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Growing and Animating Polygonal Models of Animals

Marcelo Walter and Alain Fournier

Department of Computer Science
The University of British Columbia
Vancouver - Canada
{marcelow|fournier}@cs.ubc.ca

Abstract

While there exist many computer models of animal bodies, as polygonal meshes and parametric surfaces, these are difficult to modify to take growth into account, or to animate. Growth data available from the literature usually is expressed as very sparse measurements over the body at various ages of the animal. We present here basic techniques to transfer growth data to computer models (especially polygonal meshes), which allows animation of the growth as well as animation of the body in the traditional sense.

The main technique consists of defining local coordinate systems around the growing parts of the body, each one being transformed according to the relevant growth data while maintaining their relationship with the adjoining parts and the continuity of the surface. The local coordinates also permit ordinary animation mainly as relative rotation such as in articulated objects.

We present examples with polygonal models of horses and cows, growth data from same, and motion from Muybridge’s classic photographic data.

Keywords: *animal models, polygonal meshes, growth, animation, shape evolution.*

1. Introduction

Building a computer model of a complex shape such as the body of a horse, a duck or a human is already a challenge, but allowing for the changes in shape caused by growth of the body and/or motion is even more difficult. It is nevertheless imperative to meet these challenges if we want to animate animal models.

This paper presents solutions for two specific problems:

- given an animal body model as a polygonal mesh and sparse generic growth data, how to transform the body model to simulate growth;
- given motion information, how to animate the same model and simulate various gaits, such as walking, trotting, galloping, etc.

We also want to be able to apply both transformations at the same time. This paper is not directly concerned either with the acquisition of the models or with the motion modelling *per se*, but with the integration of the two.

2. Animal Models

The most widely available form of models for animals (and in general for complex three-dimensional models) is as polygonal meshes. They come mostly from digitization of models (plaster, plastic, clay, etc..) or more rarely of real animals, and have been obtained either by input of hand chosen points on the surface from 3D input devices or by 3D scanners.

Much work has been done recently on the problem of creating polygonal meshes (and even parametric surfaces) from such data [1,2]. These models have many advantages. Since most current display architectures are dedicated to polygon rendering, speed of rendering is the most important advantage. They have, however, the distinct drawback of including no structural information about the body, and are therefore difficult to use for animation and shape evolution.

3. Shape Interpolation

The terms *morphing*, *metamorphosis*, *key-framing*, *in-betweening* are all familiar in computer graphics and refer to techniques used to interpolate between objects, and in general between shapes. Basic references go as far back as Burtnyk [3] and Reeves [4]. The technique we will use here to transfer growth data to polygonal models will be very similar to the feature-based 2D morphing techniques, for instance as described by Beyer and Neely [5]. The main differences are that we are operating in 3D (one recent example in 3D is by Lerios *et al* [6] but uses volumetric data), and we want the set of features to be organized in a structure that will allow for articulated motion as well as growing.

4. Growth data

Growth has many possible definitions depending on which aspect of the phenomenon we are trying to address. A reasonable general definition is that growth "is the increase in size and mass of the body or its parts" [7].

For all organisms which grow the changes in shape are mainly due to the different growth rates associated with the different parts of the growing organism. Brody [8] suggests two ways to investigate relative growth: a *qualitative* and a *semi-quantitative* approach. In the former approach the differential growth rates are empirically studied comparing scaled photographs of the subjects at different ages while in the latter given growth measurements are plotted as a function of age and the different slopes compared. Correlations between parts and the whole and also between different races of the same animal can thus be established. Besides being used for differential growth studies, growth measurements play an important role in animal studies where they are used to define a set of average measurements for a given race and age of some animal. The deviation in measurements from the average values for a given individual can be used as a metric to detect for example nutritional problems. Standards for livestock and poultry weights and dimensions are mainly established using a collection of growth measurements collected over a reasonable large population of the race in question.

For practical reasons – measuring animals on-site and over a large time span – much of the available data is very sparse and usually restricted to one or two measurements of some distinctive geometrical feature that can represent skeletal growth. Height at withers or at the shoulders and heart girth are the most common. Not surprisingly, very simple and empirical formulae exist to estimate the weight of some animals using only one or two easy-to-take measurements. For domestic animals such as horses and cows, where a better understanding of the growth process can improve management of livestock, one can find more detailed data. Two examples are the set of 19 parameters measured monthly from birth to 60 months for female and male quarter horses from Cunningham and Fowler [9] and the set for dairy cattle (Holstein and Jersey races) from Brody [8] with 21 parameters monthly measured from birth to 36 months old. For many other non-domestic animals there is considerably less data including only adult measurements for weight, length and shoulder height. For some large mammals the following references are a useful starting point [10, 11, 12, 13].

There are two ways to deal with the lack of quantitative growth data. The first is to use Brody's qualitative approach mentioned before, that is, derive the necessary measurements from a series of pictures of the animals at different ages (though not necessarily the same animal). The second possibility is to use data from a very close "relative" of a given animal. A typical example would be to approximate the data for zebras based on the data available for horses. Both animals have very similar shapes and therefore we should be able to compute a good approximation for a zebra based on the horse. With some care similar solution could be used to approximate, for example, the data for a tiger based on the domestic cat. Finally, in some cases we want unavailable data (for instance the growth of dragons) or unrealistic (the growth of the 50 Ft horse), and we can invent it.

5. The Local Coordinates

Each section of the body that has to grow under the control of its own growth parameters or that has to move independently of the rest is attached to a cylinder defined by the user. Cylinders have been used because they have only two degrees of freedom for size, and these map easily to the type of growth measurement available form the literature. It is not excluded in further work to add other primitives such as spheres [14]. A cylinder is positioned such that it encloses the part of the model that it controls. At the same time its position in the modelling hierarchy is determined by the user. Figure 1 shows an example of the 18 cylinders that we initially defined for the horse's body.

The whole structure is a *directed acyclic graph* or DAG, as in the classic object modelling hierarchy (see for instance Chapter 7 in Foley *et al* [15]).

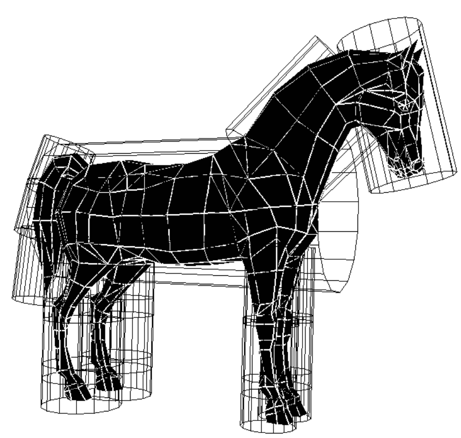


Figure 1: *The perfect cylindrical horse*

Given two cylinders, A and B, B being a child of A in the hierarchy, $M_{A\leftarrow B}$ is the transformation matrix that takes a point of B to A coordinate system, and $M_{W\leftarrow A}$ is the matrix that takes a point of A to the world coordinate system, obviously: $M_{W\leftarrow B} = M_{W\leftarrow A} \times M_{A\leftarrow B}$. The matrices of the type $M_{W\leftarrow A}$ are obtained directly from the position, orientation, and size of the cylinders in the original model space.

For the purpose of growth, it is convenient to be able to express the growth matrix of each primitive (the cylinders) in absolute terms because that is the way the data is collected from the real animals. For instance the growth of a leg is measured in absolute terms, not relative to the body to which it is attached. The information given by the user (positioning the cylinders) and the growth information together allows to express, for any primitive, the transformation to convert a point P_B in the primitive coordinate system to a point P_W in the world coordinate system.

$$P_W = M_{W\leftarrow B} P_B$$

To express the matrices in a consistent way we will assume that $M_{W\leftarrow B}$, for instance, has been decomposed into a scale, a translation and a rotation, applied in that order:

$$M_{W\leftarrow B} = [T_{W\leftarrow B} R_{W\leftarrow B} S_{W\leftarrow B}]$$

The scaling matrix $S_{W\leftarrow B}$ is in fact the growth matrix for B, which we will note G_B. It takes coordinates in B space (where the radius and length are both units) to their real dimensions in the world. We will see in the next section how this matrix is derived from the growth information. To keep the growth matrices absolute, we have to make sure that G_A does not apply to B or any of its descendents. On the other end the position of B coordinate system has to be moved according to the growth of A and its ancestors. To accomplish this we write:

$$P_W = [T_{W\leftarrow A} R_{W\leftarrow A} G_A][T_{A\leftarrow B} S_{A\leftarrow W} R_{A\leftarrow B} G_B] P_B$$

We know all the matrices in this expression (note that $S_{A\leftarrow W} = G_A^{-1}$), except $T_{A\leftarrow B}$ and $R_{A\leftarrow B}$. The latter is trivially $R_{A\leftarrow B} = R_{A\leftarrow W} R_{W\leftarrow B}$. The former can be derived by equating $M_{W\leftarrow B}$ with the whole matrix product in the above expression obtaining:

$$T_{A\leftarrow B} = [M_{A\leftarrow W} T_{W\leftarrow B} T_{A\leftarrow W} M_{W\leftarrow A}]$$

So to transform a point in B canonical space to its ancestor A canonical space, one applies:

$$P_A = [T_{A\leftarrow B} G_A^{-1} R_{A\leftarrow B} G_B] P_B$$

If A is the root, the matrix $M_{W\leftarrow A}$ takes the points to world coordinates, otherwise a similar transformation is applied to P_A to take it to the coordinate system of the ancestor of A.

6. The Growth Process

To obtain the growth matrix for each cylinder, the user attaches two features obtained from the growth data. A cylinder has two degrees of freedom for its dimension, L which controls the scale along the canonical X axis, and R which controls the scale along the canonical Y and Z axis. Figure 2 illustrates the relationship between a cylinder and its features.

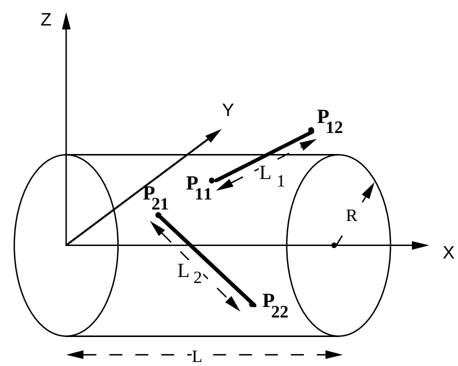


Figure 2: *Cylinder and features.*

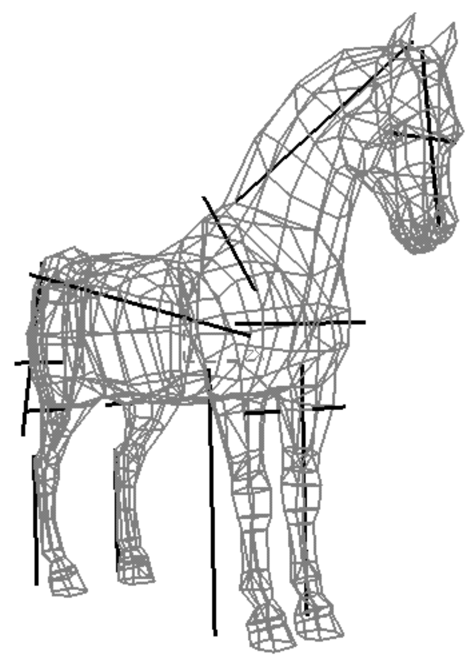


Figure 3: *Features defined for the horse.*

Figure 3 shows the features associated with the horse body. Each feature is a length measurement between two specific points on the body. For convenience we have converted all the measurements of circumference (*girth*, etc) to a corresponding diameter (in the case of obviously ellipsoidal features, we have used the approximation $2\pi R\sqrt{\frac{e^2+1}{2e^2}}$ where e is the eccentricity and R the major semi-axis). The basic assumption is that these four points are fixed in the cylinder's own coordinate system, and therefore their distances uniquely determine the size of the cylinder in world coordinates as long as the two line segments do not have the same proportions in X and in the YZ plane. If L_1 and L_2 are the *real* lengths of the features given by the growth data, and (x_{ij}, y_{ij}, z_{ij}) are the coordinates of the feature point P_{ij} in the cylinder canonical coordinate system, where $R = 1$ and $L = 1$, then

$$L_1^2 = L^2(x_{12} - x_{11})^2 + R^2[(y_{12} - y_{11})^2 + (z_{12} - z_{11})^2]$$

$$L_2^2 = L^2(x_{22} - x_{21})^2 + R^2[(y_{22} - y_{21})^2 + (z_{22} - z_{21})^2]$$

This is a linear system for the unknowns L^2 and R^2 and it has a unique solution unless:

$$(x_{12} - x_{11})^2 \times \left[(y_{22} - y_{21})^2 + (z_{22} - z_{21})^2\right] =$$

$$\left[(y_{12} - y_{11})^2 + (z_{12} - z_{11})^2\right] \times (x_{22} - x_{21})^2$$

Once R_B and L_B have been computed for a cylinder B, the growth matrix is:

$$G_B = \begin{bmatrix} L_B & 0 & 0 & 0 \\ 0 & R_B & 0 & 0 \\ 0 & 0 & R_B & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

It is important to stress that L_1 and L_2 are the lengths as measured on the animal, that R and L are the radius and length of the cylinder scaled to the real world (the scale of the model used to initially place the cylinders is irrelevant), and that the points used to define the features do not have to be inside the relevant cylinder, or even near it. The only constraint is that these points have to be assumed to be in constant positions in the cylinder's own coordinate system.

A point in space is transformed only if it is inside at least one cylinder. The initial size and position of the cylinder effectively defines the scope of its influence. To guarantee continuity as the shape changes, and to achieve a degree of smoothness in the resulting surface, the cylinders have to overlap, and therefore one has to decide how to weight the influence of the cylinders on a point which belongs to more than one. This is similar to the situation in 2D morphing [5] where the weights chosen were of the form:

$$w = \left(\frac{l^p}{(a+d)}\right)^b$$

where l was the length of the feature, d the distance from the point to the feature, and a, b and p arbitrary constants. For now we just use a weight inversely proportional to the distance from the point to the axis of the cylinder. We have not yet investigated the effect of this on continuity. In the case of extreme rotation in particular it does not prevent folding and self-intersection, but it is not a practical concern.

Finally, the growth simulation loop consists of reading, for each age and each cylinder, the lengths of the features, computing the growth matrices and applying them to compute the new coordinates of each vertex of the polygonal mesh.

7. Animation

The hierarchical model established by the cylinders can be easily used for ordinary motion control as well as growth. Any transformation local to the cylinder coordinate system is applied before the chain of transformations described above. It has to be such that it does not change the distances measured in the growth information, or that we can neglect such change. Relative transformations such as a scale matrix S or a rotate matrix R can be applied as:

$$P_A = \left[T_{A\leftarrow B} G_A^{-1} R_{A\leftarrow B} R\, S\, G_B\right] P_B$$

The matrix S can be on either side of G_B since the scalings commute. The most useful form is a simulation of the rotation of the joints of the animal during walking, trotting or galloping. For this purpose it might be necessary to create more cylinders than are required for the growth process. For example for the horse there is only one measurement for the leg from the shoulder down, when one needs to rotate at the shoulder, the elbow, the knee and the fetlock joint. This is easily accomplished since different cylinders can be controlled by the same growth data. It means of course that their relative sizes will remain the same as the animal grows.

The rotation angles have to be measured from the position in which their cylinders have been initially defined (see Figure 4 for an illustration).

8. Examples

As mentioned above, the most abundant source of growth data is for domestic animals. We will illustrate the methods with two examples, the horse and the cow. The horse data was taken from Cunningham [9] and quantifies the growth of a male quarter horse (Table 1 presents a sample of the data). For our actual examples we used 9 measurements (plus two "fake" ones for the tail) at 9 different ages (0, 3, 6, 12, 18, 24, 36, 48 and 60 months).

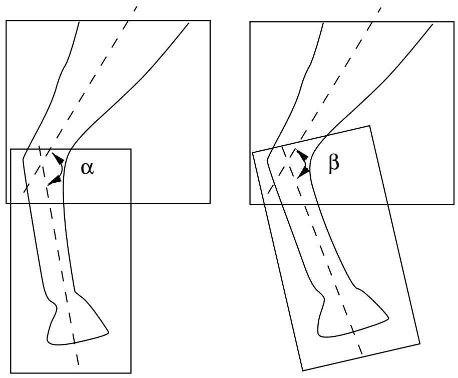


Figure 4: *Rotation of cylinders* vs *joints*

Sample data for quarter horse (inches)				
Age (months)	Length from elbow to ground	Diameter of cannon bone	Length of hind leg	Width of head
0	25.0	1.43	18.1	5.6
12	33.1	2.19	22.8	7.8
24	35.9	2.39	23.0	8.6
36	35.1	2.39	23.2	8.9
48	34.9	2.42	23.1	9.1
60	35.8	2.51	23.3	8.8

Table 1: *Some measurements for a quarter horse.*

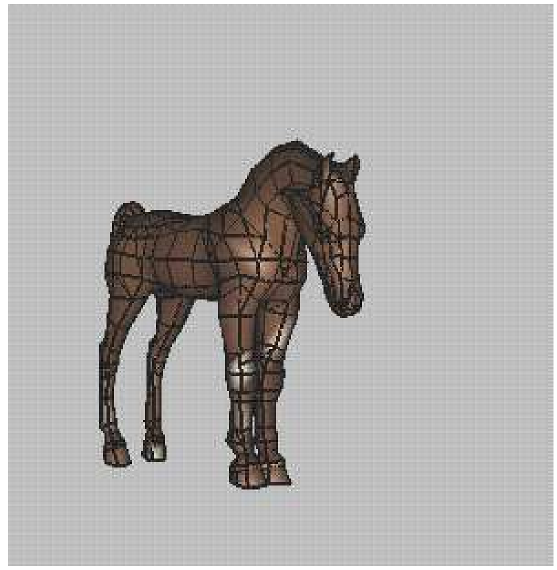
The cow data was taken from Brody [8], and quantifies the growth of Holstein cattle (Table 2 presents a sample of the data). For our actual examples we used 9 measurements at 8 different ages (0, 3, 6, 12, 18, 24, 30 and 36 months).

Sample data for Holstein cattle (cm)					
Age (months)	Height at withers	Height at croup	Depth of chest	From poll to muzzle	Width of forehead
0	70.4	74.1	28.4	23.2	11.8
12	112.6	116.8	54.5	44.3	18.1
24	126.7	129.5	64.2	52.0	20.1
36	131.6	133.7	68.4	52.1	19.7

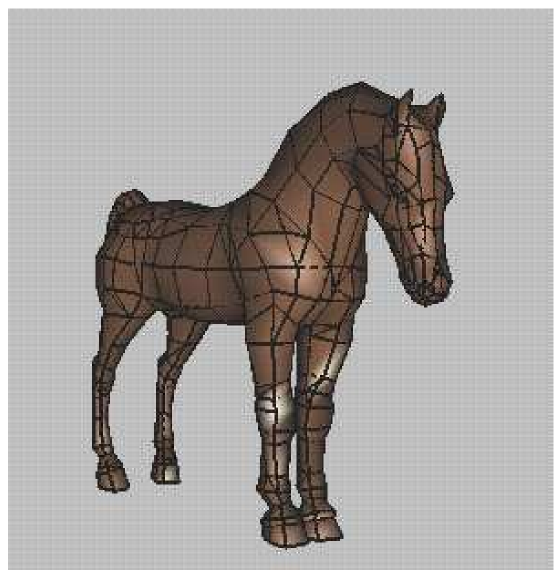
Table 2: *Some measurements for Holstein cattle.*

The polygonal model was obtained from the Viewpoint database (for more information about Viewpoint see `www.viewpoint.com`). For the purpose of illustrations we used the relatively simple models. The horse (model VP1346) contains 674 vertices and 863 polygons. The cow (model VP1323) contains 2892 vertices and 4179 polygons. The computational cost is strictly proportional to the number of vertices to be transformed.

Figure 5 shows the horse polygonal model transformed to the proportions at 6 and 36 months. Note that the proportions of the transformed horse are given by the growth data, not by the original polygonal model. Note also that



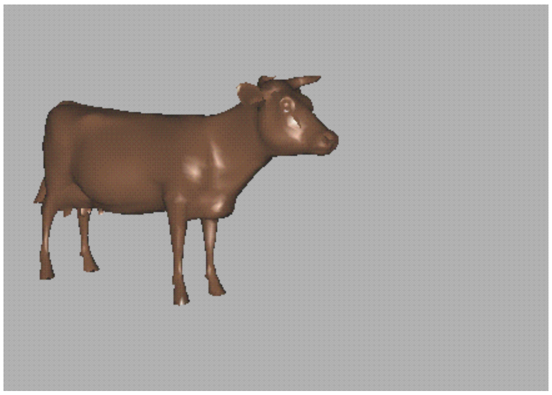
(a) Horse at 6 months.



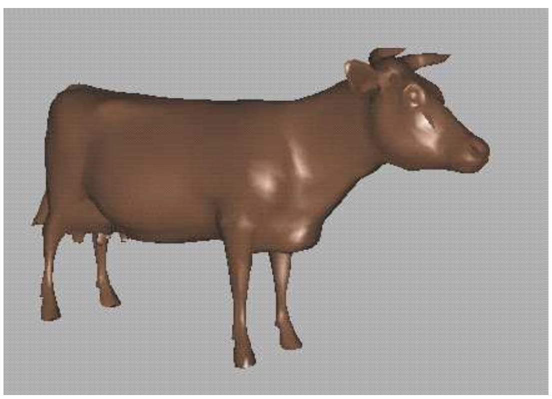
(b) Horse at 36 months.

Figure 5: *Horse transformed at 6 and 36 months.*

nothing abnormal (folding, discontinuity) happens to the surface during the transformation. All the animations referred to in this paper can be found in MPEG and SGI movie format at `www.cs.ubc.ca/spider/marcelow/eg97.html` and also in the companion CDROM for the conference.



(a) Cow at 6 months.



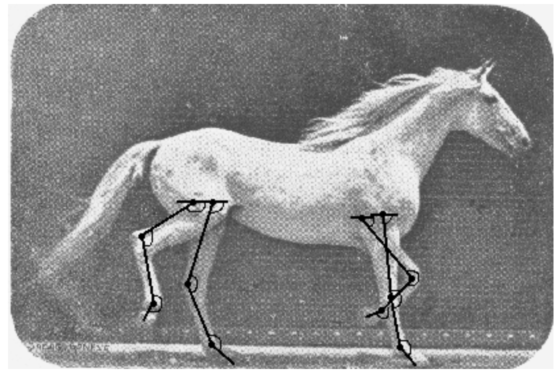
(b) Cow at 24 months.

Figure 6: *Cow transformed at 6 and 24 months.*

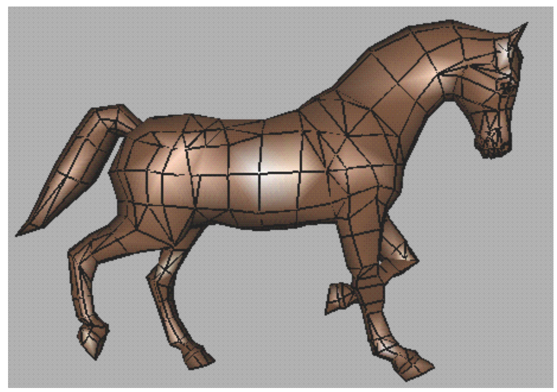
The same method was applied to the Viewpoint cow model using the Cunningham data. Figure 6 shows the cow's body at 6 and 24 months. The corresponding animation for all 8 ages can be found on the web site given.

To illustrate the transfer of motion, we used the famous photographs of Eadward Muybridge [16]. Figure 7(a) shows a frame of a trotting horse from Muybridge together with the set of lines we used to measure the joint angles between articulations in the horse's leg. Figure 7(b) shows the corresponding frame of the Viewpoint horse body trotting.

Since Muybridge's photos only show a half-stride, we exchanged the left side and right side angles for the other half-stride of the trot. We applied the same techniques to the cow. Muybridge photos actually show an ox, but only specialists would know the difference. Now that we have this structure in place, we can apply both the growing and the motion information to the same model. Figure 8 shows two frames of an animation of the horse running and growing at the same time.



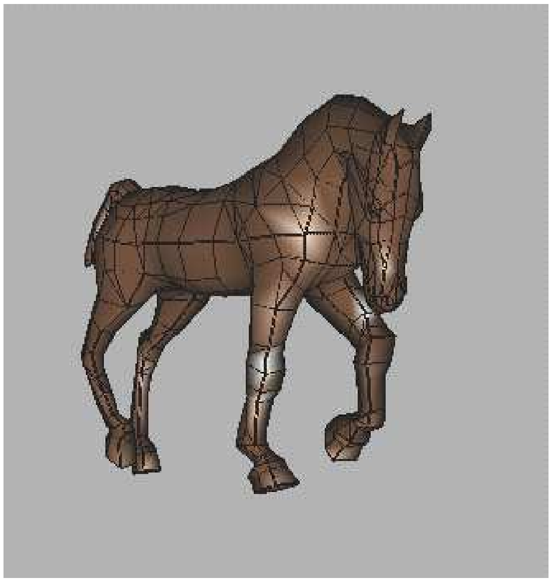
(a) Frame from Muybridge's trotting horse.



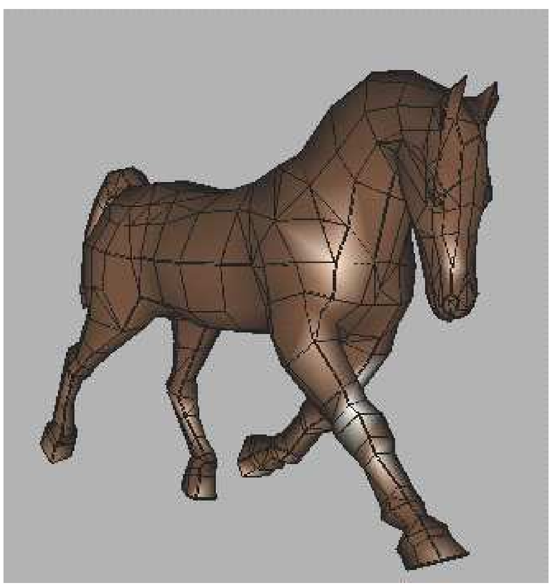
(b) Frame from our trotting horse.

Figure 7: *Muybridge's and polygonal horse trotting.*

We can also transfer one set of data to another body. For instance we can show the horse trotting like a cow (see animation on web site), or, maybe more interestingly, the cow growing like a horse. In this case we would have to make sure the cylinders over the cow's body correspond to the cylinders defined for the horse, and that the features for the horse have equivalent points for the cow. If the two body plans were very different it would not be so straightforward (or meaningful).



(a) Horse at 6 months



(b) Horse at 60 months

Figure 8: *Horse growing and trotting.*

9. Conclusion

We have shown how growth information of the type commonly found in the literature can be integrated and applied to commonly available models of animal bodies. The presented technique builds a system of local coordinates related in a hierarchical structure, defined by cylinders enclosing the relevant parts of the model and features controlling their size. The same structure can be used to animate the body by transferring motion data. In our examples the motion data was taken from photographic frames, but any system giving joint angles could have been used to control the motion. This technique can also be used to interpolate between related animal species, in particular to help in the reconstruction of bodies of extinct species in paleontology.

Any local transformation can be applied before the growth process or the relative motion, including the simulation of deformation induced by muscle contraction or the motion of the cow's belly when trotting. We plan to implement this type of transformation in the near future.

Most polygonal models of the type we used are better looking using an appropriate *texture map*. Texture mapping on a complex animal shape is not easy, and in fact the motivation for the present work is to implement a new model for animal pattern we are currently developing [17]. In this model the pattern is created "in place" on the body at the fetal stage, but grows according to the growth of the body after birth. The method described here implements this latter stage. We hope to be able to integrate both soon. There is another way to texture map with this approach. It consists in defining for every cylindrical coordinate system 2D textures coordinates obtained from the cylindrical coordinates. This is similar to the technique described by Bier and Sloan [18] as two-part texture mapping. The difficulty lies in the proper blending of the texture coordinates given within overlapping cylinders.

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