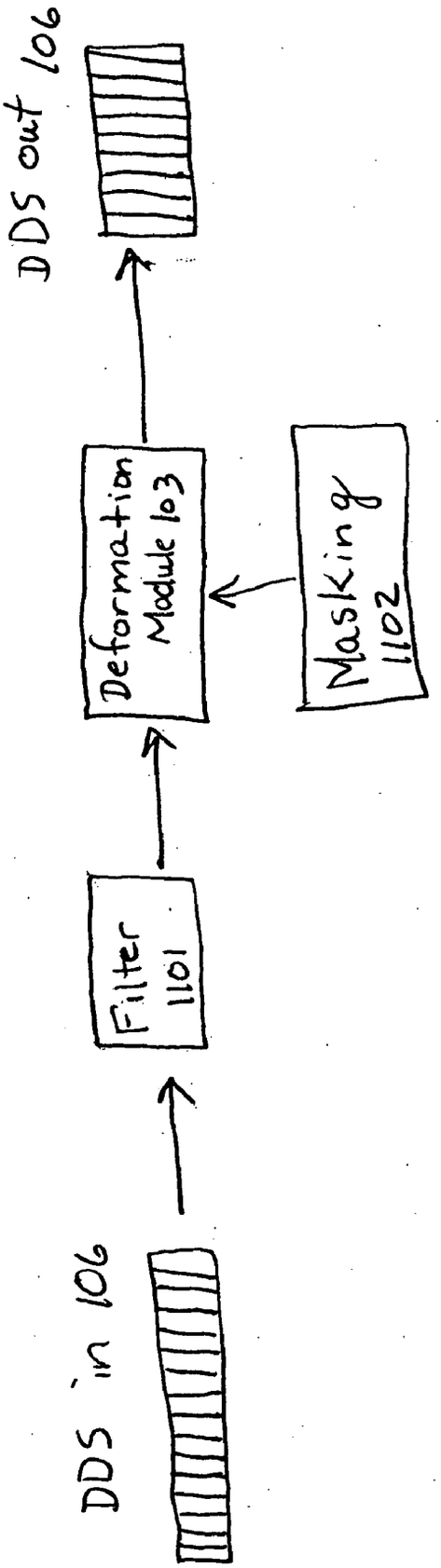


FIG. 10D.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Deformation Module 103
Masking 1102
Filter 1101
DDS in 106

FIG. 11

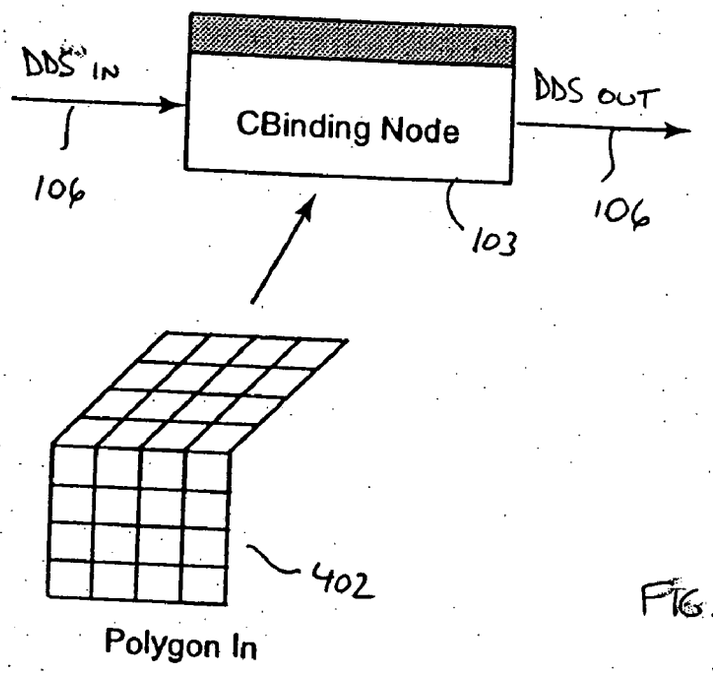

FIG. 12A

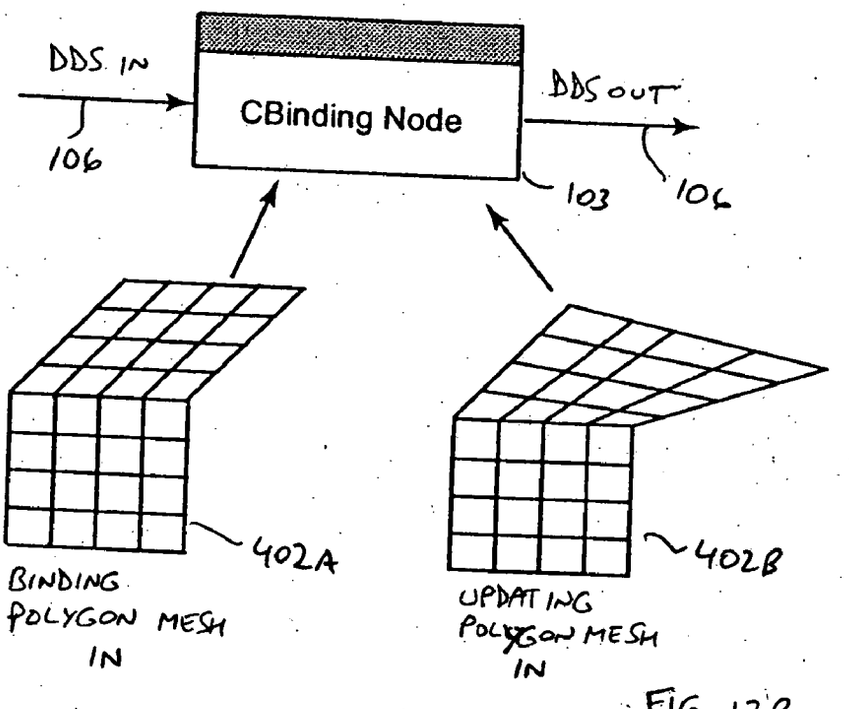

FIG. 12B

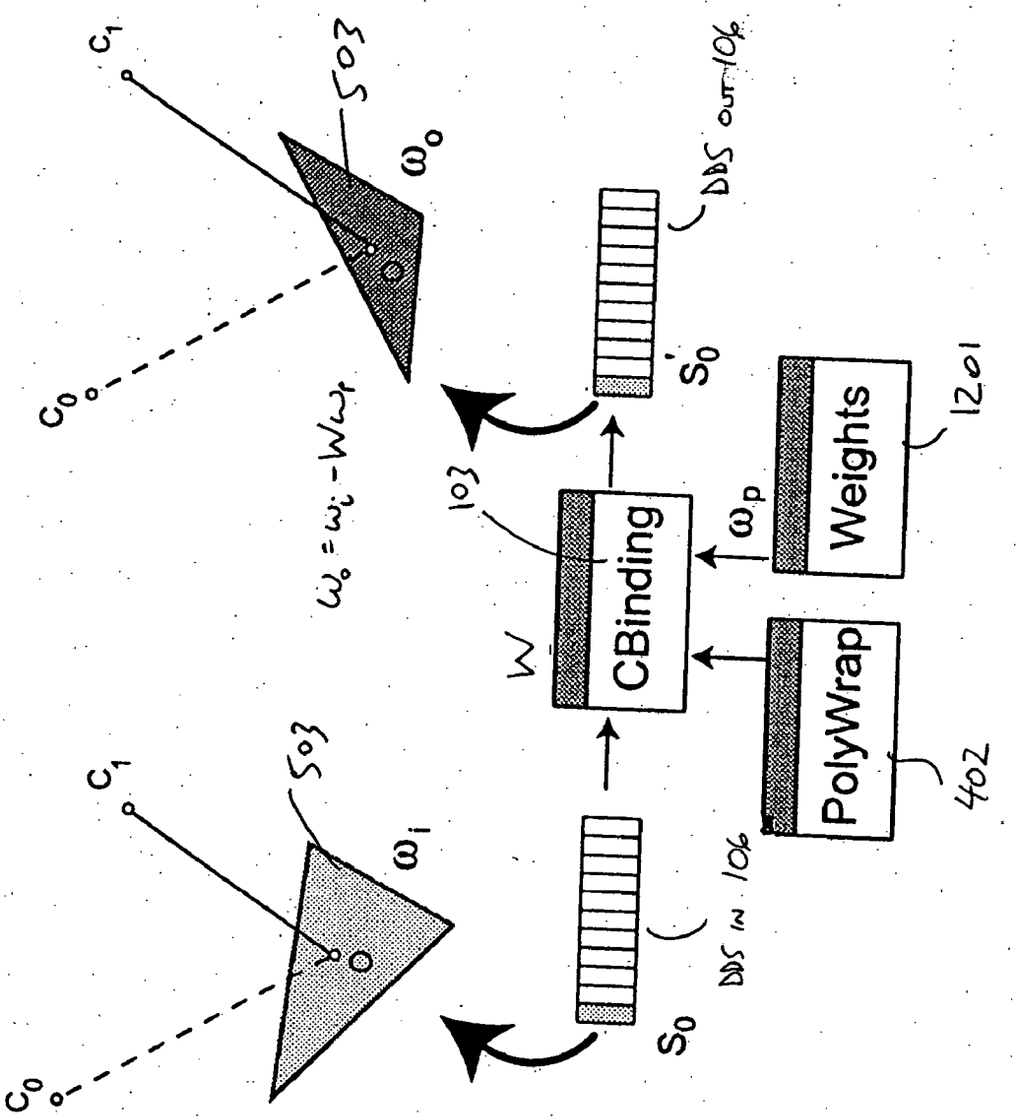
c_1
503
ω_o
c_0
$\omega_o = \omega_i - W\omega_p$
DBS out 106
S_0'
103
W
CBinding
ω_p
Weights
1201
PolyWrap
402
ω_i
S_0
DBS in 106

FIG. 13

CHARACTER DEFORMATION PIPELINE FOR COMPUTER-GENERATED ANIMATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to the following commonly owned and co-pending U.S. patent application, the disclosure of which is incorporated herein by reference:

U.S. patent application Ser. No. 10/769,154, entitled "Wrap Deformation Using Subdivision Surfaces," filed Jan. 29, 2004.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to computer-generated graphics and animation, and more particularly to techniques for defining and establishing a deformation pipeline for use in computer animation.

2. Description of the Background Art

A central task in computer-generated (CG) animation is the construction of efficient and flexible deformations of three-dimensional (3D) characters in a way that satisfy the artistic demands of animators. When such deformations are provided with sufficient flexibility, animators are able to bring a higher degree of expressiveness to their 3D characters.

As the CG animation industry matures, new efforts are being made to make CG animation as expressive and free form as traditional hand-drawn animation. Since its inception, CG animation has often relied on the principles of robotics in order to describe motions, constraints and 3D boundary detection. This is philosophically very different to the silhouette-driven style of traditional two-dimensional (2D) hand-drawn animation. Bridging the gap between the lively and expressive 2D animation and more mechanical and constrained 3D techniques is an important goal of many CG animation studios.

Traditional hand-drawn animated characters come from the mind and hands of a traditional artist. By contrast, a CG character is generated from a model, or file, in a computer system that describes a collection of 3D surfaces in some mathematical form. CG artists use computer systems and animation software to create, edit and manipulate these 3D surfaces. CG animations are then created by animation software that deforms the original poses of the CG characters into an animated sequence over a number of frames. Digital artists control the poses of the CG characters at a number of frames using character rigs, which are conventionally provided as a collection of scripts, software subsystems and animation curves that specify the motions, timings and positions of the 3D character as a function of time.

CG characters, also known as models, are typically a collection of surfaces represented mathematically either as parametric surfaces (Bezier Patches, NURBS, Catmull-Clark, B-splines, etc.) or as high-resolution polygonal meshes. These methods for representing CG surfaces are well known in the industry. Parametric surfaces are made out of a number of control vertices (CVs), which together with an appropriate basis set describe the shape of a continuous and smooth 3D surface in space. Polygonal meshes, on the other hand, are generally a collection of points in space connected to each other to form a polyhedron; in general, polygonal meshes are more primitive than parametric surfaces. In the following description, the term "vertices" is used to refer generally to either CVs (e.g., of a parametric surface) or points.

Each of these representations has its advantages and disadvantages. In the CG film industry parametric surfaces are often preferred over polygonal meshes because the continuous properties of parametric surfaces tend to produce higher-quality images when rendered at high resolution. Polygonal meshes, on the other hand, are often preferred in the CG game industry because of their lightweight data representation and evaluation.

Polygonal meshes have free form topology; that is, the vertices in the mesh can connect with each other arbitrarily. On the other hand, traditional parametric surfaces such as NURBS (Non-Uniform Rational B-Splines) have a fixed topology in which vertices are interconnected in a quadrilateral array. Subdivision surfaces, like Catmull-Clark surfaces, offer a compromise between these two approaches, having the free form topology of polygonal meshes while still maintaining a local parametric representation and smoothness.

CG animation models are typically built using standard commercial software that allows digital artists to sculpt 3D objects in the computer. Conventional commercial packages for CG animation include products such as: Maya®, available from Alias Systems of Toronto, Canada; Studio Max, available from Discreet of Montreal, Canada; SoftImage, available from Avid Technology, Inc. of Tewksbury, Mass.; and LightWave 3D®, available from NewTek, Inc. of San Antonio, Tex.

Alternatively, some animators use traditional clay models as their starting points for CG characters. The clay is then scanned in 3D on the computer, imported into one of the commercial packages mentioned above and edited for corrections.

Construction of a character rig for animating models using conventional techniques tends to be labor-intensive, requiring a great deal of artistic experience in order to make the best use of the deformers available in the commercial package to drive the model in the desired manner. The design and development of the character rig are key factors in the overall quality of the resultant animation product, since the rig effectively determines the range of possible motions and deformations available to the animator.

A rig typically includes a skeleton system, including a set of CG joints that control the bending, torsion and deformation of the underlying structure of the character. The joints of the skeletons are controlled through animation curves created by the CG animator. A mathematical description is established for connections between skeleton joint locations and positions of vertices of surfaces in the CG model. For example, in one pose the skeleton of a humanoid rests in standing position and in another pose the skeleton sits in a chair. It is preferable to provide a mathematical description that drives the CG models to deform from the standing to sitting position smoothly as the skeleton switches positions. Most commercial packages provide a binding mechanism that links the positions of skeleton joints to the locations of vertices in the CG model. Each vertex moves according to a multi-linear combination of motions of nearby joints.

Weights can be provided to guide the multi-linear combination so that the motion of the surface is smooth. Conventionally, setting up the weights for the joints in the skeleton on a given character is a manual process that can be very labor-intensive. Moreover, the weighting of vertices for the skeleton binding is highly sensitive to changes of the structure of the surfaces on the CG character. Changes such

as adding or removing a vertex on the surface, changing its parametric structure, or the like, generally void the work done on the binding weighting, forcing the individual to begin again.

In general, any significant editing changes on the CG model cause the weighting work done on the skeleton binding of a character to be voided. In addition, a character rig of a CG model cannot be easily transferred to another character that might be morphologically similar but different in terms of CG model (for example, having a different number of surfaces, number of vertices, alignment, or the like). Accordingly, character rigs generated by conventional software packages are not generic, meaning that they cannot be easily transferred from one CG model to another.

In addition, in film production the design of a character is often changed after a rig has been generated. Conventionally, most of the rigging work must then be discarded and a new rig restarted in order to adapt to these changes. What is needed, therefore, is a system and method for representing a character rig that is more independent from the specifics of any particular model. What is further needed is a system and method that provides CG animators with the ability to more effectively adapt to changes so as to provide significant cost savings. What is needed, therefore, is a system and method that allows technical directors to create generic rigs for animating whole families of characters, thus having applicability in crowd animations and simulations.

An additional challenge that exists in animation today is to bridge the gap between traditional (2D) and CG (3D) animation. Conventional systems are ill suited for such bridging, because of differences in character rigging style and also because of limitations in the layering of deformations (the way in which multiple deformers apply their effect onto the same surface of a CG model) offered by current commercially available and proprietary systems.

As discussed above, conventionally a skeleton binds to a CG model via a set of weighted multi-linear interpolations between joint positions and vertex initial locations. This binding normally takes care of the principal deformations of a CG model, such as for example the bending of an arm. However, typical CG characters for film are more complex, having numerous secondary motions taken care of by other deformers in the rig that superimpose their effects on top of the skeleton binding. For example, a deformer may be provided that bulges the bicep of the arm as it bends. Conventionally, such deformations are superimposed using any of a number of layering schemes such as sequential, parallel and/or blending. In a sequential layering scheme, the deformations are applied in the space of the post-deformed surface. In a parallel layering scheme, the deformations are applied simultaneously on the same pre-deformed space. In a blending layering scheme, a linear combination of the deformations is applied to the original pre-deformed surface.

Conventional implementations of these sequential, blending and parallel layering schemes are, in general, very diverse and difficult to unify into a single scheme. What is needed, therefore, is a character rigging system and method that provides a serialized representation of sequential, blending and parallel layering schemes. What is further needed is a system and method that is amenable to being divided and ported into a hardware API system.

Another significant limitation of conventional rig systems is an inability to provide a simple and model-independent way to create a hierarchical layering of deformations. A hierarchical layering is to one in which a later deformation is applied in the local space of the surface resulting from an earlier deformation. Hierarchical layering differs from sequential layering as follows. In a sequential layering scheme, the second deformation is applied in the global space of the surface deformed by the first deformation. For example the first deformer may bend a plane, while the second deformer grows a cone in a certain region of the bending plane. The cone always points in the same direction, no matter how the plane is bent. In a hierarchical deformation, the second deformation's effect are applied in the local space of each vertices deformed by the first deformation. Following the same example, then, in a hierarchical scheme a cone grown perpendicular to the surface of the plane would remain perpendicular to the plane regardless of how the first deformer changes the bending of the plane.

Hierarchical B-Splines are described, for example, in D. R. Forsey, R. H. Bartels AMC Transactions on Graphics Vol. 14 134-161 (1995). HB-Splines are parametric surfaces similar to B-Splines, except that the parametric domain in which they are defined can be redefined hierarchically with more detail where needed. By contrast, in a standard B-Spline, in order to increase the detail of the surface in a small region, one is forced to increase the resolution uniformly everywhere.

Hierarchical surfaces allow layering of deformations not only in the local space of the vertices, but also by scales. For example, a first deformer can create an overall squeeze and stretch deformation while a second deformation affects a small feature on a localized region of the surface, such as opening an eye. This hierarchical methodology for layering deformations and breaking up their scales is useful in making CG rigs more traditional-looking when animated.

For several reasons, existing hierarchical methodologies fall short of the actual CG production needs. Firstly, because the hierarchy is built in to the surface representation, hierarchical deformations do not generally work with surfaces such as polygonal meshes, NURBS, or Catmull-Clark surfaces. Secondly, hierarchical surfaces such as HB-Splines often fail to adapt satisfactorily to production changes. The parameter space is represented by a tree-like data structure, so that changes on the broad parametrization of the surface tend to invalidate the branches of the tree. For example, if a hierarchical surface is built as a horn extruded out of a sphere, then changing the underlying sphere form to open a mouth voids the work done on the horn. HB-Splines are also heavy structures that take a great deal of time to update.

What is needed, then, is a system and method that provides the advantages of hierarchically layered deformations without relying on a specially defined type of surface.

What is further needed is a rigging system and method capable of advanced layering methodologies, including hierarchical techniques, that can work with simple forms of CG models.

What is further needed is a technique for generating and manipulating generic, portable character rigs that avoid the limitations and disadvantages of prior art schemes.

What is further needed is a technique that allows digital artists to decouple the rigs used for the animation of computer-generated characters from the specifics of the models themselves

What is further needed is a technique that improves flexibility so as to provide the potential for more expressive animated characters

What is further needed is a technique that serializes complex deformations in order to improve performance and to facilitate hardware implementation.

SUMMARY OF THE INVENTION

The present invention provides a more flexible system for character deformation that allows digital artists to create more fluid deformations for their 3D characters, thus approximating the techniques available to 2D artists. According to the techniques of the present invention, a character deformation pipeline is established for CG animation, so as to address the above-described needs and to avoid the limitations of prior art schemes.

According to one embodiment, the invention is implemented using a data stream abstraction of one or more CG models. A serialized stack-like pipeline of modules is established; each module takes the data stream, deforms it, and passes it to the next module. This serialized architecture for the pipeline facilitates complex layering schemes that conventionally would require complex tree dependencies. The serialized architecture of the present invention unifies known layering schemes into a single implementation.

According to one embodiment, the present invention accepts CG models based on simple and common geometrical objects such as polygonal meshes, NURBS, B-Splines, subdivision surfaces, and the like, while supporting advanced layering deformation schemes for such objects.

The present invention thus provides a flexible deformation system that is resilient and able to adapt to the needs of actual CG production environments. The invention allows for changes in the CG model even after a character rig has been created, without invalidating the rigging work. Moreover the rig is generic in the sense that it can be easily ported between morphologically similar CG models.

Furthermore, the serialized architecture of the deformation pipeline of the present invention is capable of being implemented in hardware and/or via a stack based pipeline such as OpenGL.

According to one embodiment, CG models are abstracted into a data stream, referred to herein as a Deformation Data Stream (DDS). The DDS is capable of carrying information about the geometry of the surfaces of the CG model, as well as important items regarding the deformation environment of each of the vertices in the surface. Information on the deformation environment enables the building of layers of deformations in multiple spaces: pre-deformed, post-deformed, and/or local vertex frames of coordinates. The vertex environment information thus provides improved flexibility, since a user can generate deformations according to many different layering schemes without having to access data at earlier deformation stages.

In one embodiment, the DDS contains only geometrical information, that is, information regarding vertex locations and their deformation environments, and omits information indicating whether the vertices belong to a NURBS, a mesh or a subdivision surface. Thus, the deformation pipeline need not know about the "topology", the actual surface parameterization, in order to perform a deformation on the CG model. In some cases, however, where it is beneficial to provide deformers with a parametric representation of the surface containing a vertex, a second data abstraction containing topology descriptions of the surfaces in the CG model can also be used in the pipeline.

The DDS travels along a pipeline composed of a sequence of modules, each of which is assigned the task of applying a specific deformation on the data stream. As CG models travel through the pipeline's modules, the modules modify the models' vertices and deformation environments. Some of the modules contain CG skeletons, skinning bindings, secondary animation deformations, and the like.

In one embodiment, the modules of the present invention use dynamic binding algorithms, such as those presented in related U.S. patent application Ser. No. 10/769,154, entitled "Wrap Deformation Using Subdivision Surfaces". For example, in one embodiment a skeleton binds first to an intermediate object (referred to as a proxy model). The proxy model transfers deformations from the joints to the CG model's surfaces smoothly. Surfaces are bound to the proxy model dynamically, so that as the DDS enters a skin binding module it first finds an appropriate binding location on the proxy model; transformations are then applied according to the skeleton's joint movements. Should the surfaces in the DDS change on the fly, either because a similar character is being sent through the pipeline or because a change to the model has been made, the dynamic binding finds a new binding location on the proxy model. The relationship and setup of the CG skeleton to the proxy model are maintained, thus saving work by technical directors.

In one embodiment, each module in the pipeline has two inputs and two outputs, as follows:

a DDS input, including the stream of CG models prior to deformation;

a topology input, available for the module to use if needed;

a DDS output, including the stream of CG models after deformation, and

a topology output, to be passed to the next module to use if needed.

Additional inputs and outputs may also be provided.

As will be apparent to one skilled in the art, the techniques of the present invention can be applied to skinning modules as well as to other types of deformers, such as for example wire deformers, polywraps, clusters, or the like.

According to the techniques of the present invention, deformation modules thus dynamically bind to the geometry in the DDS. Deformers apply their deformations according to any of four types of layering, or binding modes: sequential, blending, parallel or hierarchical. Depending on the selected binding modes, the module binds and deforms the vertex information in the DDS differently, as is described in more detail below.

In a sequential binding mode, each deformer layers its deformation on top of the previously deformed surface. These deformations are applied using a global system of coordinates.

In a blending binding mode, each deformer binds to the original, pre-deformation geometry. The DDS contains the original vertex position in its description. Each deformer, after applying its deformation, uses a scalar parameter to blend (interpolate) its effect with the deformed geometry in the DDS input, thus adding its effect to the prior sequence of deformations. The blending binding mode allows a user to tune in or out the effect of a particular deformation within a chain of deformers.

In a parallel binding mode, each deformer binds to the original, pre-deformation geometry, and adds its own contribution to the DDS by vector addition (as opposed to linear interpolation).

In a hierarchical binding mode, rather than binding directly to vertices, each deformer binds to local centers of coordinates for those vertices (these are referred to herein as binding frames). Each vertex in the DDS has an associated local frame of coordinates. This frame of coordinates is part of the deformation environment for the vertex that can be carried by the DDS. By facilitating deformations about the local frames of coordinates, the present invention opens

possibilities for increasingly sophisticated deformations that pivot vertices about their anchor points, particularly since each vertex in the DDS can have a different local frame of coordinates.

The features and advantages described in this summary and the following detailed description are not all-inclusive. Many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification, and claims hereof.

Moreover, it should be noted that the language used in this disclosure has been principally selected for readability and instructional purposes, and may not have been selected to delineate or circumscribe the inventive subject matter, resort to the claims being necessary to determine such inventive subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram depicting the flow of a CG model's geometry through a deformation pipeline according to one embodiment of the present invention.

FIG. **2** is a block diagram depicting a pipeline for animating a series of humanoid characters, according to one embodiment of the present invention.

FIG. **3** is a block diagram depicting a layout of modules in a deformation pipeline, according to one embodiment of the present invention.

FIG. **4** is a block diagram depicting an alternative layout of modules in a deformation pipeline including branching and merging of deformations, according to one embodiment of the present invention.

FIG. **5** is a block diagram depicting a deformation module, according to one embodiment.

FIG. **6** depicts a methodology for representing a character as an element of a deformation data stream, according to one embodiment.

FIG. **7**A through **7**D depict an example of a NURBS sphere bound to a cube polygonal mesh, according to one embodiment.

FIG. **8** depicts a sample portion of a deformation pipeline including two proxy/surface binding modules.

FIGS. **9**A and **9**B depict an example of triangular binding, shown before and after a deformation.

FIG. **10**A depicts an example of a data stream item in parallel binding mode, according to one embodiment of the present invention.

FIG. **10**B depicts an example of a data stream item in blending binding mode, according to one embodiment of the present invention.

FIG. **10**C depicts an example of a data stream item in sequential binding mode, according to one embodiment of the present invention.

FIG. **10**D depicts an example of a data stream item in hierarchical binding mode, according to one embodiment of the present invention

FIG. **11** is a block diagram depicting an example of a DDS item being passed through a filter and a deformation module that is modified by an accessory masking module.

FIG. **12**A is a block diagram depicting an embodiment of a Cbinding module in which a single polygonal proxy mesh is used.

FIG. **12**B is a block diagram depicting an embodiment of a Cbinding module in which two topologically identical polygonal meshes are used, one for binding and one for updating the binding items.

FIG. **13** is a block diagram depicting weight application and determination, according to one embodiment.

The Figures depict a preferred embodiment of the present invention for purposes of illustration only. One skilled in the art will readily recognize from the following discussion that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles of the invention described herein

DETAILED DESCRIPTION

The term "surface" as used herein refers to surface representations such as NURBS, polygons, curves, subdivisions, and the like, and can also include streams of particles with positions, velocities and accelerations. In general, any point data carrying user-defined scalars and/or fields can be considered "geometry" within the context of the present disclosure, and can be deformed by the techniques of the present invention.

The techniques described herein are independent of the particular topology, or point connectivity information, of the geometry or object being deformed. For illustrative purposes, the following description makes references to animated characters as the object being deformed; however, one skilled in the art will recognize that the techniques described herein can be applied to other types of geometries and objects.

Referring now to FIG. **1**, there is shown a block diagram depicting the flow of a CG model's **151** geometry through a deformation pipeline **100** according to one embodiment of the present invention. CG model **151** includes a number of three-dimensional (3D) surfaces **152**. As model **151** passes through pipeline **100**, it gets transformed into an animated model **151**A representing a character. Deformation pipeline **100** takes as input surfaces **152** of CG model **151** as well as corresponding animation curves **153**. Each animation curve **153** describes, as a function of time (film frame), the position of various controls in the CG character rig. Deformers (not shown in FIG. **1**) within deformation pipeline **100** use animation curves **153** to create deformations on surfaces **152**. After all these deformations have been evaluated, deformation pipeline **100** outputs final deformed surfaces **152**A in the animated position. In one embodiment, deformation pipeline **100** is executed for every time frame in order to produce a sequence of animated poses.

Referring now to FIG. **2**, there is shown a block diagram depicting an example of using pipeline **100** to animate a series of humanoid characters, represented by models **151**, according to one embodiment of the present invention. Input to pipeline **100** includes a sequence of characters, represented by models **151**, as well as a sequence of animation curves **153**. The characters are morphologically similar so that the same deformation pipeline **100** can be applied to all characters. Each character corresponds to an animation curve **153**. Pipeline **100** generates output including the original set of characters deformed in animated poses. In one embodiment, for each value of the animation curves, deformation pipeline **100** creates a character animation pose for the given time frame.

Referring now to FIG. **3**, there is shown an example of deformation pipeline **100** according to one embodiment. Pipeline **100** includes a sequence of modules **102**, or deformers, each one accepting a deformation data stream (DDS **106**) and a topology **351**. Each module **102** outputs a DDS **106** and a topology **351**. Each module **102** creates a deformation in the geometry stored in DDS **106**. Also provided are head module **102**, which converts geometry **101** of the character(s) into DDS **106**, and tail module **104**,

which combines deformed DDS **106** and topology **351** back together into a geometry output **105**.

Now referring to FIG. **4**, there is shown an alternative layout of modules **103** in deformation pipeline **100** including branching and merging of deformations, according to one embodiment of the present invention. Multiple sequences of deformation modules **103** take DDS **106** from head module **102** and transform it in parallel and independently until DDS **106** reaches tail module **104** for its final recombination. In the parallel layout of FIG. **4**, the tail module **104** combines the various DDS's **106** linearly with corresponding weights. Thus, the user can specify that more importance should be placed on one sequence of deformations over another.

In one embodiment, not all modules **103** in pipeline **100** create a deformation on DDS **106**. Some modules **103** may only affect vertex information on DDS **106**, or may filter DDS **106** to exclude a geometry from further processing. Such behaviors are described in more detail below.

In one embodiment, each module **102** is an independent entity that can be duplicated and placed anywhere in pipeline **100**. In addition, pipeline **100** can be described as a graph, and can be implemented using well known techniques of graph theory, such as for example a dependency graph as found in Maya®. One skilled in the art will recognize that any other dependency graph system can also be used.

Referring now to FIG. **5**, there is shown a block diagram depicting a deformation module **102**, according to one embodiment. Module **102** functions as an independent unit that takes as input DDS **106**, performs a number of filtering and/or deformation operations, and then passes transformed DDS **106** as output. The deformation performed on the geometry in stream **106** is completely encapsulated in module **103**. Module **103** need not have any access to any data structures other than DDS **106** topology **351**. Similarly, any client object of module **103** need not have access to any data structures other than DDS **106** and topology **351** outputs.

In one embodiment, topology **351** is provided as a data structure containing information describing the topological makeup of the geometry encoded in DDS **106**. In one embodiment, topology **351** is a constant structure that module **103** reads and passes through to the next module **103**. Thus, module **103** does not perform any modifications to topology **351**. When module **103** detects an update in DDS **106** input or topology **351** input, it triggers a new evaluation. The new evaluation in turn leads to computation of a new deformation on DDS **106** input; as a result DDS **106** output is recomputed and sent to the output attribute of module **103**.

In one embodiment, pipeline **100** is implemented in a hardware graphics card specialized in the deformation of CG characters for animation and games. An example of such an implementation makes use of an OpenGL graphics card using a vertex pipeline of stacked operations, wherein the stacked operations are DDS **106** operations. As depicted in the pipeline **100** architecture of FIG. **3**, the deformation change is implemented as a stack of operations happening sequentially on a DDS **106** data structure. In the hardware implementation, the hardware card uses an underlying implementation as described above with respect to FIG. **3**; a software developer creates calls to the modules of the hardware card after providing some basic setup commands. Once hardware implemented modules are initialized, a user of this application can interact with the system as described above with respect to FIG. **2**, by sending one or more CG models **151** and their respective animation characters so that the hardware can execute the deformation modules **103** returned the animated CG model.

Deformation Data Stream (DDS) **106**

According to one embodiment of the invention, the deformed geometry is represented as a deformation data stream (DDS) **106**. The data stream format facilitates a serialized implementation of deformation pipeline **100** that can support layering schemes for deformation. In addition, the serialized implementation is amenable to hardware implementation, in some embodiments.

Referring now to FIG. **6**, there is shown a methodology for representing a character **501** as an element of data stream **106** for deformation pipeline **100**. Character M_1 **501** includes a number of discrete surfaces, denoted as S_0, S_1, . . . , S_M, each corresponding to a block **502** of binding items **503**. Each binding item **503** contains a corresponding vertex position as well as relevant vertex environment information for layering sequential, hierarchical, and other deformations. Surfaces S_i of the character are each encoded as a block **502** of binding items **503**. In one embodiment, each binding item **503** is a data object of the following form, shown for illustrative purposes in the C++ programming language:

```
class BindingItem {
private:
    int tag;
    Point cvOrig;
    Point cvCurrent;
    Point cvProjection;
    FrameItem bindingSite;
    . . . .
};
```

where:

```
class FrameItem {
private:
    int ID;
    Point orig;
    Vector basis[3];
    double weight;
    . . . .
    }
```

In one embodiment, the following objects are provided in the bindingItem structure:

Tag t (BindingItem::tag) identifying the vertex within the surface of the object.

Original vertex location C_0 (BindingItem::cvOrig) containing the original location of the vertex prior to any deformation by pipeline **100**. In one embodiment, the coordinates of this vertex location are written in a local frame of coordinates specified by {O; b**0**, b**1**, b**2**} (BindingItem::bindingSite).

For each vertex in block **502** for surface S_i, a local bindingSite, or frame of coordinates. When DDS **106** is first created by head module **102**, all vertices normally have the same local frame of coordinates (the object space system of coordinates). However, as DDS **106** streams through modules **103**, these local frames of coordinates may get transformed, as described below, and may therefore be different even among vertices on the same surface.

Projection vector α (BindingItem::cvProjection), which generally contains components on the {b**0**, b**1**, b**2**} basis set, describing the post-deformed position of the vertex. Each module **103** predicts a different deforma-

tion; according to the binding mode, the actual vertex coordinates that are being deformed changes, so that it is not necessarily C_0. Each module **103** stores in vector a the components of that deformation in the local frame of coordinates.

C_1 (BindingItem::cvCurrent), containing the final post-deformed position of the vertex. This may be different than the position predicted by a because it includes weighting, blending equations and any other post-deformation algorithm the developer of module **103** may wish to apply.

In one embodiment, the FrameItem vertex binding site data structure includes the following:

ID (FrameItem::ID) represents an integer identifier for the frame of coordinates, or bindingSite. This frame of coordinates can be computed and deformed externally in other structures, as will be described in more detail below.

O (FrameItem::orig) represents the origin for the local frame of coordinates or binding site. All other vectors in binding item **503** are referred to this origin. Hence deformation modules that manipulate the coordinates of the origin can create many different hierarchical effects on the surface vertices without affecting the relative offsets and orientations with respect to O.

The basis set of the local frame b_0, b_1, b_2 (FrameItem::basis[3]) describes the per-vertex system of coordinates where deformations get stored and, in some cases, evaluated. The deformation pipeline of the present invention does not necessarily require an orthogonal system of coordinates. In fact in the Cbinding module, described in related U.S. patent application Ser. No. 10/769,154, entitled "Wrap Deformation Using Subdivision Surfaces", the vectors b_1, b_2 are not necessarily orthogonal in order to describe local shearing deformations of the vertex binding while b_0 is orthogonal to them.

Each local frame has a weight ω (FrameItem::weight) through which modules can take user input as to how much of the full deformation to apply per vertex. When the weight value is 0, no deformation is applied. When the weight value is 1, a full deformation is applied. Values between 0 and 1 result in generation of an interpolation between the fully deformed and undeformed vertex positions.

For purposes of the description provided herein, the term "point" is used to describe an object representing a vertex or origin. However, one skilled in the art will recognize that invention is not restricted to points in a three-dimensional (x, y, z) Euclidean space. Thus, the term "point" as used herein shall be considered to refer to other features such as velocities (for example for a deformation pipeline of particles in an effects engine) or accelerations (for example in a dynamics application such as clothing simulation).

Deformation modules **103** can use binding Items **503** in various ways. A module **103** can focus on the original vertex location (cvOrig) to create a new deformation based on the original undeformed surface, or it can ignore the original vertex location and use the current vertex location (cvCurrent) to continue further deformation of the surface, or it can modify projection α and/or bindingSite to affect the local frame of coordinates. As will be apparent to one skilled in the art, the present invention facilitates a large number of deformation possibilities using a binding item **503** object.

In one embodiment, if the surfaces of CG model **151** are not static, so that their vertices change over time, then the updates on the surface vertices flow through the cvOrig item in the BindingItem data structure of DDS **106**. As a result, deformations set up for the character at a given pose are layered on top of the moving CG model **151** animation. One example of such a situation is a CG model **151** that is actually an externally driven blendshape deformation, wherein pipeline **100** controls secondary movements on model **151**.

Thus, the present invention is well adapted to handle a mix of several types of deformation pipelines **100** that may be directed toward various specific tasks.

Proxy/Surface Binding Model

As can be seen from the above description, the present invention supports sophisticated deformation layering schemes while maintaining a serialized architecture in pipeline **100**.

In one embodiment, the present invention also provides support for keeping deformation modules **103** independent from the specifics of the surfaces of CG model **151**. Deformation pipeline **100** can thereby adapt dynamically to changes in the specifics of CG model **151**. For example, referring again to FIG. **1**, in one embodiment pipeline **100** is independent of the specific topological details of the surfaces in CG model **151** and of the number of surfaces. Pipeline **100**, in one embodiment, is also independent of minor changes in the shape of CG model **151**. Thus, artists using pipeline **100** of the present invention can repeatedly reuse the same pipeline **100** build for a certain type of character, through the life of the character during the course of production. In addition, the same pipeline **100** can be used with multiple characters having the same morphological structure.

Related U.S. patent application Ser. No. 10/769,154, entitled "Wrap Deformation Using Subdivision Surfaces", described a technique for wrap deforming arbitrary types of geometry using subdivision surfaces. Wrap deformation is a technique for defoirning a geometry surface by using an auxiliary surface that "wraps" around the first. Generally the wrap surface is less detailed and resolved, and it is not uncommon to use polygonal meshes as wrap surfaces for this type of deformation.

In one embodiment of the invention, the character rig is decoupled from the actual CG model **151** by using deformation modules **103** that implement a "Proxy/Surface Binding" model. In the case of a skinning deformation, which connects skeleton joints to a CG model **151**, a proxy model (generally a rough polygonal mesh representing the CG model) is included in the deformation module **103**, to which the skeleton joints bind directly. This proxy model then uses an algorithm, as described in the related U.S. patent application, to generate a number of local frames of coordinates where the vertices of the CG model **151** bind.

Referring now to FIG. **7**A through **7**D there is shown an example of a CG model (NURBS sphere **401**) and a proxy model (cube polygonal mesh **402**). As shown in FIG. **7**A, proxy model **402** wraps sphere **401** (vertices **405** of sphere **401** are highlighted for clarity). FIG. **7**B shows corresponding binding surface **403** between the proxy model **402** and sphere **401**. In this example, binding surface **403** is computed as a Loop subdivision surface associated with the proxy polygonal mesh **402**, as described in more detail in the related U.S. patent application. Accordingly, any changes to the vertices of cube **402** transform into smooth and continuous changes on binding surface **403**. As is well known in the art, a Loop subdivision surface is a triangle-based surface of finite resolution which has a parametric representation at least locally.

As depicted in FIG. **7**C, each vertex **405** on sphere **401** associates, or binds, to the closest triangle **404** on binding

surface **403**. Appropriate offsets and frame of coordinates are calculated in these binding operations. Referring now to FIG. **7**D, there is shown a detail view of three such bindings between sphere vertices **405** and triangles **404** on binding surface **403**. Any deformation of the cube polygonal mesh **402** triggers an update of binding surface **403** via the Loop subdivision algorithm, which in turn propagates through the binding interface to vertices **405** on sphere **401** (the actual CG model).

Using these techniques, a proxy model **402** of the CG character is used to deform a CG model. Thus, the wrap deformation algorithm allows for a great amount of local control of deformations. In addition, a CG skeleton can be bound to proxy model **402**, so that the skeleton joints deform the CG model indirectly by a binding surface mechanism. An advantage of this extra level of indirection is that the skeleton/proxy rig combination, once set up and weighted, can re-bind to multiple forms of CG models without having to significantly modify the work done on the rig.

One skilled in the art will recognize that the described algorithm is just one of many possible proxy/surface binding algorithms that can be used in pipeline **100** of the present invention. In some embodiments, the present invention provides modules for proxy binding to polygonal meshes, parametric curves, NURBS surfaces, systems of particles, and the like. Similar modules can be developed for other types of proxy objects.

Referring now to FIG. **8**, there is shown a sample portion of a deformation pipeline **100** including two proxy/surface binding modules **103**A, **103**B. Module **103**A is a polygonal mesh proxy/surface binding; module **103**B is a parametric curve proxy/curve binding. Also shown are blocks **502**A, **502**B, representing items in DDS **106** associated with a CG model **151**A, **151**B. When a DDS **106** item enters module **103**A, it binds dynamically to the proxy polygonal mesh **402**. Existing deformations on the proxy model **402** then transfer to the vertices in DDS **106** Binding items **503** and stream **106** moves on to the next deformation module **103**B. As DDS **106** passes through curve proxy/curve binding module **103**B, DDS **106** item follows a similar process by which its BindingItems find a binding point on the binding curve of the parametric curve and get new coordinate positions for the surfaces on CG model **502** from deformation module **103**B.

Binding surfaces and binding curves can be created from proxy objects according to any of a number of techniques. If the proxy object **402** is a polygonal mesh, modules are provided that use Catmull-Clark and Loop subdivision surfaces to generate local binding surfaces. Each polygon in the subdivision surface has a local frame of coordinates defined by the tangent vectors on the limit subdivision surface for the given vertex of the subdivision surface. The finite resolution of the subdivision surfaces is controlled by parameters on deformation modules **103**, thus allowing users to adjust for large changes of resolution between proxies **402** and CG models **151**. In the case of NURBS proxies **402**, the convex hull can be used to define a polygonal mesh; surface binding is computed using the techniques described above. When proxy object **402** is a parametric curve, module **103** samples the curve at a given rate to obtain a sequence of local frames of coordinates. In order to fully describe a three-dimensional frame of coordinates along the curve, a differential scheme such as the Frenet or Bishop frames of coordinates is used. Alternatively, module **103** may resort to two curves: one specifying the location of the curve prior to the deformation and the other specifying the location of the curve after the deformation.

As described above, the surfaces **152** of a CG character are transformed into blocks of Binding items **503** on DDS **106**. Among the data contained in binding items **503** is the bindingSite, a local frame of coordinates for the surface vertex. Inside each module **103** where a proxy binding occurs, the bindingSite for each of the vertices gets replaced by the corresponding surface binding frame of coordinates. For example, referring again to FIG. **7**D, each vertex **405** of sphere **401** is bound by a nearest neighbor algorithm to a triangle **404** in binding surface **403** of the Loop subdivision. Each triangle **404** has a well-defined frame of coordinates, where the origin is the barycenter; two of the three basis vectors point from the barycenter to two non-degenerate triangle vertices, while the third basis vector is normal to the plane of triangle **404**. Then, triangle's **404** barycenter replaces the bindingSite.orig variable. The local frame of coordinates of triangle **404** replaces the vector's bindingSite.basis[3], and if there is a weighting value associated with triangle **404** for use during the deformation algorithm, that weighting value is assigned to bindingSite.weight.

Referring to FIG. **9**A there is shown a local frame of coordinates for a triangle **404** in a Loop subdivision surface prior to any deformations on the proxy polygonal mesh **402**. FIG. **9**B depicts triangle **404** after proxy polygonal mesh **402** has been modified. Barycenter **504** changes position, and basis set b**0**, b**1** and b**2** **603**, **601**, **602** point to different locations. During the proxy deformation, the cvProjection components remain constant while the local frame of coordinates changes; as a result, a new location is predicted. In one embodiment, the cvProjection components are calculated by caching in deformation module **103** the surface binding properties prior to any changes in proxy model **402**. In general, these properties remain constant unless the user triggers a surface rebind event, causing a new surface binding to be cached by module **103**. Thus, in this embodiment of the invention, each module **103** contains two copies of the proxy binding surface: a static version for computing cvProjection components, and a dynamic version for updating the local frames of coordinates in binding items **503** of DDS **106**.

After passing through deformation module **103**, each of the vertices in DDS **106** item has a new frame of coordinates where the deformation of module **103** was applied locally. Downstream modules **103** are free to replace or create hierarchical deformations based on this frame of coordinates. Furthermore, the deformation performed by module **103** is stored in the local frame of coordinates in BindingItem::cvProjection. This data is not necessarily the same as the position of the vertex after the module deformations have been completed (BindingItem::cvCurrent) because it does not take into account any post-deformation weighting or interpolation algorithms.

The above-described examples assume that proxy model **402** is set up as a wrap-deforming object that drags vertices of CG model **151**. One skilled in the art will recognize, however, that other configurations are possible. For example, proxy polygonal meshes **402** can be placed inside CG models **151** to work as supporting surfaces for deforming the characters. Such an arrangement may be preferable in some situations, for example to generate anatomically precise deformations. For purposes of the description herein, the term "wrap deformation" is used regardless of the placement of proxy **402** relative to CG model **151**.

Deformation Layering Schemes

Once a binding relationship between proxy **402** and CG model **151** has been established, one can define a number of layering schemes for deforming surfaces **152**.

As described above, deformation modules **103** support several different layering schemes, including parallel, blending, sequential and hierarchical. In one embodiment, these deformation schemes are supported by the DDS **106** design as follows.

Once a binding between an element of the proxy surface or curve and binding item **503** in DDS **106** item has been established, a determination is made as to how module's **103** algorithmic deformation is applied to compute a new vertex position. In one embodiment, proxy **402** binds to either C_0 (initial vertex position), C_1 (current vertex position, also known as pre-deformed position) or O (origin for an input local frame of coordinates).

Referring now to FIGS. **10**A to **10**D, there are shown examples of a binding item **503** in (a) parallel mode, (b) blending mode, (c) sequential mode, and (d) hierarchical mode. In FIGS. **10**A and **10**B, the new local frame of coordinates binds to the initial vertex position C_0. In FIG. **10**C (sequential mode), the new local frame of coordinates binds to the input current vertex position C_1. In FIG. **10**D (hierarchical mode), the new local frame of coordinates binds to O, the origin of the input local frame of coordinates. Each mode will now be described in turn.

Parallel Binding mode: As depicted in FIG. **10**A, the original vertex position C_0 is bound to the proxy/surface binding item **503**, which may be, for example, a triangle in the case of a Loop Subdivision. Module **103** predicts a new position C_2 for C_0 based on the specific deformation algorithm of module **103**. The diagram to the right of the arrow shows the result of the deformation: C_0 is still the original vertex position, C'_1 is the input current position, and C_2 is the new position predicted by the deformation algorithm of module **103**. However, C_2 is not the actual output current position; C_1 is computed as the addition of the C_0 C'_1 and C_0 C_2 vectors, as shown in the Figure. Thus, in this mode, deformations are added in vector space regardless of the order in which they are applied. Furthermore, in one embodiment module **103** has an extra weight W parameter that controls the amount of deformation to be applied per vertex, so that the final current vertex position is an interpolation between C_0 and C_1, calculated as $C_0(1-W)+W\,C_1$.

Blending Binding mode: As depicted in FIG. **10**B, the original vertex position C_0 is bound to the proxy/surface binding item **503**. Module **103** predicts a new position for C_0 based on the specific deformation algorithm of module **103**. The diagram to the right of the arrow shows the result of the deformation: C_0 is still the original vertex position, C'_1 is the input current position, and C_2 is the new position predicted by the deformation algorithm of module **103**. Again, C_2 is not the actual output current position; C_1 is computed as an interpolation of the input current position C'_1 and the new predicted deformed position C_2. Hence, the deformations of module **103** in this mode are blended, or interpolated, with previous deformations layered on top of the deformed model. The weight W used to interpolate between C'_1 and C_2 is again a parameter of module **103**.

Sequential Binding mode: As depicted in FIG. **10**C, the current vertex position C_1 is bound to the proxy/surface binding item **503**. Module **103** predicts a new position for C_1 based on the specific deformation algorithm of module **103**. The diagram to the right of the arrow shows the result of the deformation: C_0 is still the original vertex position, C'_1 is the input current position, and C_2 is the new position predicted by the deformation algorithm of module **103**. Again, C_2 is not the actual output current position; C_1 is computed as an interpolation of the input current position C'_1 and the new predicted deformed position C_2. The new deformed position is based on the input C_1 and not on the original C_0 it was in FIG. **10**B. Accordingly the final deformation is layered on top of the result from previous deformations. The deformations of each module are layered upon one another, each module having a new offset of the current vertex position. As before, a weight W in module **103** yields the final current vertex position C_1 as the interpolation of C'_1 and C_2.

Hierarchical Binding mode:: As depicted in FIG. **10**C, the origin of the local frame of coordinates O is bound to the proxy/surface binding item **503**. Module **103** predicts a new position for C_1 based on the specific deformation algorithm of module **103**. This algorithm moves the old origin O to a new location O' and then pivots the old OC'_1 offset to its new location C_2. The deformation contribution of module **103** maintains the old OC_1 offset and translates and pivots the location of that offset according to a new deformation algorithm. Again, the presence of a weight W in module **103** results in interpolation between the old current position C'_1 and the newly predicted C_2.

As will be clear to one skilled in the art, DDS **106**, and in particular the binding item **503** embodiment described above, provides and can support additional layering deformation schemes, for example based on the local frame of coordinates b_0, b_1, b_2 or based on combinations of any of them.

Similarly it will be understood that pipeline **100** can have multiple modules **103** in various binding modes, in any order and sequence. Such flexibility enormously enhances the rigging possibilities for creating sophisticated CG character rigs.

Module **103** Attributes

In one embodiment, each module **103** has its own set of attributes, or parameters, that modify and control its behavior. These attributes can include some that are specific to a given type of deformation module **103**, and some that are more general. Each attribute has a name. Examples of attributes include, without limitation:

Enabled: A Boolean attribute that enables/disables the action of module **103**. When disabled, module **103** works in a pass-through mode, so that DDS **106** data is copied directly from input to output.

DDS In: An input connection for the input Deformation Data Stream **106** provided to module **103**.

DDS Out: An output connection for the output Deformation Data Stream **106** resulted from module's **103** deformation.

Binding mode: Each module **103** can bind to incoming binding items **503** according to any of the four modes described above: parallel, blending, sequential and hierarchical.

Weight: Controls how much of the total deformation of module **103** is applied to the input DDS **106**. When a module's **103** weight is 0, it has no deformation effect. A module **103** having a weight of 1 applies its deformation in full, while a module **103** having a weight of 0.5 generates output that represents a midpoint between a fully deformed geometry and the original undeformed geometry. In one embodiment, this weight controls the operation of module **103** as a whole, while a separate, per-binding site (bindingSite.weight) weight controls weights by individual binding site. Thus, if module **103** weight is denoted as W, and the

weight associated with each binding site i is denoted as s_i, the deformation applied to the point associated with binding site i is the product $W \times s_i$.

Deformation Pipeline **100** Filtering and Masking

As described above, in one embodiment each binding item **503** in DDS **106** carries with it a tag (BindingItem::tag). The tag controls, at the vertex level, how each module **103** affects binding items **503** in DDS **106**. In one embodiment, the following tags are available: UNKNOWN, UNBOUND, PARALLEL, BLENDING, SEQUENTIAL, HIERARCHICAL. One skilled in the art will recognize that other tags may also be provided.

In one embodiment, by default a binding item **503** starts in the UNKNOWN state; as the binding item **503** passes through pipeline **100**, each module **103** deforms binding item **503** according to its own parameters and characteristics. For instance, a module **103** in parallel binding mode would modify UNKNOWN binding items **503** according to the parallel binding techniques described above.

However if the tag of binding item **503** is either PARALLEL, BLENDING, SEQUENTIAL or HIERARCHICAL then only modules **103** of the matching type modify binding item **503**. Thus, the tag acts as a filter on the deformations that will be performed on binding item **503** as it passes through pipeline **100**.

The UNBOUND tag specifies that binding items **503** are never deformed by modules **103** regardless of their binding mode. This tag allows a user to exclude binding items **503** from deformation pipeline **100** downstream.

In one embodiment, there are filter modules **103** that assign specific tags to bindingItems in DDS **106**. These are assigned by various algorithms that do not break the independence of Deformation Pipeline **100** from CG model **151**. An example of a filter module **103** is one that uses (x,y,z) coordinates and bounding boxes to specify regions covered by a given tag. Many other methods are possible.

Filter modules **103** can be placed anywhere in pipeline **100** in order to assign and modify tags of binding items **503** as they pass through as part of deformation pipeline **100**. Once a binding item **503** receives a tag from a filter module **103** along pipeline **100**, it carries that tag downstream; hence the behavior of all downstream modules **103** are affected by the same tag until a new filter module **103** is reached that may change the tag to another value.

Related very closely to filtering is the concept of "masking". Masking is supported through masking modules **103** which are attached as accessory modules to a deformation module **103**. A masking module **103** assigns tags to bindingItems in DDS **106**, but these tags live only within deformation module **103**. Masking is a form of overriding the tags that vertices carry with them in DDS **106**.

Referring now to FIG. **11**, there is shown an example of DDS **106** item being passed through filter module **1101** and deformation module **103** that is modified by accessory masking module **1102**. The binding items **503** get new tags assigned at filter module **1101**. However, as they arrive at deformation module **103**, a masking tag can override their value. As the binding items **503** exit deformation module **103**, they continue to carry the pre-mask tag value.

List of Modules

The following is a description of some examples of modules **103** that can be implemented in deformation pipeline **100** according to one embodiment: Head Module **102**. Head module **102** converts geometry items **101** defined outside deformation pipeline **100** (such as NURBS, meshes, subdivision meshes, curves, points, and the like) into DDS **106**. Module **102** initializes cvOrig and cvCurrent to be identical for all points. It also initializes binding items **503** to carry the origin of coordinates as its binding frame. Tail Module **104**. Tail module **104** is the last node in pipeline **100**. It converts DDS **106** items to actual geometry items **105** (such as NURBS, meshes, subdivision meshes, curves, points, and the like). In one embodiment, as described above, data stream **106** does not include topological information **351**; such information travels by a parallel connection (Topology) from head module **102** to tail module **104**. Such topological information **351** describes, for example, what type of geometry is represented by DDS **106**, and also includes information describing the basis set and other properties.

CBinding or LBinding Modules **103**. These are proxy/surface binding modules **103** that use polygonal meshes **402** as proxies. CBinding and LBinding modules **103** take a polygonal mesh **402** and convert it internally into a subdivision mesh **403** that acts as a surface binding for the incoming data stream **106**. As polygonal mesh **402** moves during the animation phase, the binding domain drags binding sites along. For CBinding modules **103**, the surface binding is quad-based; for LBinding modules **103**, the surface binding is triangle-based.

In one embodiment, Cbinding modules **103** use the Catmull-Clark algorithm to compute the surface binding while Lbinding modules **103** use the Loop subdivision algorithm.

Referring now to FIG. **12**A, there is shown an embodiment of a Cbinding module **103** in which a single polygonal proxy mesh **402** is used. During the first connection, a copy of mesh **402** is cached in module **103** as a reference to the exact pre-deformed position of mesh **402**. In one embodiment, binding items **503** of DDS **106** are bound dynamically to the Catmull-Clark surface generated from this cached mesh **402**. As the input polygonal mesh **402** deforms under animation curves or other rigs, its own Catmull-Clark surface provides updated positions to the local frames of coordinates, hence providing a driving force for the deformation.

Referring now to FIG. **12**B, there is shown an embodiment of a Cbinding module **103** in which two polygonal meshes **402**A, **402**B are connected to CBinding module **103**. Binding mesh **402**A (also known as a reference mesh) is a reference to a surface where binding items are bound. Updating mesh **402**B (also known as a life mesh) is the one that is edited and that updates positions of local frames of coordinates for the vertices. A user can deform both meshes **402**A, **402**B.

CurveBinding Module **103**. CurveBinding modules **103** use a parametric curve as a binding domain. As with the CBinding module **103** described above, CurveBinding module **103** can be implemented either with a reference mesh **402**A or without one.

Filter Module **103**. In one embodiment, for each binding item **503** in DDS **106**, an integer tag (BindingItem::tag) travels with the point along pipeline **100**. The effect of a deformation module **103** on a vertex in DDS **106** can be modified depending on the value of this tag. For example, if the tag for a vertex is (UNBOUND), then no deformation module **103** along pipeline **100** binds to it to deform it.

Mask Module **103**. A mask module **103** is similar in some respects to a filter module **103**. It is also used to exclude certain deformations from certain regions. In one embodiment, mask module **103** connects directly to binding deformation modules **103**. It includes a masking of the binding

domain, so that it can cancel the contributions of deformation module **103** to binding items **503** connected to certain areas of the binding domain.

Weighting Module **103**. A weighting module **103** connects directly to the binding deformation module **103**, and manages the per-point (binding item **503**) weighting to be used during deformation. Weighting module **103** can therefore be used to fine-tune deformations for selected areas of the character being animated. Weights can be assigned to binding items **503** per ID or by geographical area. Weights can also be attached directly to binding items **503** or indirectly through the binding domain where points are attached.

Relaxer Module **103**. A relaxer module **103** allows a user to add physical properties to polygonal mesh **403** (as in CBinding) to make animation more realistic. For example, a relaxer module **103** can be used to add or specify elasticity, inertia, drag, and other properties to the deformation. Relaxer module **103** can also be used to fix continuity problems on deformed surfaces **152**.

Other Modules **103**. As will be apparent to one skilled in the art, many other modules **103** can also be implemented according to well-known techniques. Such modules **103** include, for example, objects of influence, particle sources and sinks, and the like. Algorithms for performing such operations are well known in the art.

Weighting

In one embodiment, an overall sum of weights for deformations applied to a single input vertex is 1. In one embodiment, the system of the present invention performs a normalization operation to ensure that the sum of the weights is 1, so as to avoid spurious artifacts in the geometry that can result if the sum is some other value.

In one embodiment, the system of the present invention performs such normalization while maintaining serialization of operations. Per-module weights, W, are specified in relative terms; they represent the amount of deformation to be applied by a module **103** with reference to the input at that module **103**, and without reference to overall pipeline **100** or to any other modules **103**. Thus, for example, a pipeline **100** might have seven modules **103**, all of which have weights of 0.5. Since each module **103** applies its weight only with reference to its particular input stream **106** and its own deformation operations, such values are consistent and do not lead to spurious artifacts. Each module **103** applies half of its deformation and blends with half of the incoming data stream **106**.

At the beginning of pipeline **100**, binding items are given a weight of 1. This weight is the total amount of deformation that each vertex can experience. As data stream **106** passes from one module **103** to another, each module's **103** deformation weight is subtracted from the weighting of binding item **503**. For example, if first deformation module **103** has a weight of 1.0, then upon output, binding item **503** has a weight of 0.0 and cannot be affected by any further deformations. On the other hand, if first deformation module **103** has a weight of 0.25, then upon output, binding item **503** has a weight of 0.75 and further deformations on the point are still possible.

Referring now to FIG. **13**, there is shown an example of weight application and determination according to one embodiment. CBinding module **103** is shown with its attached polygonal mesh **402** and a weights module **1201**. CBinding module **103** has a local weight of W. On input, binding item **503** of DDS **106** has a weight of w_i; on output, a weight of w_o remains. CBinding module **103** performs a deformation on the input control vertex with a local weight of Ww_p, where w_p is the per-vertex weighting provided by weights module **1201**. Thus, if module **103** is in parallel binding mode and the total point weight is $W w_p=0.75$, then CBinding module **103** would perform an interpolation between the fully deformed position C_2 and the original position C_0 with a weighting of 0.75 and 0.25, respectively.

The deformation pipeline of the present invention provides a number of advantages over prior art techniques. These include, for example:

Providing a flexible, advanced and extensible deformation mechanism using as few nodes as possible.

Providing a deformation pipeline independent of the specifics of the CG model details, thus allowing users to create character rigs that are more portable among characters.

Providing a deformation pipeline which by design tolerate editing changes to the CG model(s) being deformed without invalidating the character rig.

Providing a generic deformation pipeline capable of processing batches of characters that are morphologically similar.

Providing a deformation architecture that can easily be implemented in hardware, particularly since each node is independent and serialized.

Providing a simple abstract interface for deformation nodes that facilitates easy extension to the pipeline, yet allows sufficient generality to carry unforeseen types of user-defined data.

Providing support for per-vertex attributes, filtering, weighting and masking.

The foregoing description of the embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Persons skilled in the relevant art can appreciate that many modifications and variations are possible in light of the above teaching. Persons skilled in the art will recognize various equivalent combinations and substitutions for various components shown in the figures. It is therefore intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

Reference in the specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment.

Some portions of the detailed description are presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like.

It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate

physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms such as "processing" or "computing" or "calculating" or "determining" or "displaying" or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

The present invention can be implemented as a standalone software application for installation and execution on a general purpose computer or workstation. Alternatively, it can be implemented as a plug-in for an existing software application.

The present invention also relates to an apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may comprise a general-purpose computer selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a computer readable storage medium, such as, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, and magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, magnetic or optical cards, or any type of media suitable for storing electronic instructions, and each coupled to a computer system bus. The present invention can also be implemented in hardware, for example in a specialized graphics card for performing computer animation operations.

The algorithms and modules presented herein are not inherently related to any particular computer or other apparatus. Various general-purpose systems may be used with programs in accordance with the teachings herein, or it may prove convenient to construct more specialized apparatuses to perform the required method steps. The required structure for a variety of these systems will appear from the description below. In addition, the present invention is not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the invention as described herein. Furthermore, as will be apparent to one of ordinary skill in the relevant art, the modules, features, attributes, methodologies, and other aspects of the invention can be implemented as software, hardware, firmware or any combination of the three. Of course, wherever a component of the present invention is implemented as software, the component can be implemented as a standalone program, as part of a larger program, as a plurality of separate programs, as a statically or gram, as a plurality of separate programs, as a statically or dynamically linked library, as a kernel loadable module, as a device driver, and/or in every and any other way known now or in the future to those of skill in the art of computer programming. Additionally, the present invention is in no way limited to implementation in any specific operating system or environment.

What is claimed is:

1. An animation deformation pipeline embodied in a computer-readable storage medium, comprising:

a head node embodied in a computer-readable medium, the head node configured to convert a geometric representation of an object into a data stream;

a plurality of deformation nodes embodied in a computer-readable medium, each deformation node configured to receive the data stream from a node, and for applying a deformation to the data stream;

a tail node embodied in a computer-readable medium, the tail node configured to convert the deformed data stream into a geometric representation of a deformed object wherein topology information describing the topology makeup of the geometry encoded in the data stream is passed through the plurality of deformation nodes separate from the data stream without altering the topology information.

2. The animation deformation pipeline of claim **1**, wherein at least a subset of the deformation nodes apply deformations in response to manipulation of a polygonal proxy model.

3. The animation deformation pipeline of claim **1**, wherein each deformation node passes the data stream to a succeeding node.

4. The animation deformation pipeline of claim **1**, wherein at least a subset of the deformation nodes apply deformations using a sequential binding mode.

5. The animation deformation pipeline of claim **4**, wherein, at least a subset of the deformation nodes apply deformations to the result of a previous deformation node.

6. The animation deformation pipeline of claim **4**, wherein each deformation node receives, within the data stream, a representation of i point, deforms the point, and passes, to a succeeding node, a representation of the deformed point.

7. The animation defonnation pipeline of claim **1**, wherein at least a subset of the deformation nodes apply deformations using a parallel binding mode.

8. The animation deformation pipeline of claim **7**, wherein at least a subset of the deformation nodes apply deformations by combining influences of at least two polygonal proxy models.

9. The animation deformation pipeline of claim **7**, wherein each deformation node receives, within the data stream, a representation of a point, deforms the point, and passes, to a succeeding node, a representation of the undeformed point.

10. The animation deformation pipeline of claim **7**, wherein each deformation node receives, within the data stream, a representation of a point, deforms the point, and passes, to a succeeding nod; a representation of the deformed point and a representation of the undeformed point.

11. The animation deformation pipeline of claim **1**, wherein at least a subset of the defonnation nodes apply deformations using a blend binding mode.

12. The animation deformation pipeline of claim **11**, wherein at least a subset of the deformation nodes generate output that interpolates a current deformation with output of at least one other deformation node.

13. The animation deformation pipeline of claim **1**, wherein at least a subset of the deformation nodes apply deformations using a hierarchical binding mode.

14. The animation deformation pipeline of claim **13**, wherein at least a subset of the deformation nodes apply deformations to a local origin point of an input binding site.

15. The animation deformation pipeline of claim **1**, wherein at least a subset of the deformation nodes are associated with a user-specifiable weight parameter that controls the relative amount of deformation applied by the node.

16. The animation deformation pipeline of claim 15, wherein each deformation node associated with a user-specifiable weight generates output representing a weighted combination of the input to the deformation node and the result of the deformation applied by the node.

17. The animation deformation pipeline of claim 15, wherein the weights are normalized over the entire pipeline.

18. The animation deformation pipeline of claim 15, wherein the weights are not normalized.

19. The animation deformation pipeline of claim 1, wherein each deformation node applies its deformation by:

determining a binding site for at least one control vertex of the object; transforming the binding site;

propagating the transformation of the binding site to the control vertex of the object, to establish a new location for the control vertex; and deforming the object according to the new location of the control vertex.

20. The animation deformation pipeline of claim 17, wherein the binding sites are locations in a subdivision surface.

21. The animation deformation pipeline of claim 19, wherein the binding sites are components of a polygonal proxy model, and wherein propagating the transformation comprises deforming a subdivision surface, wherein to subdivision surface passes smooth deformations to the control vertices of the object.

22. The animation deformation pipeline of claim 1, wherein each deformation node generates data stream output for another node, the data stream output comprising a representation of to deformed object.

23. The animation deformation pipeline of claim 1, wherein the data stream comprises a plurality of binding items to be deformed by deformation nodes.

24. The animation deformation pipeline of claim 23, wherein the binding items comprise tags specifying binding modes.

25. The animation deformation pipeline of claim 24, wherein each deformation node has a binding mode, and wherein each deformation node applies deformations on binding items having a tag specifying a matching binding mode.

26. The animation deformation pipeline of claim 24, further comprising at least one filter node for modifying tags.

27. The animation deformation pipeline of claim 24, wherein at least one binding item comprises a tag specifying that no deformations are to be applied, and wherein the deformation nodes allow the binding item having the tag to pan without deformation.

28. The animation deformation pipeline of claim 24, further comprising at least one masking node for modifying tags.

29. The animation deformation pipeline of claim 28, wherein the masking node modifies a tag to specify that a binding item be excluded from deformation by a particular deformation node.

30. The animation deformation pipeline of claim 1, wherein each node comprises a graphics hardware component.

31. The animation-deformation pipeline of claim 1, wherein: the object comprises a plurality of surfaces;

the data stream comprises at least one data block for each surface of the object;

and each deformation node applies a defonnation by modifying at least one data block associated with the object surface being deformed.

32. The animation deformation pipeline of claim 31, wherein each surface is associated with a plurality of control vertices, and wherein each data block

comprises a binding item entry for each control vertex of the surface associated with the data block.

33. The animation deformation pipeline of claim 1, wherein each deformation node comprises a user-specifiable attribute for enabling and disabling the node.

34. The animation deformation pipeline of claim 1, wherein each deformation node comprises a user-specifiable attribute indicating a blending mode.

35. The animation deformation pipeline of claim 1, wherein each deformation node comprises a user-specifiable attribute indicating a weighting factor.

36. A method for deforming a computer-generated object using a deformation pipeline, comprising:

converting a geometric representation of an object into a data steam;

for each of a plurality of deformation nodes, receiving the data stream and applying a deformation to the data stream;

passing topology information describing topology makeup of the geometry encoded in the data stream through the plurality of deformation nodes separate from the data stream without altering the topology information;

converting the deformed data stream into a geometric representation of a deformed object; and

displaying the geometric representation of the deformed object.

37. The method of claim 36, wherein for at least a subset of the deformation nodes, applying a deformation comprises applying the deformation in response to manipulation of a polygonal proxy model.

38. The method of claim 36, further comprising, for each of the deformation nodes, passing the data stream to a succeeding node.

39. The method of claim 36, wherein for at least a subset of the deformation nodes, applying a deformation comprises applying the deformation using a sequential binding mode.

40. The method of claim 39, wherein for at least a subset of the defonnation nodes, applying a deformation comprises applying the deformation to the result of a previous deformation node.

41. The method of claim 39, further comprising, for each of the deformation nodes, receiving within the data stream a representation of a point, deforming the point, and passing, to a succeeding node, a representation of the deformed point.

42. The method of claim 36, wherein for at least a subset of the deformation nodes, applying deformations comprises using a parallel binding mode.

43. The method of claim 42, wherein for at least a subset of the deformation nodes, applying a deformation comprises combining influences of at least two polygonal proxy models.

44. The method of claim 42, wherein each deformation node receives, within the data stream, a representation of a point, deforms the point, and passes, to a succeeding node, a representation of the undeformed point.

45. The method of claim 42, further comprising, for each of the deformation nodes, receiving, within the data stream, a representation of a point, deforming the point, and passing, to a succeeding node, a representation of the deformed point and a representation of the undeformed point.

46. The method of claim 36, wherein for at least a subset of the deformation nodes, applying a deformation comprises applying deformations using a blend binding mode.

47. The method of claim 46, further comprising, for at least a subset of the deformation nodes interpolating a current deformation with output of at least one other deformation node.

48. The method of claim 36, wherein for at least a subset of the deformation nodes, applying a deformation comprises applying deformations using a hierarchical binding mode.

49. The method of claim 48, wherein for at least a subset of the deformation nodes, applying a deformation comprises applying deformations to a local origin point of an input binding site.

50. The method of claim 36, further comprising, for at least a subset of the deformation nodes, receiving a user-specifiable weight parameter controlling the relative amount of deformation applied by the node.

51. The method of claim 50, further comprising, for at least a subset of the deformation nodes, generating output representing a weighted combination of the input to the deformation node and the result of the deformation applied by the node.

52. The method of claim 50, further comprising normalizing the weights over the entire pipeline.

53. The method of claim 36, wherein, fur at least a subset of the deformation nodes, applying a deformation node comprises:

determining a binding site for at least one control vertex of the object;

transforming the binding site;

propagating the transformation of the binding site to the control vertex of the object, to establish a new location for the control vertex; and deforming the object according to the new location of the control vertex.

54. The method of claim 53, wherein the binding sites are locations in a subdivision surface.

55. The method of claim 53, wherein the binding sites are components of a polygonal proxy model, and wherein propagating the transformation comprises deforming a subdivision surface, wherein the subdivision surface passes smooth deformations to the control vertices of the object.

56. The method of claim 36, further comprising, for each deformation node, generating data stream output for another node, the data stream output comprising a representation of the deformed object.

57. The method of claim 36, wherein the data stream comprises a plurality of binding items to be deformed by deformation nodes.

58. The method of claim 57, wherein the binding items comprise tags specifying binding modes.

59. The method of claim 58, wherein each deformation node has a binding mode, and wherein, for each deformation node, applying a deformation comprises applying a deformation on binding items having a tag specifying a matching binding mode.

60. The method of claim 36, wherein:

the object comprises a plurality of surfaces;

the data stream comprises at least one data block for each surface of the object;

and wherein, for each deformation node, applying a deformation comprises modifying at least one data block associated with the object surface being deformed.

61. The method of claim 60, wherein each surface is associated with a plurality of control vertices, and wherein each data block comprises a binding item entry for each control vertex of the surface associated with the data block.

62. The meted of claim 36, further comprising, for each deformation node, receiving a user-specifiable attribute for enabling and disabling the node.

63. The method of claim 36, further comprising, further each deformation node, receiving a user-specifiable attribute indicating a blending mode.

64. The method of claim 36, further comprising, for each deformation node, receiving a user-specifiable attribute indicating a weighting factor.

65. A computer program product for defaming a computer-generated object using a deformation pipeline, comprising:

a computer-readable medium; and

computer program code, encoded on the medium, for:

converting a geometric representation of an object into a data stream;

for each of a plurality of deformation nodes, receiving the data stream and applying a deformation to the data stream;

passing topology information describing the topology makeup of the geometry encoded in the data stream through the plurality of deformation nodes separate from the data stream without altering the topology information; and

converting the deformed data stream into a geometric representation of a deformed object.

66. The computer program product of claim 65, wherein for at least a subset of the deformation nodes, the computer program code for applying a deformation comprises computer program code for applying the deformation in response to manipulation of a polygonal proxy model.

67. The computer program product of claim 65, further comprising computer program code for, for each of the deformation nodes, passing the data stream to a succeeding node.

68. The computer program product of claim 65, wherein for at least a subset of the deformation nodes, the computer program code for applying a deformation comprises computer program code for applying the deformation using a sequential binding mode.

69. The computer program product of claim 68, wherein for at least a subset of the deformation nodes, the computer program code for applying a deformation comprises computer program code for applying the deformation to the result of a previous deformation node.

70. The computer program product of claim 68, further comprising, for each of the deformation nodes, computer program code for receiving within the data stream a representation of a point, deforming the point, and passing, to a succeeding node, a representation of the deformed point.

71. The computer program product of claim 65, wherein for at least a subset of the deformation nodes, the computer program code for applying deformations uses a parallel binding mode.

72. The computer program product of claim 71, wherein for at least a subset of the deformation nodes, the computer program code for applying a deformation comprises computer program code for combining influences of at least two polygonal proxy models.

73. The computer program product of claim 71, wherein each deformation node receives, within the data stream, a representation of a point, deforms the point, and passes, to a succeeding node, a representation of the undeformed point.

74. The computer program product of claim 71, further comprising, for each of the deformation nodes, computer program code for receiving, within the data stream, a representation of a point, deforming the point, and passing,

to a succeeding node, a representation of the deformed point and a representation of the undeformed point.

75. The computer program product of claim **65**, wherein for at least a subset of the deformation nodes, the computer program code for applying a deformation comprises computer program code for applying deformations using a blend binding mode.

76. The computer program product of claim **75**, further comprising computer program code for, for at least a subset of the deformation nodes interpolating a current deformation with output of at least one other deformation node.

77. The computer program product of claim **65**, wherein for at least a subset of the deformation nodes, the computer program code for applying a deformation comprises computer program code for applying deformations using a hierarchical binding mode.

78. The computer program product of claim **77**, wherein for at least a subset of the deformation nodes, the computer program code for applying a deformation comprises computer program code for applying deformations to a local origin point of an input binding site.

79. The computer program product of claim **65**, further comprising, for at least a subset of the deformation nodes, computer program code for receiving a user-specifiable weight parameter controlling the relative amount of deformation applied by the node.

80. The computer program product of claim **79**, further comprising, for at least a subset of the deformation nodes, computer program code for generating output representing a weighted combination of the input to the deformation node and the result of the deformation applied by the node.

81. The computer program product of claim **79**, further comprising computer program code for normalizing the weights over the entire pipeline.

82. The computer program product of claim **65**, wherein, for at least a subset of the deformation nodes, the computer program code for applying a deformation node comprises computer program code for:

determining a binding site for at least one control vertex of the object; transforming the binding site;

propagating the transformation of the binding site to the control vertex of the object, to establish a new location for the control vertex; and deforming the object according to the new location of the control vertex.

83. The computer program product of claim **82**, wherein the binding sites are locations in a subdivision surface.

84. The computer program product of claim **82**, wherein the binding sites are components of a polygonal proxy model, and wherein the computer program code for propagating the transformation comprises computer program code for deforming a subdivision surface, wherein the subdivision surface passes smooth deformations to the control vertices of the object.

85. The computer program product of claim **65**, further comprising, for each deformation node, computer program code for generating data stream output for another node, the data stream output comprising a representation of the deformed object.

86. The computer program product of claim **65**, wherein the data stream comprises a plurality of binding items to be deformed by deformation nodes.

87. The computer program product of claim **86**, wherein the binding items comprise tags specifying binding modes.

88. The computer program product of claim **87**, wherein each deformation node has a binding mode, and wherein, for each deformation node, the computer program code for applying a deformation comprises computer pro gram code for applying a deformation on binding items having a tag specifying a matching binding mode.

89. The computer program product of claim **65**, wherein: the object comprises a plurality of surfaces;

the data stream comprises at least one data block for each surface of the object;

and wherein, for each deformation node, the computer program code for applying a deformation comprises computer program code for modifying at least one data block associated with the object surface being deformed.

90. The computer program product of claim **89**, wherein each surface is associated with a plurality of control vertices, and wherein each data block comprises a binding item entry for each control vertex of the surface associated with the data block.

91. The computer program product of claim **65**, further comprising, for each deformation node, computer program code for receiving, a user-specifiable attribute for enabling and disabling the node.

92. The computer program product of claim **65**, further comprising, for each deformation node, computer program code for receiving a user-specifiable attribute indicating a blending mode.

93. The computer program product of claim **65**, further comprising, for each deformation node, computer program code for receiving a user-specifiable attribute indicating a weighting factor.

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