Animating the Escape Response of *Stomphia coccinea* from *Dermasterias imbricata* Modeled Using Implicit Surfaces

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Abstract

Many of the most interesting behaviors in the biological world have to do with interactions between species. The predator-prey interactions among aquatic organisms is an interesting part of the natural world which has not been seen much in computer animation. This paper explores the interaction between various sea anemones and the starfish *Dermasterias imbricata*. Although a simulation between a specific sea anemone, *Stomphia coccinea* to *Dermasterias imbricata* was created, an approach was taken such that different anemones can with minor parameter changes be used to replace *S. coccinea*. The animation was created using a parametric keyframe approach of procedural models. The anemone and starfish were modeled using the *BlobTree* . The implicit model within the system is defined as a hierarchical composition of multiple objects. Using a hierarchical construction of the model, we can refine the model locally and deform it globally while maintaining the integrity of surface details.

Keywords Implicit surfaces, hierarchical surfaces, parametric key-frame animation, local refinement, global deformation, marine creatures, procedural models

1 Introduction

This section provides a general introduction to implicit surfaces and the application presented in this paper. The surface of an implicit object denoted by S may be derived from an implicit function $f(x, y, z)$. This function represents the points of space whose value equals some threshold denoted by T.

$$S = \{M(x, y, z) \in \mathcal{R}^3, f(x, y, z) = T\}$$

Implicit models have been used in a number of applications such as geometric design, scientific visualization and computer animation. Implicit surfaces offer the advantage of guaranteed smoothly blended and continuous surfaces.

Invertebrates are animals lacking backbones and many of them have small, soft, flabby bodies that drift, crawl, burrow, glide or inch their way along. Since implicit objects are suitable for modeling smoothly blended, soft objects which deform during motion and undergo topology changes this makes them an ideal modeling and animation tool for invertebrates. We have chosen to model the structure and behavior of two such creatures, the sea star and the sea anemone. Not only do these creatures have incredibly beautiful variations in structure but they also exhibit interesting behaviors. The escape response of certain anemones from *Dermasterias imbricata* has been of great interest to many scientists. The reason for this is that anemones have relatively simple nervous systems but they have a relatively complex escape response. So over the years researchers have been trying to understand the neural basis of this behavior. The chain of events due to specific triggers which release the swimming behavior and the coordinated motor activities which follow within a few seconds, is not a simple reflex but shows that the sea anemone posse some elaborate and effective structures as can be seen by their performance. Although the motion may seem random, detailed studies of the motion shows that all anemones which respond to *D. imbricata* display a sequence of patterns [16]. There are diverse applications of this response[3], including behavioral [16] [18], neurophysiological (the discipline involving the study of the makeup and function of the nervous system) [17] morphological (a branch of biology that deals with the form and structure of animals and plants)[14], ecological [13] and chemical.

The main aim behind this paper is to study the general behavior of sea anemones to the starfish *Dermasterias imbricata* and to animate the behavior of a specific anemone, *Stomphia coccinea* to *Dermasterias imbricata*. As a result a procedural approach was taken to model *S. coccinea*. By changing various parameters different anemones could be built and made to interact with *D. imbricata* and depending on the parameters involved, the appropriate reactions are simulated.

The paper is organized as follows. In section 2, we summarize previous work in this area. A detailed description of the behavior of *S. coccinea* to *D. imbricata* is given in section 3. Section 4 describes the implementation details. Section 5 presents our conclusions and future work.

2 Related Work

Previous relevant work will be discussed in this section. The *BlobTree* and the hierarchical implicit surface refinement technique, used to build the models, the collision-based spiral phyllotaxis approach used to position the anemone's tentacles and a description of how the models were created will be outlined in this section.

2.1 The *BlobTree*

The *BlobTree* [23] provides a hierarchical data structure for the definition of complex models built from implicit surfaces, CSG Boolean operations and field warping functions. The implicit model within the system is defined as the hierarchical composition of multiple objects (Figure 1). The surface of an implicit object can also use attributes such as 2D textures. The *BlobTree* has been extended to incorporate textures as described in [21].

2.2 Hierarchical Implicit Surface Refinement

Since the *BlobTree* creates a static model, then once the structure is defined it can't be easily changed. A hierarchical implicit surface refinement technique to

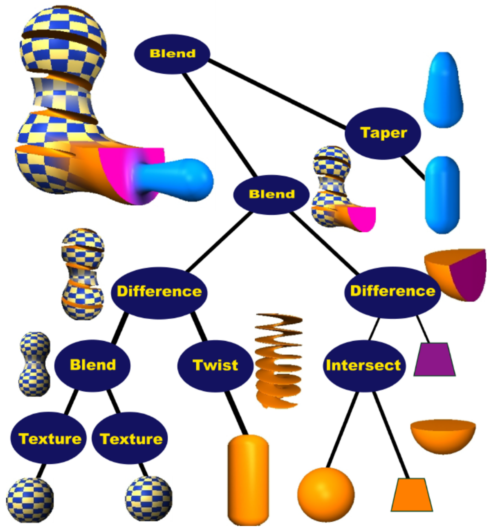

Figure 1: Example of a model built up from a *BlobTree* [23]

further extend the use of the *BlobTree* was introduced in [11]. This method consists of a hierarchical representation and construction of implicit objects.

- **Hierarchical Representation of Implicit Surfaces**

  An implicit object is created as a hierarchy of implicit surfaces. Each hierarchy contains local surfaces and a set of sub-hierarchies. Local surfaces are defined by the *BlobTree* as leaf nodes relative to higher level hierarchies. Sub-hierarchies are defined as internal nodes and represent local surface detail. Surface details related to a specific surface being refined are within the same hierarchical level. Using this representation, implicit objects at each level consist of the local surface S^i_{global} and all the surfaces of its sub-hierarchies $\sum S^i_{sub-surface}$ at level i:

  $$S^i_{surface} = S^i_{global}\ OP_{refinement} \sum S^i_{sub-surface}.$$

  where $OP_{refinement}$ represents the operation of the hierarchy.

  This hierarchical structure of implicit surfaces is illustrated by Figure 2.

  According to refinement operations, four kinds of hierarchies are designed:

  - Blending
  - Controlled Blending
  - Precise Contact Modeling
  - CSG

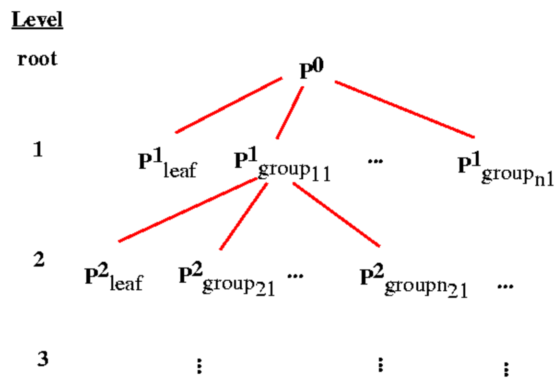

Figure 2: Hierarchy of the implicit object

They represent four different kinds of operations that combine global surfaces with their details. Blending uses the super-elliptic blending method described in [1]. Controlled blending is implemented by the method proposed in [8]. Precise contact modeling uses the approach described in [6]. CSG operations perform intersection, difference, or union between the local surface and the refined surface.

- **Surface Construction**

Initially an implicit surface is used to create a root hierarchy. A sequence of sub-hierarchies are then recursively built by refining selected surfaces. These refined surfaces S^i are introduced to define local surface details.

The final implicit object is obtained by combining all the leaf surfaces according to the different hierarchical properties. The lowest level is processed first. Then the surface constructed at this layer is combined with the higher level surfaces using blending, controlled blending, precise contact modeling, or CSG operations. This process continues until all the higher level surfaces are included.

This method offers two main advantages, the ability to apply hierarchical local refinement and to apply global deformations to models. Local refinement allows the user to introduce more detailed surfaces at any given level. Global deformation changes the overall shape of the surface while maintaining the integrity of surface details.

2.3 The Collision-based Model of Spiral Phyllotaxis

This section gives a general overview of spiral phyllotaxis and its application to generate collision-based models, used to position the anemone's tentacles. Phyllotaxis is the regular arrangement of organs such as flowers or leaves often seen in many plants. It is characterized by spirals or parastichies, composed of sequences of adjacent organs forming the structure. The number of parastichies running in opposite directions are usually two consecutive Fibonacci numbers [5]. The divergence angles, taken from the center of the structure, measured between consecutive formed organs is close to the Fibonacci angle of $360^0\tau^{-2} = 137.5^0$ where $\tau = (1+\sqrt{5})/2$. The quality of the pattern generated depends on this angle [15].

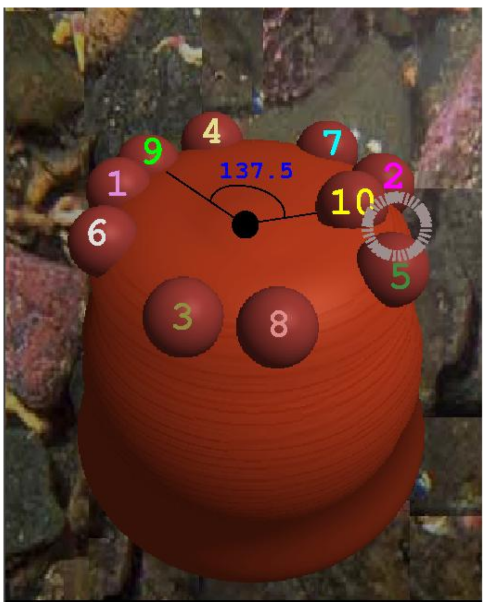

Figure 3: The collision-based model of phyllotaxis. Tentacles are distributed on the anemone's upper disk using a fixed divergence angle of 137.5^0 and are displaced when collision occurs to the next inner layer, tangent to the upper disk

The collision-based model of phyllotaxis proposed in [5] is used to distribute primordia on the surface of the receptacle. Primordia are a group of cells that can be initially identified as a future body part. In [5], the receptacle is viewed as a surface of revolution, generated by a curve rotated around a vertical axis. Spheres which represent primordia are added to the structure sequentially with a divergence angle of 137.5^0. A horizontal ring at the base of the receptacle is formed by this initial group of primordia. When a primordium just added collides with an existing one, the addition of primordia, to this ring stops. The colliding primordium are moved along the generating curve, tangent to its closest neighbor. The next group of primordia are placed similarly, on generating curves tangent to their closest neighbors, determined by the divergence angle as shown in Figure 3. The addition of primordia continues until there is no more room to add another one. Since anemones have flower-like tentacle arrangements, a slightly modified collision-based phyllotactic method was used to arrange the tentacles as described in [12].

2.4 Modeling *S. coccinea* and *D. imbricata*

This section gives a general description of the sea anemone, *S. coccinea* and sea star, *D. imbricata* summarized from [12]. Sea anemones live attached to firm objects in the sea, usually the sea floor, rock or coral. They come in many shapes, sizes and colors and are made up of four main components the column, base (pedal disk), upper disk and tentacles. The columnar body has a single body opening, the mouth, which is surrounded by tentacles. The tentacles protect the anemones since they are studded with nematocysts (stinging capsules) and catch its food. *S. coccinea*'s base, upper disk and column form the main body and were modeled using two torii and a cylinder. The tentacles were modeled using a tapered line primitive and were placed on the anemone's upper disk using a modified version of the phyllotactic pattern as described in [12]. The tentacles were placed in 4 cycles either in 6,12,18,36 = 72 or 6,10,16,32 = 64 (with 6 being the innermost cycle), taken from [20]. The starfish was modeled using five cones for the arms and a bump texture was applied using a random distribution of spheres tangent to the surface. The models were created using a hierarchical representation which allowed the structures to be easily animated and locally and globally deformed. Since they were built using a procedural method different parameters could be changed to create different types of anemones or sea stars. The models used to create the animation were slightly modified versions of those found in [12]. The sea anemone's tentacles were arranged in 4,4,8,16 cycles = 32 with 16 being the outermost layer and the starfish's bump texture which was previously created using point primitives was replaced by a texture.

3 Behavior of the Anemone and Starfish

One of the best studied and most dramatic escape responses of marine invertebrate is the detachment of *S. coccinea* in response to *D. imbricata* [3]. A general description of the response of anemones to *D. imbricata* will be explained, followed by a more detailed description of the reaction and lastly some characteristics specific to the anemone, *S. coccinea* will be outlined.

- **General Behavior**

  Nearly all sea anemones which respond to *D. imbricata* display the following behaviors taken from [16]:-

  1. *Tentacles and sphincter response*
  2. *Expansion*
  3. *Detachment* (sometimes)
  4. *Swimming movements*
  5. If swimming movement occurs, *Recovery* is the last step

  Detachment doesn't always occur and may be regarded as a side effect and the swimming movements do not occur until the column has elongated.

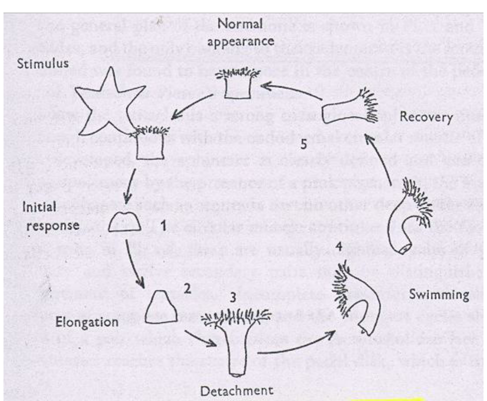

Figure 4: The main features of the swimming behavior of the sea anemone *S. coccinea* to *D. imbricata*

- **Detailed Behavior Description** The general five step behavior just outlined will be explained in more detail. This description was mainly taken from [16] but also from these sources [17][3] and the behavior is also illustrated in figure 4 taken from [16].

  1. *The initial response phase* occurs when the upper surface of the starfish *D. imbricata*'s is brought into contact with the anemone's tentacles. The tentacles then adhere to the starfish on contact. After an inactive period of at least five seconds, the tentacles and sphincter muscle contract. As a result both the tentacles are drawn inwards and the oral disk closes. (The sphincter muscles are derived from circular muscles of the column and are located at or near the edge of the column just below the tentacles).

  2. *The elongation phase* occurs after stimulation by *D. imbricata*, the anemone expands much beyond its normal size. Elongation of the column is due to contraction of the circular muscle. Once a responding anemone begins to elongate, water rapidly enters the gastrovascular cavity (internal cavity) through the mouth; one anemone, for example took in water equal to one-sixth of its previous volume. The end result is that the tentacles and disk reappear and expand to their fullest extent.

  3. *The detachment phase* is variable, as an anemone may show swimming movements without detaching from the substratum. More usually it will appear to detach itself with a vigorous upward jerk. Unless the foot is firmly attached it will decrease in diameter.

     The activity has two main components:-

     (a) *The 'Jerk'* which is due to contraction of the parieto-basilar muscles (they generally run from the column to the pedal disk), which lift the pedal disk from the surface. The center of the foot, becomes convex owing to the increased coelenteric pressure and thrusts the anemone upwards. If the parieto-basal contraction spreads more slowly from one side, forming a concentric groove, detachment will proceed more gradually.

     (b) At the same time, *the pedal disk decreases in diameter*.

  4. *The swimming phase* may occur whether or not detachment occurs. The actual swimming movements are preceded by elongation of the column. In a vigorous response the column of the anemone often performs a whirling movement about its axis before the usual abrupt bending movements begin. This whirling movement, if rapid is the one which initially propels the animal into the 'swimming' motion. The swimming motion consists of a serious of bending actions of the column.

5. *The recovery phase* occurs when the anemone comes to rest on its side and is relatively unresponsive to *D. imbricata* and other stimuli. The column becomes shorter and as the circular muscle is relaxed. The disk and tentacles return to normal. During this time the anemone may not respond to renewed stimulation , such as simulation from the starfish. The surface of the pedal disk presently exhibits a marked facility of adhesion, and as it re-attaches to the substratum the ordinary sessile position is regained. The normal position may be regained with corresponding speed, but in some cases the whole recovery phase lasts longer. Once the anemone has re-attached, it will usually respond to stimulation with *Dermasterias* by swimming again.

- *S. coccinea's* **Response To** *D. imbricata*

  The anemone, *S. coccinea's* general behavior to *D. imbricata* is the same as those outlined in the beginning of section 3. Specific properties of this behavior related to the *S. coccinea* species will be described in this section. In *S. coccinea*, the more elongated the column, the more vigorous the swimming activity. As described in [19], initiation of the escape behavior in *S. coccinea* occurs after contact with the sea star, in the case of *D. imbricata* it occurs after contact with the starfish's upper surface, which contains a chemical that apparently triggers swimming [22]. Originally thought to be an aminopolysaccharide [22], the active chemical has since been identified as Imbricatine, a member of the class of alkaloids formerly known only from plants [3]. A solution of Imbricatine can cause detachment in *S. coccinea*.

4 Implementation Details

The animation was created using a parametric keyframe approach. The models were created using hierarchical implicit objects that were modeled procedurally. This section describes the techniques used to build the animation scenes and gives a detailed description of the operations applied to create the animation phases. Lastly, the approach taken to animate the *BlobTree* will be outlined.

4.1 Approaches Used to Generate the Scenes

The frames were generated using a number of key approaches:-

- **Procedural Modeling**

  The models were created procedurally by associating various algorithms and parameters with the objects as described in [12]. For example a modified collision-based phyllotactic algorithm was used to place the tentacles on the anemone's upper disk. The parameters used in the scene were related to the anemone and starfish.

  The anemone had the following parameters associated with it:-

  1. The length and radius of body.
  2. The radii of upper and lower disk.
  3. The number of tentacles.
  4. The length and radius of the tapered line used to create the tentacles and their orientation parameters (eg random bend angles, ranges).
  5. The tentacle patterns and the number of layers used.
  6. The material properties for all the model components.

  A number of parameters shown below were used to create the starfish:-

  1. The number of arms.
  2. The length and radius of the cones used to create the arms.
  3. The orientation of each arm.
  4. The material properties (these can include complicated properties such as bump texture details).

- **Parametric Keyframe Animation**

  Each object was characterized by a number of parameters as described at the beginning of this section. The keyframes were created by specifying the appropriate set of parameter values at specific times, parameters are then interpolated and images are finally individually constructed from the interpolated data. The parameter values are created using tracks, that will be described in 4.3. Five phases as described in section 3 were associated with the anemone, These include the initial response, elongation, detachment, swimming and recovery phase. The behaviors that were associated with each phase could be modified or the intensity of them could be increased or decreased via parameter modifications. The anemone had a number of phases associated with it, in a specific sequence.

- **Hierarchical Implicit Object Construction**

  The hierarchical approach was used to ease both the modeling and animation process. Using this method, the anemone was built with four layers, the lower disk, column, upper disk and tentacles. Global deformations, which include affine transformations and space warping were applied to the model. The operations were always applied to the column. For example when the anemone's column was scaled, the upper layers, which include the upper disk and tentacles had the same transformations applied to them and were automatically adjusted. Similarly when the column of the anemone was bent during the swimming motion, the upper layers automatically adjusted. The bending properties of implicit objects were used or controlled as needed. For example the tentacles blend with the sea star's arm when they touched, since they were required to blend on contact. However, controlled blending described in [8] was applied between the tentacles, so that they would not blend with each other.

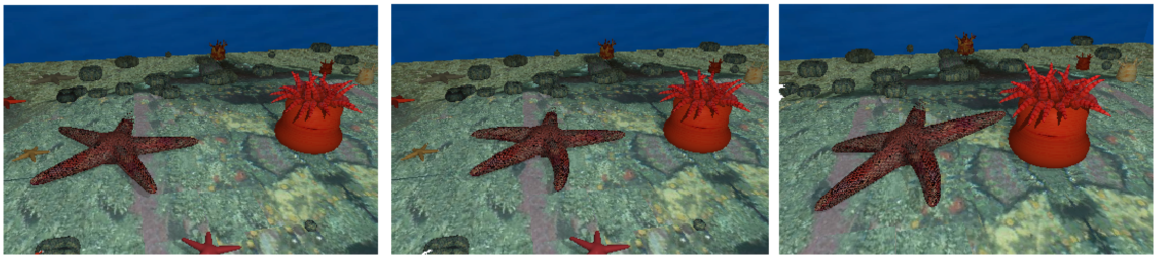

Figure 5: The starfish moves towards the anemone

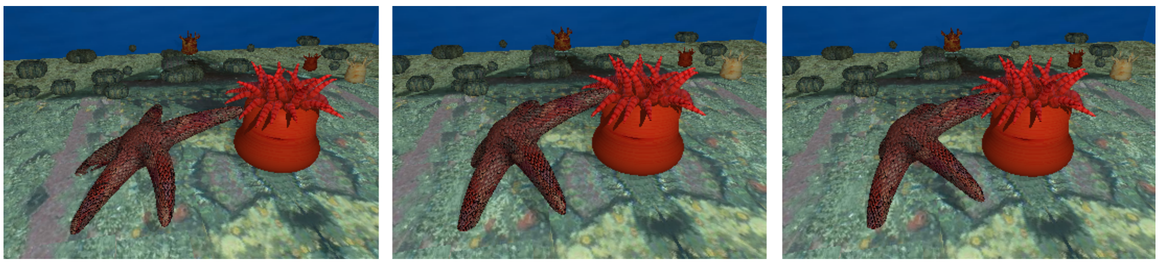

Figure 6: The starfish’s arm touches the anemone’s tentacles

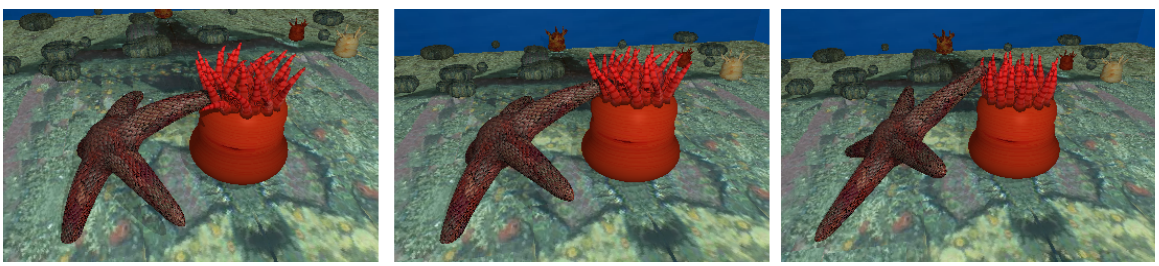

Figure 7: The anemone’s tentacles are made to bend inwards

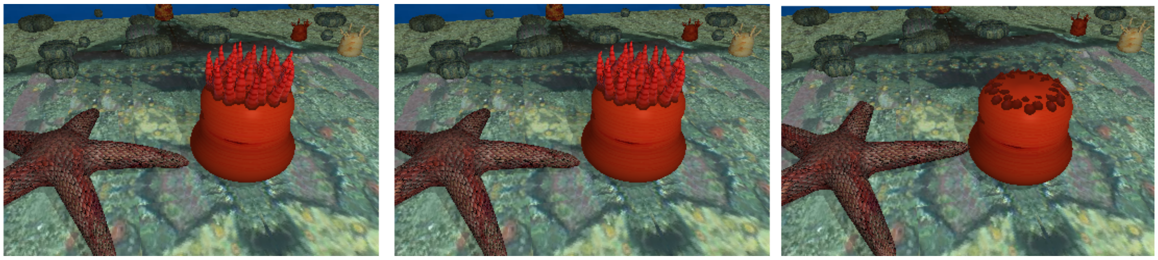

Figure 8: The anemone's tentacles move into the upper disk

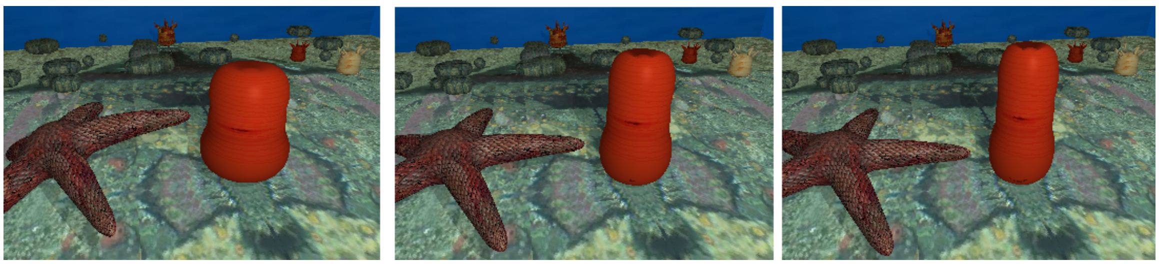

Figure 9: The anemone with hidden tentacles begins to elongates

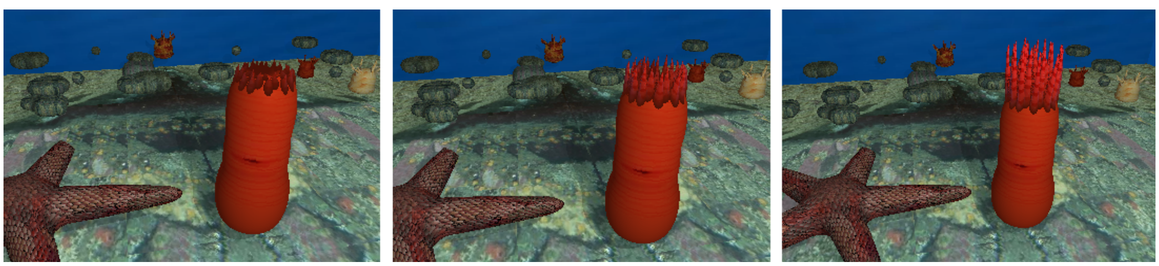

Figure 10: The anemone's tentacles reappear and elongate

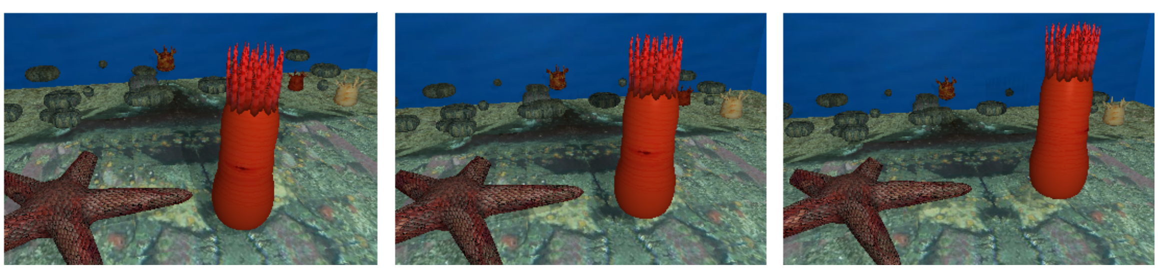

Figure 11: The anemone moves upwards and spins about the y axis

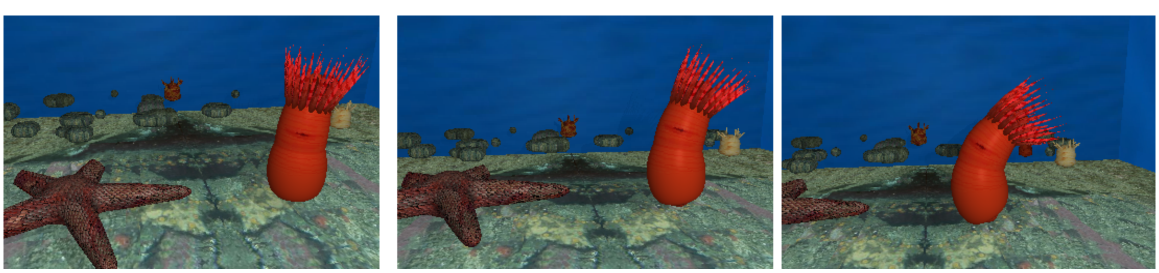

Figure 12: The anemone bends

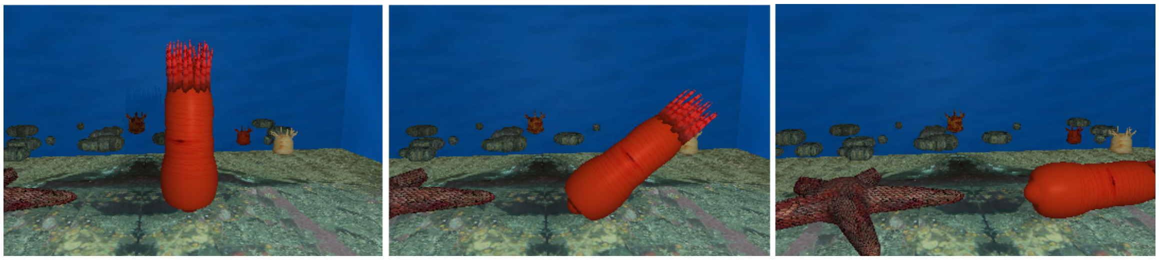

Figure 13: The anemone falls to its side

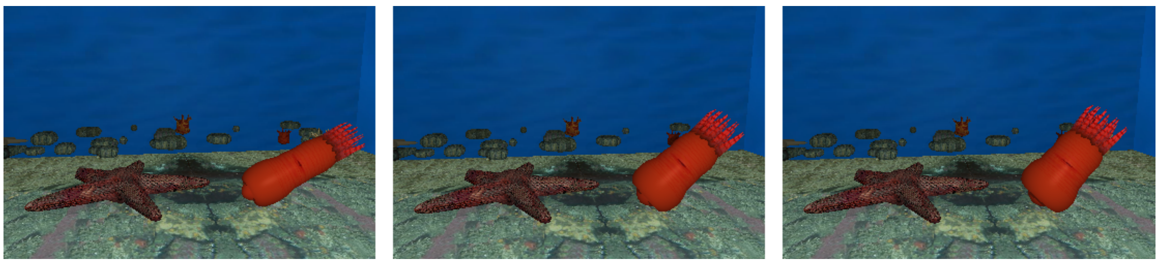

Figure 14: The anemone's body orientation and size are gradually restored

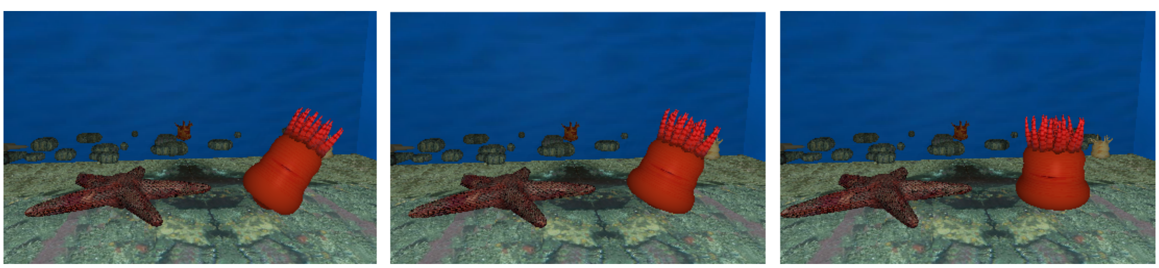

Figure 15: The anemone's body orientation and size are gradually restored

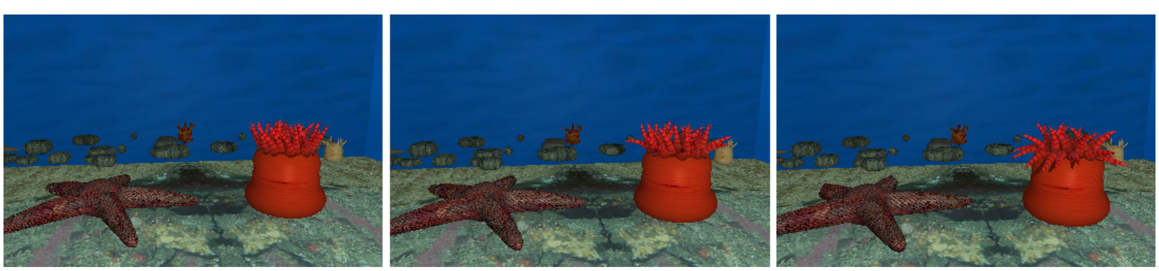

Figure 16: The anemone's tentacles length and size return back to normal

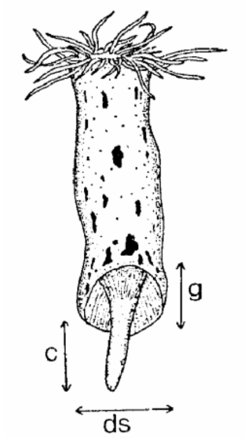

Figure 17: The shape of the detached elongated *S. coccinea*

4.2 Animation Phases

This section describes the operations applied to create the animation. Section 4.3 contains more details related to tracks used to obtain parameter values. Initially the starfish moves towards the anemone with a slight bending movement of its arms. The motion is created using a nurbs path to orient the starfish's movement as shown in figure 5. The starfish then moves towards the anemone and its arms bend to touch the tentacle surface as shown in 6. The anemone then goes into a sequence of phases :-

1. *The initial response phase*

   The tentacle orientations begin to change due to the sphincter muscle contraction and they begin to gradually move inwards. This is achieved by using the modified collision-based spiral phyllotaxis algorithm to generates the tentacles. The tentacles were put in four layers

   (a) *layer one*, the innermost layer, bends inwards from 0^0 to 120^0

   (b) *Layer two*, bends with random orientations, between 0^0 to 90^0.

   (c) *Layer three*, bends outwards from 60^0 to 150^0

   (d) *Layer four*, which is the outermost layer, bends out the most and is assigned a random bend angle between 60^0 to 270^0.

   To simulate the movement of the tentacles, the outermost layers gradually became the next innermost layer. This process is repeated until all tentacles are part of layer one that is oriented inwards. This gradual process is shown in figure 7. The tentacles then move gradually into the upper disk of the anemone as illustrated in figure 8

2. *The elongation phase*

   A global scaling operation is applied to the anemone's hierarchical structure. Since there are no tentacles at the beginning of this stage , the column's scaling automatically only seen to be applied to the upper disk as illustrated by figure 9. It continues to elongate and gradually the tentacles reappear as shown in figure 10. They continue to elongate until they are longer than their original length. A sketch of the body shape after the elongation stage is illustrated in figure 17 taken from [4].

3. *The detachment phase*

   Global translation and rotation is applied to the anemone's hierarchical structure. The anemone translates in the y direction and then rotates about its y axis a number of times as shown in diagram 11.

4. *The swimming phase*

   A bending operation is applied to the column of the anemone and the upper disk and tentacles are automatically readjusted as shown in figure 12

5. *The recovery phase*

   The anemone rotates about the z axis a total of 90^0 as shown in diagram 13 and as a result the anemone falls on its side. The affine transformations that were originally applied to the anemone then gradually get reversed. The anemone rotates up to a standing position and scales down to its normal size. The tentacles return to their normal length and their normal layer distribution which is 4,4,8,16 cycles = 32 . As a result the normal tentacle orientations are restored. The final recovery steps are illustrated by figures 14, 15 and 16.

Our animation approach should allow us in the future to generate different anemone and starfish structures by modifying the various object parameters. Certain optional phases can be removed to create different sequences and they can also be intensified or made simpler as required by modifying the object parameters ranges for any specific motion.

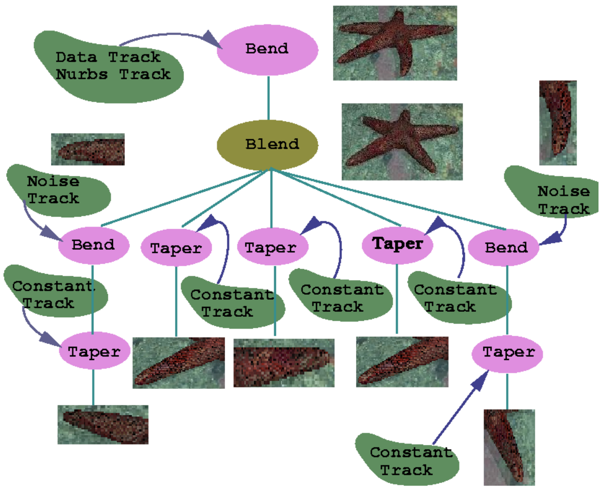

Figure 18: The blobtree structure used to create the star, along with the tracks used with this model

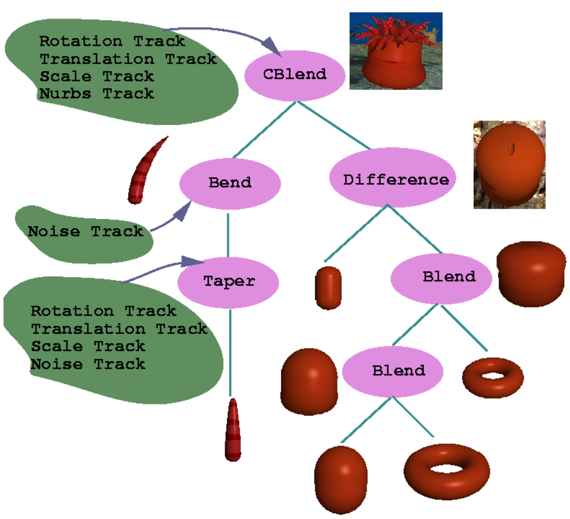

Figure 19: The blobtree structure used to create the anemone, along with the tracks used with this model

4.3 Animation in the *BlobTree*

This section defines tracks, the overall track hierarchy created and their application to animate the starfish and anemone. The *BlobTree* was animated using the concept of tracks. A track is the set of events that describe the activity of a parameter over time. It may be queried to return a value for any given point in animation time as described in [7]. A hierarchy of tracks was created which includes, three main kinds of tracks , matrix tracks, path tracks and multiple tracks. Matrix tracks include affine transformation matrices and the constant matrix track which has the same value at all points in time. Path tracks include, interpolation tracks such as uniform and non-uniform linear tracks and various curves. The curves include nurbs, bspline and bezier curves. Multiple matrix tracks are used to combine tracks together either by addition, subtraction, multiplication or division. There are also data tracks used to store a list of values at specific points in time, a noise track and a constant track that returns the same value at all points in time. The *BlobTree* used to model the starfish is seen in figure 18. The starfish is made up of tapered line primitives that are blended together. The line primitives represent the star's legs. Two of these legs were bent. To animate the starfish the approach described in section 4.2 was used. The values generated were created using tracks. As seen in figure 18 , the arms were tapered using constant values taken from a constant track and were bent using random values generated through the noise track. A nurbs track was used to move the whole starfish and a data track was used to store the angles for each sea star leg. The *BlobTree* used to create the anemone is shown in diagram 19. After the body is created a difference operation is used to create the mouth of the anemone. The tentacles, had various track values associated with them at different points in time, these include noise tracks, to generate random tentacle bending angles and matrix tracks such as scale, rotation and translation tracks. Finally the anemone was moved in the scene using values generated from nurbs, rotation, scale and translation tracks. Currently tracks represent a separate hierarchy from the *BlobTree* .

5 Conclusions and Future work

In this paper we have presented a method to create the interaction of two invertebrates, the sea anemone, *S. coccinea*, and the sea star, *D. imbricata* as a new application of the *BlobTree* . The model combines implicit surfaces, CSG, controlled blending, 2D texture mapping and the collision-based model of phyllotaxis. We have found that the *BlobTree* provides an excellent structure on which to base such models. We are also working on generating more realistic images using rendering techniques such as Photon maps [10, 9] to correctly reproduce the effect of transparency and translucency, observed in some of these creatures. The results show implicit surfaces as a tool capable of animating complex sea creatures using a parametric keyframe approach. We are currently looking into creating a behavioral physically based animation. The creatures could be created with built in instincts for avoidance, escape and wandering as appropriate for both predators and prey. The physically based animation will be done using the precise contact modeling techniques of Cani-Gascuel and Desbrun [2], including volume preservation. These features will enable use to create accurate simulations of these objects and their environment. We are also planning on adding virtual muscles to the anemones to have more precise control of their motion, contracting the muscles or relaxing them responding to obstacles or threats in the immediate environment as appropriate. Animation tracks should be applicable to any node in the *BlobTree* . We are investigating the extension of the *BlobTree* to incorporate these features to provide better tools for implicit modeling and animation.

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