Visual Patterns in the Plant Kingdom

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Fig. 1. Real (left) and virtual (right) *Codiaeum Variegatum* generated with our approach.

***Abstract*—There has been a lot of progress in modeling and rendering elements of our Natural World for computer graphics tasks. In the Plant Kingdom, techniques for modeling the visual patterns presented in many natural objects (such as stripes on a watermelon) have advanced far less than methods for modeling the shape and reflectance properties of individual or large collections of elements (such as leaves and trees). In this paper we explore a procedural model for synthesis of many familiar visual patterns from the Plant Kingdom. Our results show that in this context a procedural model has advantages over other texturing techniques such as texture mapping and procedural noise, since these patterns are usually needed in great quantity, and at least for some plants, with many geometric variation, assigning consistent texture coordinates is a challenge. We show results for fruits, mushrooms, and small decorative plants.**

***Keywords*-visual patterns; plant kingdom; clonal mosaic patterns**

I. INTRODUCTION

Among the many Natural Phenomena already addressed in computer graphics, we can say that for the Plant Kingdom the focus has been more on geometric modeling of individual shapes and collections of elements, such as trees and vegetation in general, together with reflectance properties of plant tissue. In contrast not much attention has been paid to modeling detailed visual patterns of individual elements, such as the stripes on a watermelon or spots on flowers. The usual solution for modeling these patterns uses texture mapping or, for more irregular patterns, a noise-based texturing function might be used. However, such patterns are familiar, ubiquitous, present individual visual variation, and typically needed in great number. Although texture mapping is a common choice, we advocate that in this case a tailored procedural texturing approach might be more appropriate, since a good designed procedural model addresses these requirements. In this paper we first establish a simple taxonomy for classification of visual patterns in the Plant Kingdom and then investigate the use of a previously defined procedural model able to generate unstructured and structured visual patterns found in many plants, fruits, leaves, and vegetation in general. In Fig. 1 we illustrate one result of our approach for simulation of a small shrub known as *Codiaeum variegatum*.

II. RELATED WORK

There has been a large body of literature addressing natural elements from the Plant Kingdom. From an exhaustive search in the main bibliographic databases such as graphbib from ACM/Siggraph and DBLP we estimate a total of approximately 150 publications. From this total, less than 6% addressed visual patterns as proposed in this paper. In this review we first highlight few approaches dealing with the many aspects of the Plant Kingdom followed by a more in depth look at the related work specific for patterns.

The Plant Kingdom first appeared in graphics as late as 1979, where the paper by Yessios [1] introduced a drafting system for wood, plants, and rocks. The pioneering paper by Vogel [2], although not published in a graphics conference or journal, introduced a mathematical formalism for modeling the seed structure of a sunflower head. Individual shapes and collections of trees, flowers and vegetation have a long tradition in graphics mainly due to the work of Prusinkiewicz and colleagues [3], [4], [5] who extensively developed L-systems into a powerful engine for many graphics tasks in the Plant Kigdom. The reflective properties of plant tissue has also been addressed for instance by Wang and others [6], where a realtime illumination model is presented. Soler [7] and Habel [8] investigated the physics of light-matter interaction in the context of leaves. The small hairs in some plants was the goal of Fuhrer, Jensen and Prusinkiewicz [9] whereas the work by Tan *et al* [10] builds a 3D geometric model of a plant from a collection of few real images. The research in this area is still strong, as exemplified by a recent contribution for faithful reconstruction of trees from collection of points [11].

Runions and colleagues [12] presented a biologically-motivated model for synthesis of leaf venation patterns. Many striking types of venation patterns were possible by modeling the sources and distributions of hormones (auxin) on a dynamic leave shape. Hong, Simpson, and Baranoski [13] introduced explicit 3D modeling of the veins as the main factor defining leaf shape. Their work also accounts for shape and color variation in leaves.

When it comes to flowers, Ijiri and colleagues [14] use a model with biologically-motivated constraints to achieve more realistic-looking shapes whereas [15] presents a dynamic shape model which allows modeling the full cycle of flower growth, from bud to adult shape. The work by Zhou and colleagues [16] investigated flower color patterns and share few goals with our own work. They used a reaction-diffusion system to model basic gray-scale patterns which are later translated into colors using a pigment database.

A very active area has been modeling the inner part of fruits and vegetables. Owada and others [17] presented an interactive system for modeling the surface and interior of fruits. From a set of illustrations, arbitrary cuts on the object are possible and the new information is synthesized with texture synthesis techniques. Pietroni and colleagues [18] use real images as input to a local reference frame of a 3D model. From this input new arbitrary cuts or carving the virtual object is possible. The work in [19] creates 3D internal content from user-defined 2D sketches on cross-sections which are propagated to 3D space and [20] defined the inner structure by repeatedly pasting solid texture exemplars. More recently, diffusion surfaces were introduced by Takayama and others [21] where internal illustrative representations of some fruits and vegetables are possible. Instead of using a 3D volumetric solution, they applied a modified version of positive mean value coordinates algorithm to diffuse colors inside the object from nearby surfaces. In spite of this extensive body of work, visual patterns in the Plant Kingdom remain largely unexplored.

III. BIOLOGICAL BACKGROUND

A. A Possible Classification for Visual Patterns in the Plant Kingdom

Visual patterns are ubiquitous in the Plant Kingdom. From the beautiful intricate display in many flowers to simple stripes or spots, the range of variation is astonishing. In order to address the synthesis of these patterns for computer graphics tasks, we propose a simple initial taxonomy. We classify the patterns as either structured or unstructured (or random) patterns. Structured patterns exhibit regular features which allow us to quantify one or more visual cues, such as the number of stripes or number of spots. Unstructured patterns, on the other hand, have no direct way of quantifying a prominent feature and vary much among individuals. Fig. 2 exemplifies the two possibilities. The winter squash presents a regular number of stripes whereas the lungworts herb shows a blotchy pattern of lighter green irregular spots which defies a quantitative description. Most patterns are defined with only two basic colors, although more colors are possible.

(a) Winter Squash (*Cucurbita pepo*).

(b) Lungworts (*Pulmonaria officinalis*).

Fig. 2. Structured and Unstructured Patterns in the Plant Kingdom.

B. Plant Pigments

The Plant Kingdom presents greater diversity of pigments when compared with mammals. Whereas for mammals two pigments only are responsible for visual colour diversity, in plants there are four main types: anthocyanins, betalains, carotenoids and chlorophylls [22]. Plant pigments are specialized compounds which absorb light of certain wavelengths and reflect others. They are responsible for the wide range of colors and patterns seen in many specimens of the Plant Kingdom. The colorful patterns act as attractors of animals for seeding and pollination, and specially chlorophylls and carotenoids, as part of the photosynthesis process. Some pigments have been used as food colorants and dyes, and are therefore of great utility for human life and health.

Anthocyanins, derived from flavonoids, have the wider color range, with variations in scarlet, pink, purple, and blue. They have been divided into at least six major groups, and, among their functions, they help in protecting plant tissues against excessive irradiance, preventing chloroplasts from receiving high light intensities [23]. Betalains are found only in vegetables from the *Caryophyllales* family [24]. Divided in two groups, they are known to have colors ranging from red to violet (betacyanins) and from yellow to orange (betaxanthin) [25]. Carotenoids are the most common pigment in nature, ranging from yellow to red colors. Divided in two big groups - carotenes and xantophylls [26], there are more than 700 different known types of carotenoids [27]. Finally, chlorophyll pigments are known for their green coloration, since they absorb mainly red and blue light, so this light can be used on the photosynthesis process. Fig. 3, show examples of Anthocyanins, Betalains and Carotenoids, respectively.


(a) Anthocyanin (*Petunia hybrida*). (b) Betalain (*Portulaca grandiflora*). (c) Carotenoid (*Tagetes Patula*).

Fig. 3. Examples of Pigments.

C. Pattern Formation in the Plant Kingdom

There has been little research addressing visual pattern formation in the Plant Kingdom, even though the background genetics is well known [28]. A welcoming exception is the work by Korn [29] where an explanation for the stripped watermelon (*Citrullus lanatus*) skin is presented. Korn postulated that the Clonal Mosaic model [30] would be a possible candidate to explain such patterns. There are a large number of watermelon cultivars, estimated at more than 1200 worldwide, with variations on the basic stripped pattern, and even some examples without stripes at all. Korn advanced the idea that a pre-pattern of evenly spaced vascular bundles running longitudinally could be related to the dark green stripes seen on the watermelon skin. Korn elaborated on the similarities among the watermelon striping and clonal mosaic patterns, stating that "...developmental sequence described for watermelon has the important features of the clonal mosaic model for animal coat patterns" presented in [30]. In this paper we take this possibility ahead and explore the Clonal Mosaic model as a pattern generator for various structured and unstructured visual patterns in the Plant Kingdom.

IV. OUR MODEL

The advances in the Clonal Mosaic Model are the starting point for this investigation. For completeness, we briefly review it here. For more details we refer the reader to the original papers [30], [31]. The model assumes that the coat patterns for some mammals represent a spatial arrangement of epithelial cells - a Mosaic - where all pattern elements are derived from a single mother cell, and are therefore clones. The pattern results from the simulation of the interaction between cells of different types. The type of a cell defines its behavior in the system and although the model handles an arbitrary number of types of cells, for simulation of plant patterns we restrict to only two types which we call foreground (represented as F) and background (represented as B) cells.

The information attached to a given type is: color, division rate, probability for the cell to be of a particular type, probability for the cell to switch to another type (defined for every pair of types), and adhesion, which models the strength of repulsion among cells, and is defined for every pair of types (represented as α). The current implementation of the probability functions is context-independent.

Initially, a user-supplied number of random positioned cells is spread over the 3D model's surface. This possibility avoids the usual problems of texture mapping, such as distortions and the mapping itself, since the pattern is directly computed on the surface. The implementation assumes that the only forces acting on the cells result from cells maintaining their sizes under adhesion control. The mobility of cells is a response to these forces. Cell size is maintained by introducing a repulsive force between cells that depends on the distance between them and on the adhesion values. Equilibrium is reached by a relaxation scheme. Only cells within a given repulsive radius are considered neighbors. The repulsive radius is determined proportionally to the average ideal area for each cell and scaled by a user defined scaling value w_r. The rate of relaxation events is user controllable, and defines a day in the system. For each time step, we have ρ relaxation events. The relationship between ρ and the division rate models the relationship between cell subdivision and cell motion.

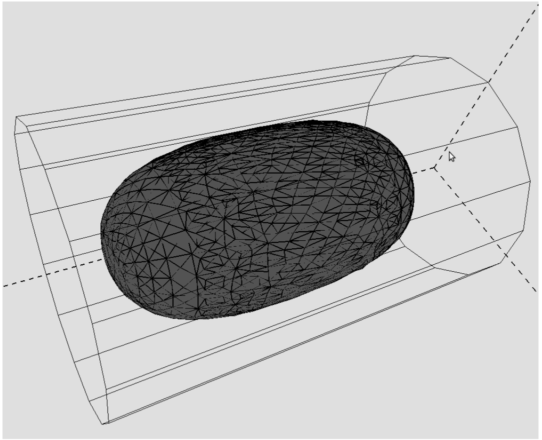

Fig. 4. Cylinder as control primitive.

During a division event one cell splits into two. We can think of these as *parent* and *child* cells. The child cell can be of a different type than its parent, based on a probability matrix given by the user. The child cell inherits all the attributes corresponding to its type. The position of the new cell is uniformly random within a circle of diameter arbitrarily chosen to be 1% of the repulsive radius centered at the position of the parent cell. The exact time for the division of a cell is given by a Poisson distribution with average equal to the rate of division for the cell. The Poisson distribution models small variations on the timing for mitosis, otherwise the cells would all split at the same time.

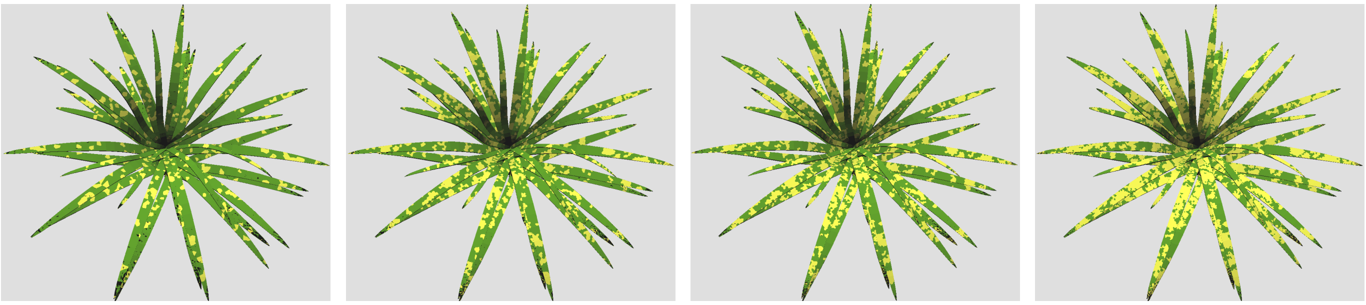

Fig. 5. Natural aging. From an almost green to an almost yellow *C. variegatum*. Total number of simulation days given by $5, 15, 20, 30$.

Cells are represented as points for computation. To turn cells into a tessellation of the surface, we compute their Voronoi polygons and use them for display purposes.

In order to provide local control during the simulation we can enclose the whole object being textured, or parts of it, by cylinders. For instance, some natural objects exhibit solid colors in some parts. We can use the control provided by the cylinder to prevent patterning in the polygons covered by it. The same cylinder can control many properties of the model with the help of images attached to the cylinder. For each vertex we compute cylindrical coordinates and use these to access the corresponding position on a image controlling a given feature. Fig. 4 shows a watermelon object and its control cylinder.

V. RESULTS AND DISCUSSION

In this section we illustrate the flexibility of the model for pattern generation and compare our results with techniques which could, in principle, be applied towards the same results. Our implementation is not yet GPU-friendly and therefore our results vary from few seconds to 35 minutes in some cases. In Table I we present the main parameters used. The final Clonal Mosaic pattern is expressed as a collection of Voronoi polygons. In order to color these polygons, each cell type will have an assigned RGB color which we hand-picked from images of the target fruit or plant.

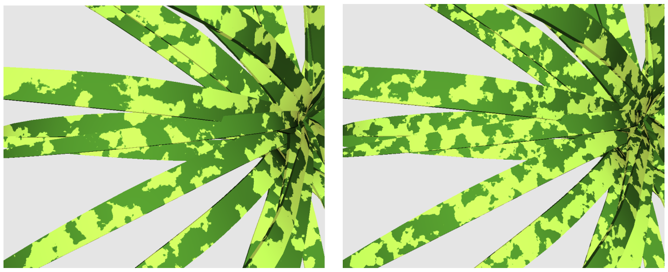

Fig. 6. Result applying noise and trying to simulate pattern evolution through time. Compare this with the result in Fig. 7.

In Fig. 1 we show side by side a real and virtual shrub known as *Codiaeum variegatum*. We can see that the procedural clonal mosaic texture is visually similar to the real pattern. The sequence in Fig. 5 illustrates another possible advantage of a controlled procedural technique. We can follow the development of the pattern through time, as the plant ages. In this sequence we show snapshots of the same simulation taken at increasingly number of days, from 5 to 30 days. The pattern changes from almost totally green to mostly yellow, mimicking the real aging of this plant.

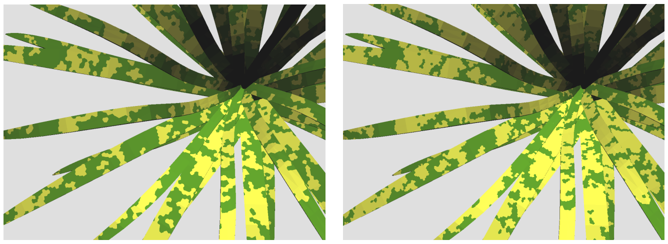

Fig. 7. Pattern aging through time with the Clonal Mosaic simulation. The group of cells defining a blotch expands its border consistently.

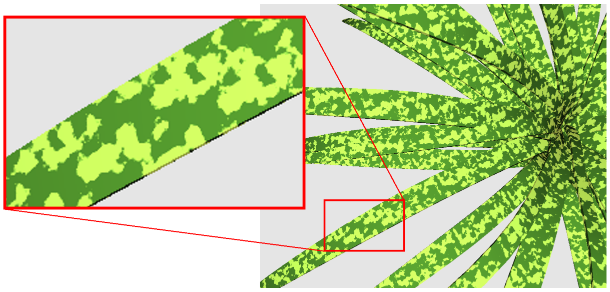

Fig. 8. Noise Repetition. Another potential drawback of using noise for the types of patterns addressed in our work.

Since the unstructured patterns are very irregular, we investigated how well we could generate some of the results with procedural Perlin Noise. While it is true that some results could indeed be generated this way, we noticed some limitations in procedural noise that our model does not have. Our approach based on cells allows a continuous and coherent growth of a group of cells, whereas with noise we do not have fine control over scale of the elements. This drawback is illustrated in Fig. 6 and Fig. 7. Increasing the scale of noise does not guarantee that contiguous areas will increase

TABLE I
VALUES OF PARAMETERS.

Figure	Days	w_r	Cells	α_{FF}	α_{BB}	Division FF	Division BB
Fig. 1	35	1.0	2000	0.5	0.8	10	10
Fig. 5	5-15-20-30	1.0	10000	0.5	0.8	5	10
Fig. 9	30	1.0	2000	0.5	0.8	10	10
Fig. 12	20	1.0-2.0-3.0	10000	0.5	0.9	5	10
Fig. 10	20	0.5	10000	0.5	0.9	5	10
Fig. 11	20	0.5	10000	0.5	0.9	5	10
Fig. 13	20	3.0	6000	0.7	0.9	6-8-20	8

Fig. 9. Individual visual variation provided by the model.

consistently, as they do in the Clonal Mosaic result.

Another potential drawback of procedural noise is the repetition of elements. In Fig. 8 we illustrate this problem where the same irregular yellow blotch repeats itself. This effect is distracting and highly noticeable. The Clonal Mosaic patterns do not show this same problem.

One advantage of procedural models is their power to generate many individual variations of the same pattern. In Fig. 9 we illustrate this possibility with three unique individuals of the same *C. variegatum* species. They all share the same simulation parameters, but with different seeds for the random number generator.

The second set of examples uses the watermelon as target object. Fig. 10 illustrates a more common type of spherical watermelon whereas the result in Fig. 11 shows an exotic and expensive type known as square watermelon, mainly grown in Japan by letting the fruit develop inside a glass box. From these two examples, we can see that the Clonal Mosaic patterns adapt easily to different geometries.

Fig. 10. Spherical watermelon.

Fig. 11. Example of cube watermelon.

As previously mentioned, watermelons present a great variation in appearance. A procedural model can easily handle, for instance, stripes of various widths, as exemplified in Fig. 12. For these results, we used an increasing value for the weight of the repulsive radius, since a higher radius allows more cells in the neighborhood computation. For all watermelons results, we used an image with stripes attached to the control cylinder. This image, illustrated as an inset in the leftmost watermelon in Fig. 12 defined the spatial position of initial stripes on the watermelon's surface. The sequence in Fig. 13 illustrates the pattern on a type of fungi known as *Amanita muscaria*. These do not belong to the Plant Kingdom, but nevertheless we show that Clonal Mosaic patterns can also be used in this case. This result also illustrates the use of cylinders to control the final pattern. A texture map was used to control where cells could

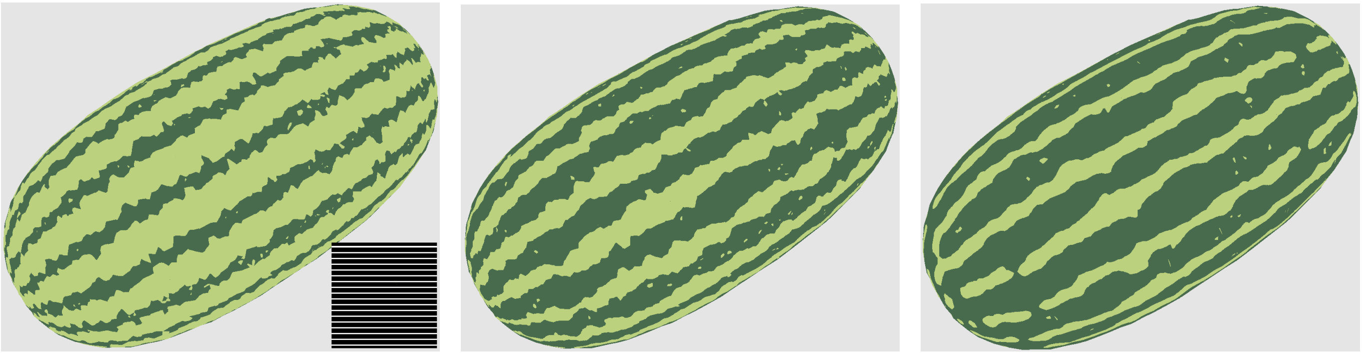

Fig. 12. Example of watermelon *Citrullus lanatus* with increasing width for the stripes.

Fig. 13. Variations for the red mushroom *Amanita muscaria*. The black and white inset in the first virtual mushroom shows the texture map used to create cells only in the mushroom's head.

be created, only in the mushroom's head.

VI. CONCLUSIONS

In this paper we explored the potential of the Clonal Mosaic model as a procedural engine for synthesis of visual patterns in the Plant Kingdom. We illustrate the potential of the model with results for two-color structured and unstructured visual patterns such as stripes on watermelons and irregular blotches on plants. We consider these results evidence that the Clonal Mosaic model is a good candidate to render visual patterns in the Plant Kingdom, but much more is needed. We have to extend the investigation to account for more than two color patterns and other more complicated pigment distribution as seen in some flowers. Another possibility is to couple the pattern formation process with the growing of the fruit or plant, allowing a dynamic patterning mechanism governed by growth data.

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