Swarm Grammars - A New Approach to Dynamic Growth

Sebastian von Mammen, *Evolutionary & Swarm Design Group*

Abstract— **In this paper we present a new approach to dynamically breed artificial structures. By embedding swarm agents into the framework of formal grammars we build a bridge between symbol-based production systems and three-dimensional, real-time construction procedures that are driven by moving, reactive, autonomous agents. In a small number of simulations we focus on the swarm agent abilities to coordinate with one another, and to respond to the environment. First results allow for a cautious, yet optimistic look at possible fields of application and future work.**

I. Introduction

The key to many successful complex systems, such as neural networks, lies in their artful way of organizing their inherent interdependencies. However, the more parts of a system play together, the more difficult becomes its design. Thus, engineering a system of high complexity easily results in tremendous efforts to solve conflicts and to (re-)gain the desired synergetic properties.

Conventionally engineered products, such as cars, can be a good example for this overwhelming challenge (see [1]). Even though the steadily growing number of parts (sensors, motors, safety devices, etc.) can be considered rather effective in regard to their very own purposes, the subsequent growth in complexity leads to a significant increase in failures of the overall systems.

We assume that when reaching a specific level of complexity, even with sophisticated means of consolidation (see the broad area of *Software Engineering*), we might not achieve the necessary clarity to spot and resolve all possibly arising conflicts. Also, we might not be able to create the synergetic effects or properties that we are aiming for. However, by the introduction of *controlled* and *intelligent growth*, we might overcome these flaws. Control of growth is necessary, since the resulting structures have to fulfill specific constraints in order to serve their purposes. By intelligent growth we address to the task of incorporation of dependencies between the different parts of a structure as well as between the structure and its environment.

Inspired by the great interaction capabilities of *artificial swarms* (for example in [2]) and the beauty of structures exhibited by *l-systems* [3], we developed a swarm- and grammar-based system that creates three-dimensional structures. These *swarm grammar* systems cover both, dynamic growth that is directly linked to its environment (including the swarm agents themselves), and controlled structural growth by organizing the swarm via a formal grammar.

The paper is structured as follows. After an exemplary description of the implemented swarm grammar system, we show results regarding different sets of production rules, different flocking parameters of the swarm agents, and the interaction of a swarm grammar system with the environment. We conclude with a summary and possible aspects of future work.

II. Description of a Swarm Grammar System

As mentioned above, swarm grammar systems (or shorter swarm grammars) require swarm agents on the one hand, and a formal grammar on the other hand.

A. Swarm Agents

A swarm agent is represented as a pyramid indicating the direction of its velocity by its orientation. All agents that are within the field of view of a particular swarm agent are called its *neighbors*. Throughout this paper the field of view is defined as a cone of a length of 3.5 length units and an angle of 2.0 degrees radians. By adjusting the velocity of an agent in accordance with its neighbors, flocking formations emerge. In conformity with the *boids* model [4], the basic urges of a swarm agent comprise *alignment* towards the average direction of the neighborhood, *separation* from some of the neighbors (if the distance is below a threshold constant called *crowding*, see [2]), and *cohesion* towards the average position of the neighbors. In addition, some randomness in the change of velocity as well as an urge towards the simulation center are thrown in. The different urges are weighted and summed up to form the acceleration of an agent. The values of acceleration and the velocity are limited by given constants. Obviously, the assignment of different sets of parameter values yields various agents.

B. Grammar and Building Process

Now, consider an agent of a specific configuration a symbol of a deterministic, context-free grammar. Without a differentiation between terminal and non-terminal symbols, production rules are directly applied to an agent, whereas one agent is simply substituted by the symbols/agents introduced by the head of the applicable production rule. A start symbol has to be provided, so that the simulation knows with which agent to start. The simulation terminates when the agents run out of energy that is passed on from one agent generation to the next and which is converted into parts of the built 3D structure. In Figure 1 you see the basic building process that is performed by a swarm agent. After a number of iterations a swarm agent would build a cylinder reaching from the last checkpoint on its route (dashed line) to its current location, whereas the new location would become the new checkpoint.

In our simulations we diminish the radius of the cylinder analogously to the energy level of the swarm agent which is not indicated in Figure 1. If another number of iterations is reached, a last cylinder is immediately built to the current location of the swarm agent and it disappears, making way for its successors. The counters for both, the building process and the production of rules are reset after reaching their predefined limits.

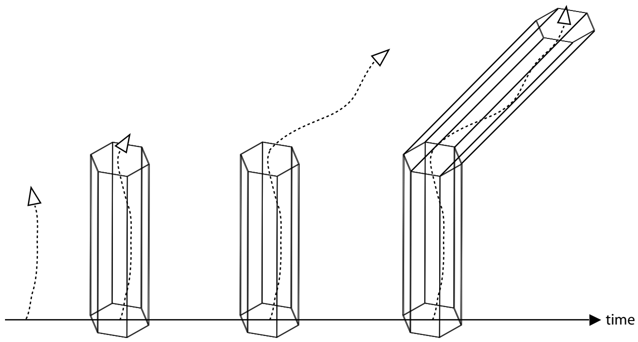

Fig. 1. Swarm agent building cylinders along its flight route.

C. Formally Spoken

All in all there is a set of swarm agents whose individuals are addressed as symbols of a formal grammar and which are defined by a field of view, weightings for various acceleration urges and constants to keep the acceleration and velocity values in check. Starting with one agent for one construction, a set of production rules of a deterministic context-free grammar repeatedly defines the successors of an agent. Finally, there are constants that determine when a construction element is built, when a production rule is applied, how much energy is lost by the creation of a construction element, and when the agent has run out of energy and cannot reproduce itself anymore.

III. Basic Structures

In this section we shed light on the effects that emerge when modifying the production rule set of a swarm grammar on the one hand, and of the integrated flocking parameters on the other hand.

A. Modifications of the Production Rule Set

We first present several different tree-like structures that stem from various sets of production rules. Only a fairly limited number of specific swarm agents is used to allow for focusing on the effects of the production rules.

Consider the swarm agents A, B and C which are all steadily driven upwards and additionally take the urge of separation and some random movement into account. The corresponding flocking weights are shown in Table I. Various tree-like structures can be produced by the application of different sets of production rules, as seen in Figures 2, 3, 4, 5, and 6.

TABLE I

Flocking parameters of agents A, B and C.

Agent	*Separation*	*Random*
A	0	0.01
B	1.7	0.01
C	13.7	0

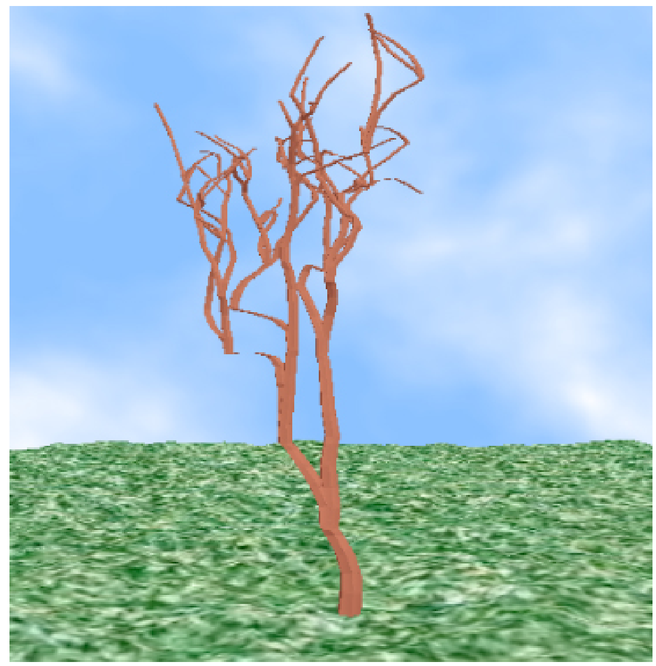

Fig. 2. $S = A, P = \{A \rightarrow AB, B \rightarrow A\}$.

The swarm grammar shown in Figure 2 with the grammatical description $S = A, P = \{A \rightarrow AB, B \rightarrow A\}$ results in a structure that gives a relatively spindly impression, thus being easy to analyze. The spontaneous looks of the branches can clearly be derived from the small degree of random movement which is inherent in both agents, A and B. All ramifications follow the same scheme: when they are created, agent B moves away from agent A due to its urge for separation, whereas agent A is mainly driven upwards. The branches are formed correspondingly.

Compared to the structure in Figure 2 the one in Figure 3 has a massive branching factor culminating in an eye-catching crown. The production rule $A \rightarrow ABA$ suffices to challenge the computational resources of the simulation by exponential growth in its literal sense. The small green bits in the tree tops are swarm agents that could not finish their constructional task before the process had to be cancelled.

A structure of another kind is presented in Figure 4. Here, the complexity arises from very few but bursting productions. The general impression of impulsive growth stems again from the random movement of agent B.

Even though the major production rule of the swarm grammar represented in Figure 5, namely $A \rightarrow BBBABBB$, creates a large number of agents, the outcome is quite simple. The second production rule, which is $B \rightarrow \emptyset$, takes care of

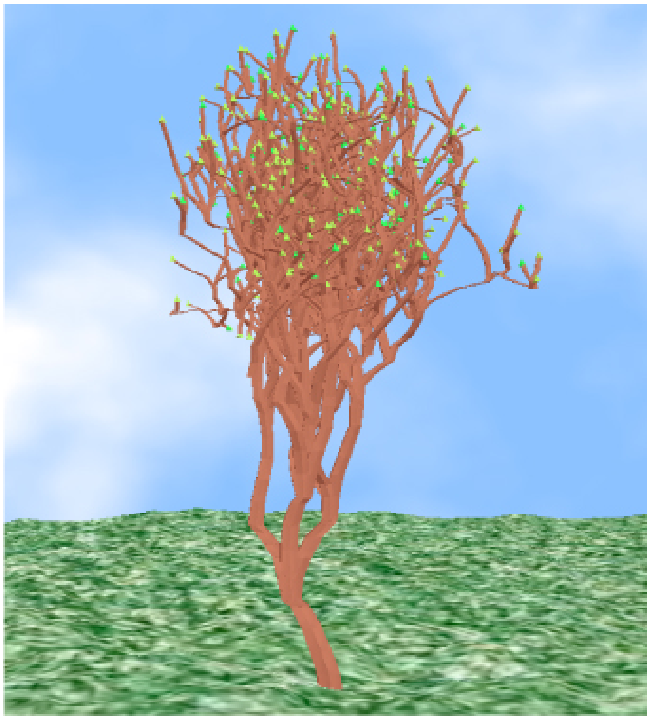

Fig. 3. $S = A, P = \{A \rightarrow ABA, B \rightarrow A\}$.

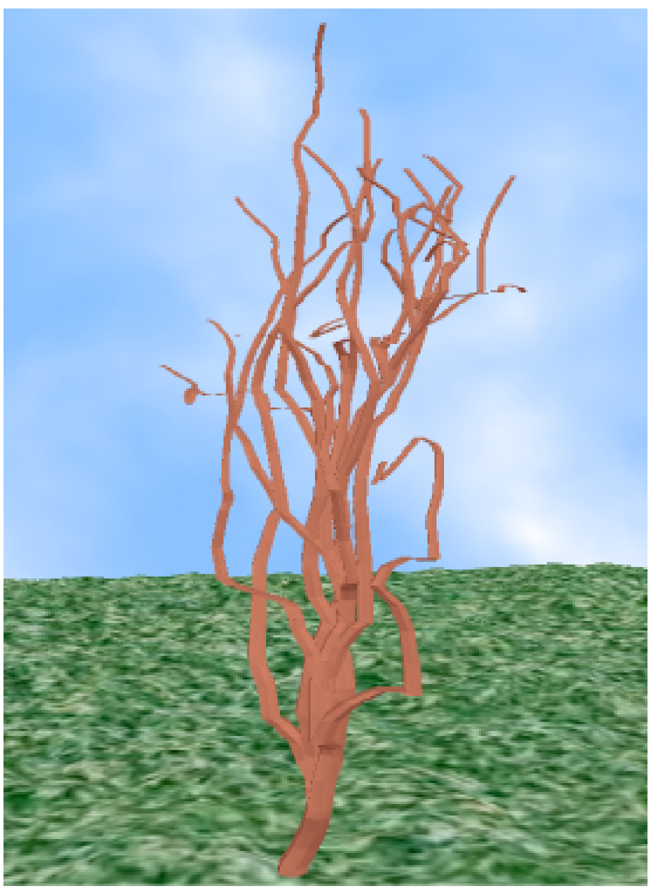

Fig. 4. $S = A, P = \{A \rightarrow BBBA, B \rightarrow A\}$.

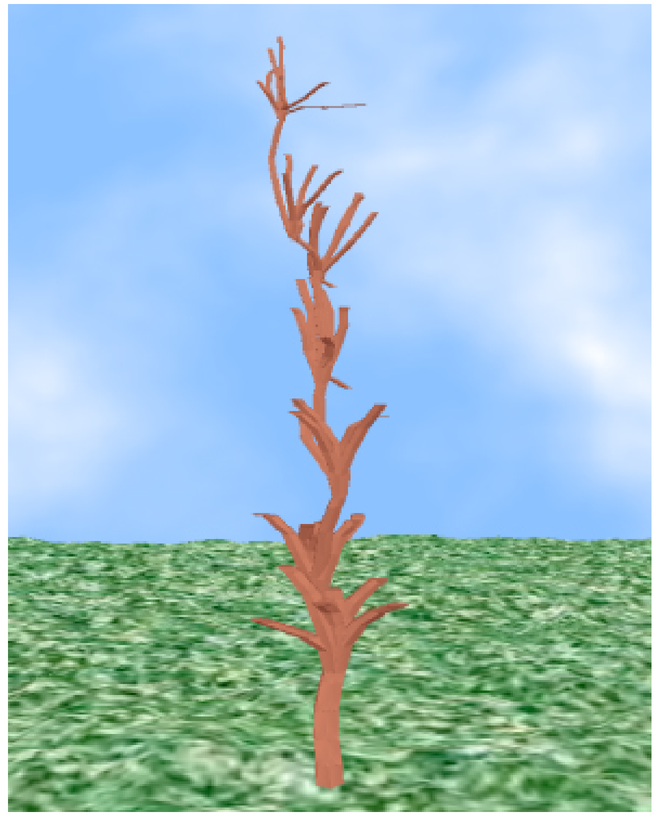

Fig. 5. $S = A, P = \{A \rightarrow BBBABBB, B \rightarrow \emptyset\}$.

removing all B agents at the next opportunity.

In Figure 6 three agents come into operation. In addition to A and B, agent C come into play which has an even higher priority on separation than B. Also, opposite to both hitherto employed agents, C has no randomness in its movements but is mainly driven upwards.

B. The Influence of Flocking Parameters

In contrast to focusing on the effects that spring from the underlying production rules of swarm grammars, we now have a look at modifications to the flocking parameters. That is why the simplest rule set possible, $P = \{A \rightarrow AA\}$, is chosen which includes the aspect of branching, so several agents appear in the simulations. The provided rule implies that all swarm agents in one simulation realize the same set of flocking parameters. In [2] several sets of flocking parameters were evolved that result in interesting swarm formations. Three rather deviating swarm configurations, listed in Table II, are used to illustrate their significance in regard to the resulting structures. Figures 7, 8, and 9 show the pure flocking behaviors that emerge when the parameter sets (1), (2) and (3) of Table II are applied. At the same time, each of the figures includes a screenshot of the structures that grow when these swarm formations are used in the outlined, simple swarm grammar. Unlike in the swarm grammars that were presented before, the swarm agents do not follow a general upwards urge anymore. In order to see the flow of construction in the static pictures, we colored the

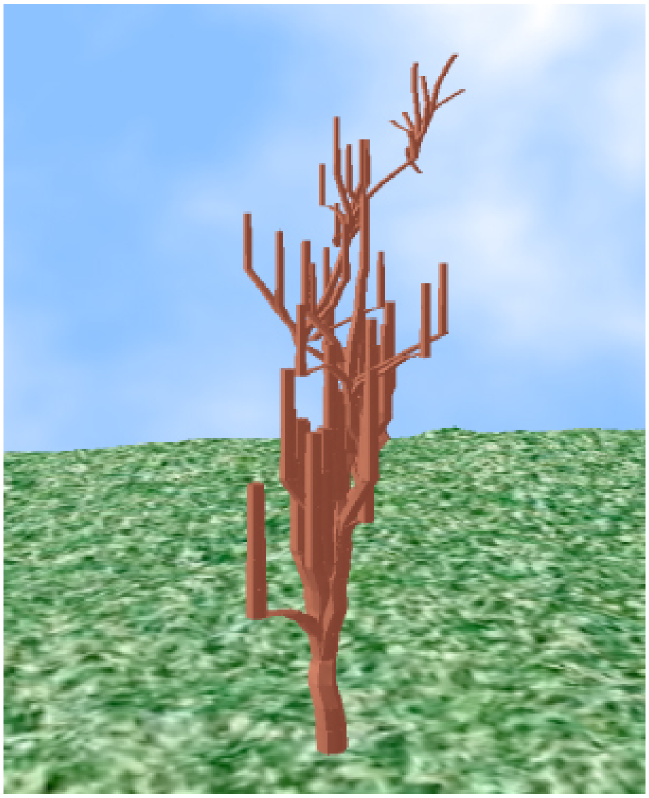

Fig. 6. $S = A, P = \{A \rightarrow BBBABBB, B \rightarrow C, C \rightarrow \emptyset\}$.

construction elements according to their age - the lighter the color, the earlier it was built.

TABLE II

FLOCKING PARAMETER SETS THAT LEAD TO: (1) THE SO-CALLED LARGE RING FORMATION, (2) A LINE FORMATION, (3) A LOOSE STATIONARY CLUSTER SWARM, AND (4) A MESSY FIGURE EIGHT FORMATION.

	(1)	(2)	(3)	(4)
Separation	1	5	5	2
Random	1	5	6	3
Alignment	5	7	2	7
Cohesion	10	8	0	3
World Center	14	8	7	6
Crowding	0.14	0.14	0.23	0.01
a_{max}	39	38	40	40
v_{max}	9	13	6	6

The second image of Figure 7 shows a structure that is spherically spanned around the world center of the simulation. The large ring flocking contributes to a somewhat loose and impulsive character of the formed structure.

The construction presented in Figure 8 does not exhibit any branching at first sight. However, this illusion originates from the almost perfect flight coordination of the swarm agents. Looking closer at the u-turn in the upper right-hand side of the image reveals a gap in the construction. This is a result from multiple agents that build a very similar, but

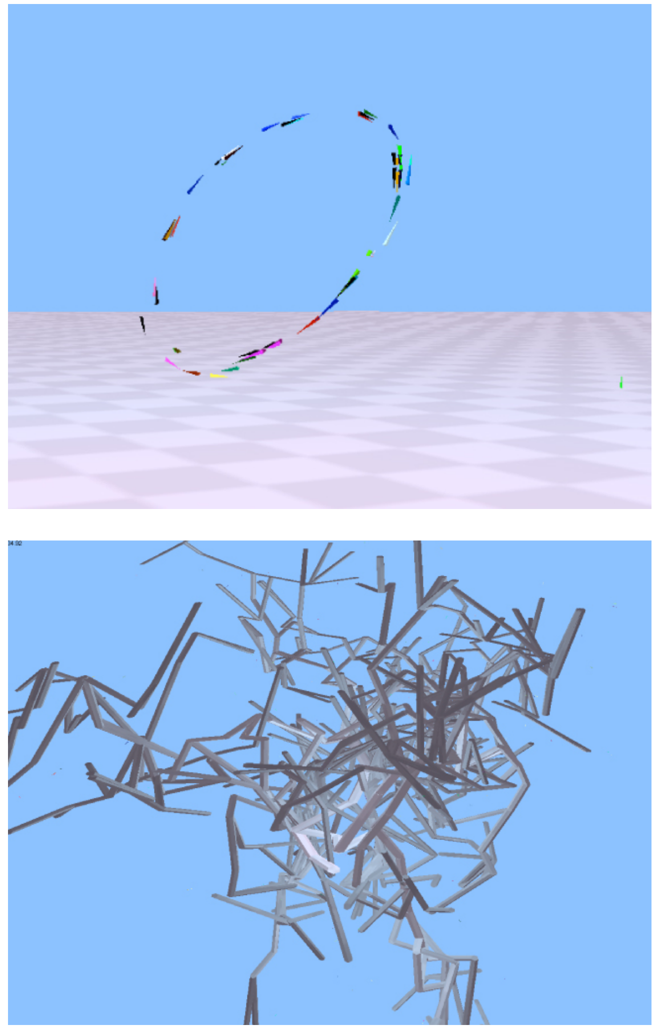

Fig. 7. Above: a large ring formation of a swarm. Below: the corresponding construction, only applying the production rule $A \rightarrow AA$.

not identical fibers at the same time. For large parts of the structure there is a smooth course of construction. Yet, there are spontaneous and forceful turns once in a while, 4 times in the presented picture.

Our last example for the impact of flocking parameters on the outcome of swarm grammars is based on a so-called loose stationary cluster formation, see Figure 9. The cluster formation of the swarm agents is directly reflected by the big lumps at the bottom of the picture. Since the flocking parameters allow for a rather dynamic flight, single agents can leave one swarm cluster and join another one at some other location. This might be the reason for the large contiguous, almost circular structure at the right-hand side of the picture.

IV. Interaction with the Environment

Artificial swarms can easily be designed to interact with their environment. In this section we present three kinds of interactions with static or dynamic elements of the environment. In Table III the flocking parameters of the employed

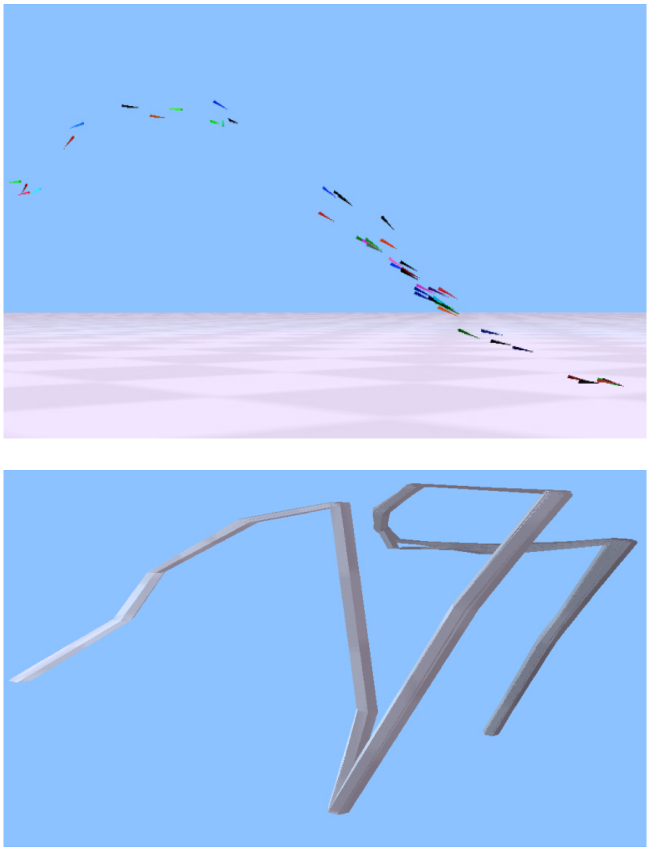

Fig. 8. Above: a line formation of a swarm. Below: the corresponding construction, only applying the production rule $A \rightarrow AA$.

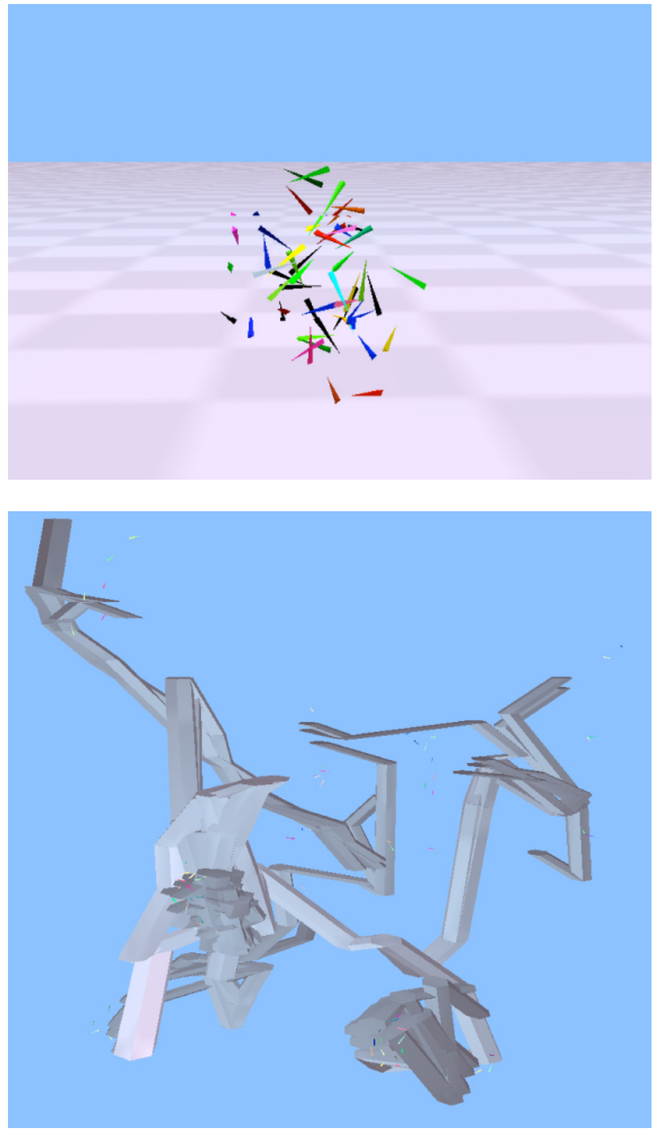

Fig. 9. Above: a loose stationary cluster formation of a swarm. Below: the corresponding construction, only applying the production rule $A \rightarrow AA$.

agents are listed. Production rule sets as well as special features of the simulations or swarm grammars are mentioned where applicable.

Figure 10 shows an example of interactions with non-moving objects in the environment. All employed agents, F, G and H tend towards the world center, which is a location beyond the wall and far up in the sky (like a sun). However, as soon as a swarm agent tries to penetrate the wall it bounces back (by an immediate reversal of the x and z components of the acceleration-vector of the agent, and an impulse into this newly set direction). After the structure has outgrown the wall, the swarm agents are not prevented anymore from moving towards their destination.

As soon as the world center becomes dynamic, its movement is reflected in the construction of those swarm agents that tend towards it. This can be seen in Figure 11, where the world center orbits the y-axis of the simulation far up in the sky. Since both involved agents, D and E, tend towards the world center, the picture reveals a circular, upwards screwing structure. In order to better recognize the construction elements of the different agents, D was assigned a very light, and E a darker color. As D does not feel the urge to separate from its neighbors, it almost perfectly forces up around the y-axis. The constructions of E outgrow the ones of D since E is allowed to have a greater velocity value.

Finally, we show how interaction from and into both ways might work. In the previous examples, the swarm grammar agents were the only ones influenced in their movements. Now, consider a second swarm that is not part of a swarm grammar, but is just flocking in the environment. Both swarms would influence each other as soon as some of their individuals dropped into the field of view of the other swarm agents. In regard to the swarm that does not build anything, this effect can hardly be captured in a screenshot. However, the swarm grammar agents witness the exertion of influence of the other swarm by leaving a trace in 3D. The first image of Figure 12 shows the structure that would be built by the swarm grammar (only comprising agent I), if no other swarm was around. The movement of agent I is not driven by any randomness, so that any deviation from the presented structure has to be seen as the result of other external factors. The second image of Figure 12 displays a scene where the interaction between just flocking and swarm grammar agents is still in progress. The blue pyramids represent agents that organize their flight in a “messy figure eight formation” - their parametric description is again taken from [2] and listed in Table II. During the course of the simulation a completely different structure emerges. Also, during run-time, the influence of the swarm grammar agent on the other swarm is obvious: as long as the swarm grammar agent is present, there is a very high probability of the other flock-mates encircling agent I.

TABLE III

FLOCKING PARAMETER SETS OF AGENTS D, E, F, G, H, AND I.

	D	E	F, G, H	I
Separation	0	10	80	33
Random	10	2	4	0
Alignment	0	0	10	11
Cohesion	0	0	0	10
World Center	10	1	1	5
Crowding	0	10	10	1
a_{max}	30	30	10	27
v_{max}	2	5	4	2

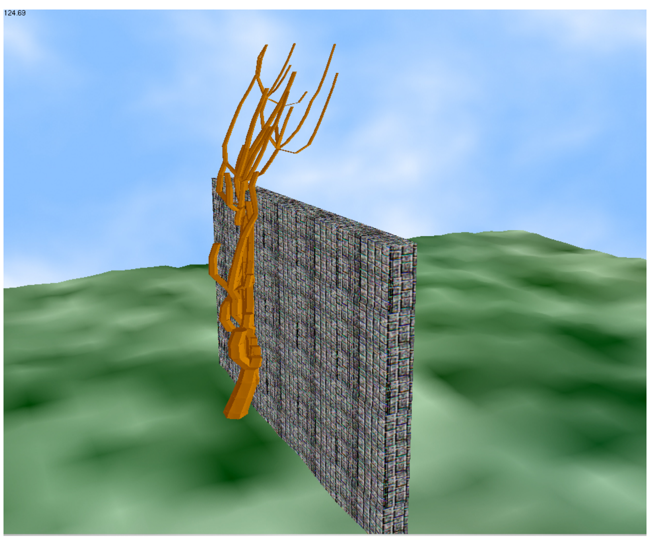

Fig. 10. $S = F, P = \{F \to GHFGH, H \to G, G \to \emptyset\}$.

V. SUMMARY

Organization of sets of swarm agents by using deterministic, context-free grammars, enables us to transfer the connectivity which is inherent in rewriting systems onto structures that are created by swarm coordination. The underlying grammar has a tremendous effect on the resulting topology, whereas the employed swarm features determine the overall looks of the construction. However, sometimes both parts of a swarm grammar are intertwined to such a high degree, that the single contributions cannot be clearly narrowed down, see for example Figure 8.

Swarm agents have a natural capability to cope with contexts: by consideration of global urges (such as the

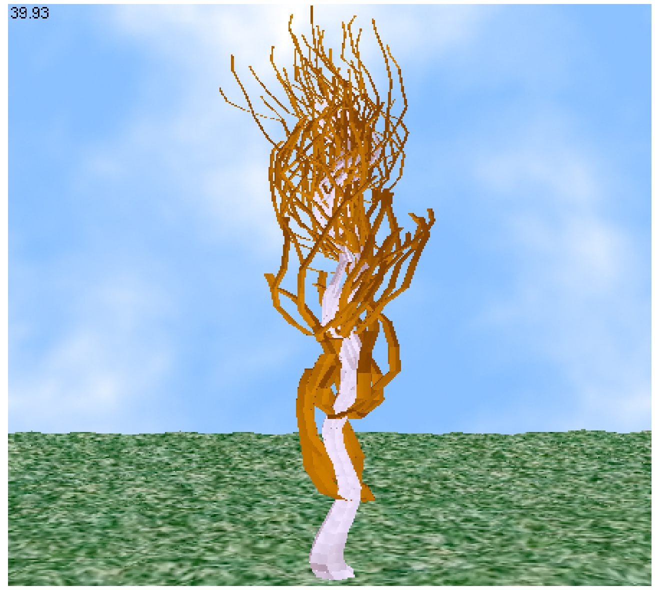

Fig. 11. $S = D, P = \{D \to EDEDE, E \to \emptyset\}$.

“world center”), or through reaction on their perceived neighborhood. Stepwise, we led through simulations that consider attracting or repelling objects of static or moving nature. The given examples hint at the great potential swarm grammars might have to grow controlled and yet intelligently, as explained in Section I.

The specific model of a swarm grammar that we used throughout this paper, in which swarm agents on top of a branch direct the growth of three-dimensional structures, strongly reminds of the development of plants (see, for example, [5]): the growth of *coleoptides* of grasses is steered by processing signals that are sent from the tip of the shaft (using the pheromone *auxin*).

VI. FUTURE WORK

There are a lot of possibilities to continue the development, and to start the application of swarm grammars. After an outline of potential improvements and extensions in regard to the presented swarm grammar system, we conclude with more general ideas about the concept of swarm grammars.

In the presented simulations each swarm grammar agent counts the number of iterations that have passed since its creation. After a predefined value is reached, the agent would ask the grammar to be removed and substituted. There are at least two extensions possible in this situation. Firstly, the “branching constant” could be included into the parameters of each swarm grammar agent. This would allow for a greater diversity of swarm agents, not to mention the increasing number of possible structures to be built. Secondly, an extension might be useful, where the application of production rules is dynamically triggered by reflective agents. This would boost the spectrum of imaginable interactions between the agents, their simulation environment, and an external user.

Different from the concept of swarm movements that we acquired from [4] and [2], one could imagine individuals that

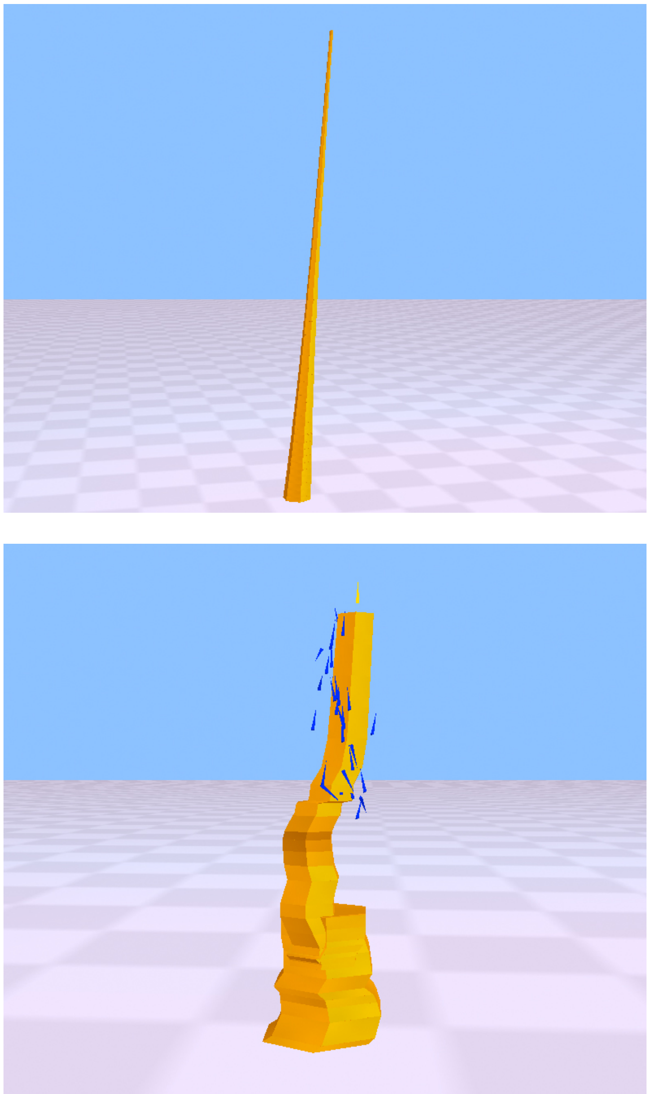

Fig. 12. Above: Agent I, described in Table III, working on its own ($P = \{I \rightarrow I\}$), with a high tendency towards the "world center" which is far up in the sky. Below: Agent I is guided by 30 agents that fly in a "messy figure eight formation" (see Table II).

can only travel on the ground (such as ants), or individuals that can only perform right-angled turns, for example when breeding conductor paths. For such applications, it might also become important to change the three-dimensional representations of the single construction elements that are glued together.

A very small step to soar the expressiveness of the swarm grammar would be the introduction of non-deterministic production rules. Paired with the randomness in the flight patterns of some agents, this would be a great opportunity to foster the organic look of the bred structures. As seen in Section IV, swarm agents that do not build structures also contribute to the accomplishments of a swarm grammar. Therefore, the alphabet of a swarm grammar should be extended to comprise non-building individuals, too.

In general, addressing agents of any kind as symbols of a formal grammar provides a broad scope of defining hierarchies on multi-agent systems. The use of the resulting connections can alter depending on the application: to create visual manifestations of structures, communication structures, or structures that define an order/report hierarchy. In the presented scheme, the active swarm agents are substituted after some iterations. But of course, grammars could also be used to reorganize the interdependencies of a fixed number of agents.

All in all, swarm grammars represent an approach to grow complex networks. They can, of course, be represented as a small set of symbols, and hence be seen as a *generative DNA*. In accordance with the analogy of the previous section to the growth of grass, we would classify the organizational level of swarm grammars to be one level above cell division, enlargement and differentiation.

Acknowledgments

Christian Jacob mainly inspired the idea of the incorporation of formal grammars and swarm systems. Endless dialogs with Marcin Pilat and Navneet Ballah encouraged the investigation of growth and complexity. Lance Hanlen hinted at the connection between swarm grammars and the pheromone-driven growth in plants. Jon Klein contributed indirectly to this work by providing the simulation software *breve* in which all the presented results were produced, see [6]. Thank you all!

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