The Map and the Flock – Emergence in Mapping with Swarm Algorithms

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Abstract

In mapping for computer music and interactive media, flocking algorithms represent a special case, offering dynamic, self-organised domain translations. In this article we attempt a classification of fundamental mapping relationships that can be established with the help of swarm simulations. By regarding flocks as systems of abstract entities, a number of models arise that deal with the re-assignment of perceptual and semantic qualities to the simulated entities. These models represent basic mapping processes, but become domain-specific when used for music and interactive art. To illustrate these concepts, we outline a number of strategies that relate to musical practice, fostering an understanding of the role of swarm simulations in mapping. We show two artistic use-cases where these concepts are applied in an exemplary manner. In the first artwork, swarms play a central role in the compositions presented in an audio-visual installation, and serve as intermediate translation space between audience and artwork. In the second realisation, swarms interact with dancers and together they control the visual and musical aspects of the piece. Both examples show how the emergent behaviour of flocks can be mapped conceptually and evoke natural phenomena, thus making the mapping relationships less predictable and more organic.

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Flocking algorithms are an important class of rule-based emergent systems that enable the exploration of life-like behaviours and structures. The algorithms represent abstract formalisms that need to be translated into a perceivable output in order to become accessible to a human audience. This translation, be it visual, musical, or physical, forms an important part of the artistic process. In the case of flocking algorithms, this task needs to be approached by posing the classic mapping questions of how to generate coherent output appropriate for the emergent behaviour displayed by these multi-agent systems. In many applications, an additional layer of mapping is necessary, when the flocking algorithm is exposed to some kind of control, either from a direct human-computer interaction or some other form of significant data originating from outside the simulation.

Conceptually, a flocking algorithm can fulfil different roles in a generative system. It can either be the source of all activity as well as generate the main constitutive shapes and behaviours of a work, or it may represent an intermediate step in a system that is governed by other principles of control. In the latter case, the flocking algorithm transforms input from a control domain to a target domain and hence functions as a mediation layer in the mapping system. Swarms offer the ability to decouple low-dimensional parametric inputs from higher-dimensional target domains such as synthesis processes, sound spatialisation systems or symbolic structure generators. Finally, flocking algorithms may also be regarded as a means of translation on a conceptual or perceptual level, where the intrinsic qualities of the emergent behaviour of a swarm evoke or allude to phenomena normally occurring in the domain of natural experiences.

In the following article, we wish to discuss the potential of these algorithms and their application from both a conceptual and practical point of view. We attempt to explore the concepts systematically, based on the insights obtained as the result of artistic realisations and developments that took place within two research projects. In order to ground these concepts in real artistic applications, the experiences gained by applying flocking algorithms are discussed with the aid of two exemplary use-cases.

Background

The adaptation of scientific simulation techniques as generative mechanisms, which control the creation of music and image, provides a vast field for artistic experimentation (Dorin 2001; Galanter 2003; McCormack 2003). Of particular interest are simulations that model complex natural phenomena. Such phenomena are characterised by a structural organisation, which emerges from processes of self-organisation and combines regular and chaotic properties. These characteristics establish on a metaphorical level a proximity to the aesthetic principle of balancing order and disorder. It is through a simulation-based abstraction that a similar proximity can be established on a formal and operational level. In this context, biological phenomena are of special interest as they exhibit a particularly high level of complexity. Algorithms that model these phenomena are often derived from research in the field of artificial life, where their development forms an important part of the scientific methodology.

A classic example of such an algorithm is flocking simulation (Eberhart et al. 2001). These simulations were originally invented in order to model the coordinated movements within large groups of individuals such as flocks of birds or schools of fish. Such simulations operate by formalising biological organisms as abstract entities, so-called agents, whose properties and behaviours are implemented as vector quantities and distance-based mathematical transformations. It is the characteristics and flexibility of these formalisations that render flocking simulations useful for musical and artistic applications. Accordingly, swarm simulations enjoy a high level of popularity in algorithmic music and generative art, and their application has been explored by numerous artists such as Blackwell and Bentley (2002); Blackwell and Young (2004); Boyd et al. (2004); Shiffman (2004); Ramos (2004); Uozumi (2007); Uozumi et al. (2008); Davis and Karamanlis (2007).

It may be tempting to use swarm simulations or any other type of scientific simulation as a generative "ready-made", whose numerical output is post-processed in some manner in order to meet the particular requirements of a musical and visual method. However, such an approach falls short of transforming a simulation into an artistic tool that informs the conception and realisation of a work on a more fundamental level. Rather, this approach imposes the scientific context, within which the simulation was originally developed, onto an artistic work and thereby leads to a naïve confusion of scientific and artistic motivations. The main assertion of this article is that the planning and realisation of mapping relationships between a simulation and a musical or visual form are an important part of the translation of concepts and mechanisms that were originally situated outside of the arts into integral elements of artistic creation.

Mapping Concepts

Any simulation represents a computer-based operationalisation of functional relationships among highly abstract syntactic entities. While a simulation is meant to maintain the structural and behavioural aspects of a natural phenomenon on a formal level, it is semantically and perceptually entirely disconnected from said phenomenon. In a broader sense, the design of mapping strategies using flocks deals with the re-assignment of outside perceptual and semantic qualities to the simulated entities. Accordingly, the realisation of a generative artwork that provides a meaningful experience involves the central task of establishing mapping mechanisms, which exploit the syntactically powerful but perceptually indeterminate characteristics of a simulation.

Fundamental Relationships

An arbitrary number of mapping strategies exist that permit to relate aesthetic qualities of an artwork to simulation-based processes. The following paragraph attempts to organise this space of possibilities into a limited number of fundamental categories. These categories are specified in an extremely abstract and generic form in order to make them applicable to a wide range of simulation-based music and art forms. In addition, the categories are not mutually exclusive. The practical examples of swarm music relationships that follow in the latter part of this article demonstrate several of these fundamental mapping relationships at the same time.

Formal Relationships deal with the establishment of correspondences between simulation-based processes and computational mechanisms that underpin the creation of music and image. The simplest form of a formal relationship deals with the selection and application of the numerical output of a simulation in order to control specific parameters of a rendering process. This numerical data is usually mathematically transformed in order to match the number, range and dimensionality of the target parameters. Simple mathematical transformations such as scaling or the application of transfer functions preserve the continuity and dynamics of the simulation's numerical output. In this case, the continuity can be used as an aesthetic principle that causes an analogous continuity and dynamics in the behaviour of the rendering mechanism. If, on the other hand, the simulation produces numerical output at intermittent intervals or if this interval is created through mathematical discretisation, for example by applying thresholds, the numerical input to the rendering algorithm gains the characteristics of an event. These events can subsequently serve as triggers to create discrete perceptual events.

A different and more sophisticated category of *Formal Relationships* deals with the establishment of an organisational similarity between a simulation and a rendering mechanism. Such a mapping could for instance be based on the assignment of spatial properties to elements in both the simulation and rendering mechanisms. This assignment transforms the elements into components of a shared spatial organisation that relate to each other based on proximity criteria. An alternative form of mapping arises from the transfer of hierarchical organisations from the level of the simulation to that of the rendering system. Such an approach is possible if both the simulation and the rendering system use modular components, which are organised in tree-like graph structures or other forms of hierarchical groupings.

Ontogenetic Relationships are based on the assignment of identical properties and behaviours to the elements in both the simulation and the rendering system. Accordingly, these elements can be considered to represent entities, which exist at the same time in the simulation and rendering environment. A simple example of such a mapping would assign to each simulated object an equivalent object in the rendering system. As a result, formally discernible objects in a simulation can be transformed into perceptual objects. A similar form of mapping applies such equivalence to a group of elements. By doing so, group specific qualities of homogeneity or diversity can be translated into analogous qualities of a perceptual mass or cloud. The strongest form of ontogenetic relationship is established by matching the modelling characteristics between the simulation and rendering system. In this case, the simulation and rendering system merge into a single system. As a result, the simulated elements and processes become inherent parts of the rendering system and thus contribute to the perceptual result.

The establishment of a *Conceptual Relationship* between a simulation and an artwork helps to situate the simulation as an integral part of an artistic idea. Such a relationship emerges for instance by abstracting an artistic creation process to such a degree that it becomes comparable to the formal characteristics of a simulation. As a result, a simulation is applied as a synthetic mechanism that embodies aspects of an artist's compositional strategy. Alternatively, a conceptual relationship may be established through the opposite approach. Such an approach assigns metaphorical connotations to the simulation and transfers it to the domain of affinity that is connected to a familiar artistic experience (Lakoff and Johnson 1980).

Interaction Relationships provide a simulation with the means of sensing and responding to a physical gesture in such a way that a subsequent transformation through the rendering system gives rise to a perceivable feedback. This type of relationship complements the traditional mapping between simulation and rendering with an additional step that relates the output of a sensory system to properties and processes, which are intrinsic to the simulation (see figure 3). The dynamics of gestural activities manifest themselves across the first mapping step as a perturbation of the simulation's internal dynamics. This perturbation emerges eventually through the second mapping step as a form that is part of the generated aesthetic result.

Finally, *Ecological Relationships* serve to establish a shared space within which the perceptual and behavioural properties of simulated entities and humans overlap and interrelate. Such a situation resembles an ecosystem in the sense that the activities of its various inhabitants become part of dense network of causal relationships. The flexibility and openness of this mutual engagement needs to be defined through the design of specific ecological relationships (Gibson 1986).

Mapping Swarms to Music

Generative art emphasises the utilisation of processes for the automated creation of artworks (Galanter 2008). These processes are often the result of formalisms or data collections that were not originally created with an artistic intention. Therefore, every artistic realisation involves the task of establishing a meaningful correspondence between the characteristics of the underlying process and the aesthetic properties of the piece. These correspondences have to mediate between the algorithm's intrinsic properties, the perceptual peculiarities of the chosen feedback modalities and any stylistic constraints or requirements imposed from the outside.

Direct Parameter Mapping is the simplest and most commonly applied correspondence between swarm behaviours and sound processes. It translates agent properties directly to musical parameters. The agent position in a Euclidian space, for example, is directly converted into a position in the parameter space. The relationship established in this way is particularly compelling when it connects to familiar metaphors of spatial geometry. Other common metaphors applied in these mappings are those that describe acoustic or musical properties. Examples of these metaphors are "high–low" for pitches or "left–right" for stereo panning.

In the case of a *one-to-one* mapping, every single agent is associated with an individual sound-generating unit. Even if these individual units are simple from a technical point of view, the emergent characteristics of the swarm as a whole may produce a rich sound output. In order to match the number of musical parameters that are controlled by a swarm, the dimensionality of individual agent properties needs to be adapted. For this purpose, several agent properties such as position, velocity, and acceleration are combined in a *many-to-one* mapping. As a last step before being applied, the values of these agent properties need to be scaled and possibly discretised in order to limit them to what the sound control parameters require.

Regardless of the specifics of the mapping, it is always the emergent characteristics of the swarm behaviour that are rendered audible in the musical result. The acoustic output, for example, exhibits movements whose velocity and diversity match those of the agents: they cluster or disperse depending on the strength of attractive and repulsive forces among agents, and they reveal textural qualities depending on the number and movement patterns of the agents. Thus, the overall sonic "Gestalt" is formed by a multitude of entities that relate to each other. Other examples of this perceptual fusion in traditional computer music processes are additive or granular synthesis techniques.

Applying swarm properties to spatialised audio represents a straightforward connection between agent parameters and acoustic properties. Rather than assigning the agent's position to the parameter space of a sound property, the agent position is directly mapped to the position of a source in a spatialised audio scene. Rendered on a multi-speaker surround system, the sound objects become entities in the space and the swarm's movements and spatial behaviours are reproduced in an evidently perceivable manner. As a consequence, virtual and physical spaces fuse into one.

The distinct spatial properties of swarms may also be exploited by establishing a *Proximity-based Mapping* between agents and musical control parameters. For this purpose, the agents' properties are projected as points into a parameter space. The Euclidian distance between these points may then be applied to change sound synthesis parameters or trigger musical events. This approach is attractive because it takes into account the inherently spatial nature of swarms. Since the number of agent properties does not need to match the number of control parameters, this approach also offers an interesting flexibility when the number of agents or musical control parameters changes throughout the course of a piece. Examples of this spatial correspondence concept would be the mapping of agent positions to playback positions of sound-files – using one dimension of the swarm's Euclidian space mapped to the time-axis of a sound-file – or the triggering of sound playback by detecting an agent's proximity.

Procedural Mapping represents the next higher level of relationship between flocking algorithms and sound processes. In all the mapping methods presented so far, the role of the swarm was limited to merely *modulating pre-specified* control parameters. Procedural mapping, however, assigns an entirely different and less constrained role to a swarm. Here, the audio signal-flow is *constructed* on the fly according to rules whose execution depends on the properties of the swarm. While the swarm simulation progresses, the audio signal-flow continues to evolve as the rules are applied to its structure over and over again. Although this approach offers great flexibility, finding satisfying technical and aesthetic solutions poses major challenges. On a technical level, the sound synthesis engine needs to support on-the-fly reconfiguration, the dynamic range of the resulting audio signal has to be kept within permissible limits, and the computational demands of the signal processing chain must not exceed the available processing power. On an aesthetic level, the challenges stem from the fact that the introduction of construction rules for the audio signal-flow adds a second generative layer and an additional level of complexity. Accordingly, it becomes difficult to make aesthetically informed design decisions for such a system. In addition, it becomes difficult to preserve the "Gestalt" perception of a swarm's behaviour. Despite these challenges, procedural mapping may arguably be regarded as an aesthetically rewarding form of swarm-based computer music.

Conceptual Mapping occurs when formal elements, which are shared between flocking algorithms and music or image processes, constitute the core link. Working with these conceptual analogies or resemblances becomes part of the creative process and informs the chosen materials and processes before a mapping task as such is approached.

Conceptual Mapping between swarms and music represents a cross-domain mapping and generates a blended space. The two spaces of swarm simulation and music or image are partially projected onto a third space, the blend, which unites the common characteristics of both domains. Thus "[t]he blend has emergent structure not provided by the inputs." (Fauconnier 1997, 150) The model of this intermediate, intersecting domain serves as an abstract template for many mapping concepts. The proposition of perceptual spaces as defined by Arfib et al. (2002) in their strategies for mapping between gesture and sound synthesis is an exemplary application of this model.

A fundamental challenge in generative art and composition relates to the establishment of meaningful and traceable mapping relationships between the underlying algorithmic processes and the resulting aesthetic output (Bisig and Neukom 2008). Viewed from this perspective, the customisation of the generative algorithms themselves as a means of matching a particular artistic goal do indeed offer a valid mapping method (Schacher et al. 2011).

Any computational model of natural phenomena such as flocking behaviours represents a mathematical abstraction of reality. In order for the properties and behaviours of the natural system to be applicable to music, they have to be reduced to a level of generality that enables their creative reconfiguration into an artificial phenomenon. However, the process of abstraction also strips the natural phenomenon of its naturally perceivable characteristics. As a consequence, the computational model loses many of the essential qualities that were present in the original system. It thereby becomes less constraining and facilitates the application of a wider variety of musical strategies than the original phenomenon.

Connecting physical properties of a swarm simulation directly to physical-model based synthesis may serve as an exemplary use-case for this type of conceptual mapping (see also the description of the piece 'Membranes' below). The physical attributes that constitute the forces, which determine the behaviour of a flock can be derived directly from the functions of the physics-based system that the flock is designed to interact with. In this case, applying the concept of forces concurrently in both domains generates an inherent mapping relationship.

Practical Approaches to Mapping with Flocks

The fundamental categories and mapping concepts described here only make sense when viewed in concrete implementations. The leap from concept to application requires a clear strategy for dealing with the different domains involved (Schacher 2010). This is true not only when composing autonomous artworks that use swarms in conjunction with electronic media, but in particular for situations where a performer interacts with a generative system that uses this class of algorithms.

For composers, on the one hand, it is important to be aware of the non-linearity of a performer-driven musical form. The sonic materials need to be organised in ways, which render their recombination possible in many permutations. In addition, a number of compositional constraints need to be addressed by such an interactive algorithmic system: the structural organisation and layering of media material; the establishment of correspondences among media both within a modality and across different modalities; the arrangement of media into coherent paratactic, i.e. parallel structures; and the temporal development of these structures all have to be clarified. At the beginning of the compositional process lies the task of recognising structural similarities that are shared by a particular swarm simulation and the intended musical process. The awareness for such similarities should inform the design of the behavioural characteristics of the swarm and the composition of the musical algorithms. Ideally, they will be implemented simultaneously and reflect each other conceptually. The implementation of the mapping relationship between the flocking algorithm and the musical processes then follows as a consequence from the previous choices.

For choreographers, on the other hand, a great deal of similarities between flocking algorithms and dance can be found and applied. The interrelationships and feedback loops between dancers, swarm simulations, music and image offer the opportunity to shape the basic elements of choreography. Swarm simulations constitute multi-agent systems that model group formation and spatial movement. In this, the simulations deal directly with some of the fundamental constituents of dance. Both swarm simulations and choreography deal with relationship between local and global patterns, with the occupation of space through clustering and dispersion, and with the synchronisation of behaviours. The distinction between individuals and groups is blurred in the sense that individuality appears both on the level of the single dancer/agent and on the level of the entire group. By relating to these analogies, the choreography can integrate more closely with swarm behaviours and create a clear conceptual mapping.

For the performer, finally, one of the main challenges when interacting with emergent structures is the unpredictable nature of the output produced by the swarm. In order to be able to deal with this uncertainty, the learning process needs to include the memorisation of the guiding principles of the interaction between flock and output. Such a learning process helps to establish the necessary familiarity with the musical materials, the mappings and the combinations afforded by the interactive system. To achieve this, it is important to gain an understanding of the rules of play, and to be able to enter into the performance without having to assert total control over the entire interaction process (Schacher 2012).

Lastly, a common technique for working with swarms is to visualise the simulation in a graphically reduced manner. This so-called 'scientific visualisation' preserves the spatial and temporal patterns of a simulation through a symmetrical "one-to-one" mapping onto visual properties. Thanks to this unambiguous visualisation it becomes easier to assess the aesthetic potential of a simulation.

Research Projects and Software Tools

The studies and artistic realisations that form the basis for this article have been conducted in the context of two research projects entitled Interactive Swarm Orchestra (ISO) and Interactive Swarm Spaces (ISS). These projects were aimed at establishing a systematic framework for the integration of swarm simulations as generative processes in computer-based music and art. The scope of these research activities encompassed the identification of creative strategies, the development of technical tools and the realisation of prototypical artworks.

As part of the technical activities, the development of a flocking simulation environment named *ISO-Flock* was of particular importance. *ISO-Flock* is an open source C++ library that is geared towards the development of a wide range of flocking behaviours (Bisig et al. 2008). The library is highly generic and it abstracts the characteristics of agent properties and behaviours to a level of generality that dispenses with any semantic relationships with physical and biological aspects. This abstraction abandons the model character of the simulation in favour of an operationalisation of the fundamental principles of spatial self-organisation and coherence. This enables the conception and realisation of artistic and musical works, which are based on other principles than swarm behaviours (Schacher et al. 2011). As a result, the simulation itself can become the embodiment of an artistic idea and can thus form an integral part of the musical and visual composition process.

ISO-Flock provides an OSC-based communication interface both for receiving configuration commands and for sending simulation data, thus permitting the modification and re-configuration of the simulation at run-time. This messaging system enables the simulation to run as a standalone server application that communicates with any OSC capable client software in the artistic tool-chain. Thanks to this, artists and musicians can work with various programming languages and environments for the creation and modification of swarm simulations, as well as software for sensor-data acquisition and camera tracking. This makes the simulation responsive to extended forms of interaction.

The swarm simulation software has subsequently been extended with a graphical user interface (see figure 1). The interface was initially intended as a tool for non-expert users to facilitate the manipulation of the simulation but has proven to be equally important as a means for the rapid creation and experimentation with different simulation types. For an in-depth discussion of these tools, please refer to (Bisig and Kocher 2012).

[Figure 1 about here.]

Example Pieces

The following two use-cases serve as an illustration of the application of flocking algorithms in varying roles to interactive and performance situations. Different mapping concepts are applied in these pieces. In one of the cases the swarm serves as a mapping algorithm itself, whereas in the other case mappings are used to translate into or out of the simulation domain.

Flowspace

The first use-case for the application of flocking simulations to music is the interactive, immersive, audio-visual installation *Flowspace* that was developed by the authors between 2008 and 2010. It was shown twice to the public in the context of a thematic exhibition about sound, space and virtuality entitled "Milieux Sonores" (Maeder 2010) in Zürich in 2009 and San Francisco in 2010.

The architectural structure of the installation takes the shape of a dodecahedron measuring about four meters (approximately 13 feet) in height. The frame carries in its vertices a twenty-channel speaker-array pointing inwards and represents a perfectly symmetrical, spherical setup for surround audio. All but one of the pentagonal faces are covered in fabric and some are used as rear-projection surfaces. The frame offers enough standing space for four to five visitors and presents them with an immersive experience.

The shape of the installation informs the characteristics of the installation's generative contents. As a result, the architecture of the installation supports the blending of physical and virtual space. The simulation space overlaps with the installation space that surrounds the visitors. In addition, the simulation space is mapped onto a two-dimensional segment of the Dodecahedron surface and forms part of the installation's interface. This enables the visitors to experience a spatial immersion within the virtual flock and to simultaneously assume an observer position outside the simulation (see figure 2).

[Figure 2 about here.]

The installation creates an interactive, immersive, and generative environment for audio-visual compositions that are controlled through simulations of flocking behaviour. *Flowspace* uses these generative algorithms not only for the creation of aesthetic feedback, but also to establish coherence among spatial, perceptual, behavioural, and social phenomena that manifest themselves in this installation in an ecological way (Schacher 2009).

Multiple layers of behavioural relationships are present simultaneously. Mapping connections are established at the intersections of the different layers: between interaction, simulation, spatialised sound, and visualisation. The behaviours of the visitors and the swarm agents affect each other on multiple levels, which differ in immediacy and spatial extension. By touching the surface of the interface, the visitor's touch is mapped to the spatial positions of a particular class of agents. Other agents subsequently respond to these changes. These interrelating agent-behaviours transform the scope of the visitor's action from an initially local and immediate effect to an element that contributes to the emergent dynamics of the installation's audio-visual compositions. Different combinations of properties exist for swarm simulation and audio-visual processes and are organised as discrete states in a finite state machine. The selection of states is controlled by the visitor's long-term level of activity. The installation's characteristic as a hybrid ecosystem results from the interrelations among the activities of its natural and virtual inhabitants that occur on several temporal, spatial, and causal levels. The simplicity and immediacy of the interface's physical manipulation and its subsequent effect on the installation's responses provides a natural form of interaction, which helps to balance the visitors' intuition, familiarity, curiosity, and surprise.

Strong perceptual relationships form an important aspect of the experience. In *Flowspace*, the audio-visual compositions and the visual and tactile feedback of the interface are linked by mapping to the same swarm simulation. The installation provides feedback through the modalities of touch, hearing, and vision. The correlation among these modes shapes the aesthetic experience, directs the visitor's attention and enables the perception of the installation's emergent behaviours. The translations and mappings between the different elements is what effectively constitute this correlation. In an abstract sense, the different states of the pieces and their expressive characteristics correspond to affect spaces, as described in concepts that formalise emotions in autonomous systems (Masuch et al. 2006).

In the exhibitions, the installation presented three pieces by different authors, which were all centred around a swarm simulation and interactively generated sound and image.

The algorithm in the first piece, entitled *Impacts*, explores the possibility of a hierarchical field of relationships within several flocks. On a secondary level the perceptually salient events are extracted from the continuous flow of data and used as basic impulses for the music: the impacts of (near)-collisions between agents are used to generate the discrete notes that form the musical "Gestalt". This swarm–music realisation represents a *Formal Relationship* of direct mapping based on proximity (see figure 3).

[Figure 3 about here.]

In the second piece, called *Flow*, the musical idea centres on periodically changing agent neighbourhoods, rendered audible through rhythmical musical structures. The agents of the secondary flock tend to settle into cyclical trajectories. That causes them to encounter primary agents in a periodical fashion, which forms the basis for the creation of the rhythmical structures. Sounds are triggered whenever a secondary agent gets sufficiently close to a primary one. The duration, amplitude and frequency spectrum of the sounds are obtained from the position of the primary agent, the distance between the agents and the secondary agent's velocity, acceleration and jerk (the first, second and third derivatives respectively of position changes over time). Here again, the swarm–music realisation creates a *Formal Relationship* of proximity-based direct mapping (see figure 4).

[Figure 4 about here.]

In the third piece, named *Membranes*, the swarm simulation and sound synthesis technique are both based on the same physical model: the behaviour of interconnected springs. The flocking simulation consists of two types of flocks: a primary, mostly stationary flock and a secondary, mobile flock, which implements a mass-spring system. In this model the agents represent point masses that are connected to their neighbours through elastic springs. As the secondary agents evade the primary agents, some of the connected neighbours move beyond the breaking distance of the springs. Consequently, these springs are removed from the simulation. New springs are formed whenever two secondary agents get sufficiently close to one another. Whenever a spring is created, a corresponding acoustic spring is instantiated and becomes audible in a strong but brief impulse excitation. The musical result of this mapping is produced through the combination of a diffuse musical background, which is punctuated by bright sound events that occur in correlation with the events inside the swarm simulation. In this realisation, finally, we find an *Ontogenetic Relationship* of mapping, where both flock and sound synthesis share the same physical characteristics and behaviours.

All three pieces create a *Conceptual Relationship* where the shared elements between flock and music or image processes bridge the domains thereby unifying them. An *Ecological Relationship* exists in the synergistic space that is shared by visitors and the artificial flocks, and the *Interaction Relationship* arises from the generation of synthetic sound and images in reaction to the visitors' behaviour (see figure 5).

[Figure 5 about here.]

Stocos

The second use-case extends the scope of the application of flocking algorithms to the domain of interactive dance, music and image in a stage setting. The piece *Stocos* was developed in close collaboration between one of the authors, the choreographer Muriel Romero and the composer Pablo Palacio (Bisig and Palacio 2012). *Stocos* focuses on the notion of gesture as a means of connecting bodily movement, simulation-based movement, sound synthesis and video rendering (see figure 6). In this model, on an algorithmic level, gesture can be abstracted as an energy-motion trajectory through space. This abstraction establishes a formal compatibility and consistency among the elements of the performance. The simulation is based on the coherent spatial movement of flocking agents. The sound generation mechanisms uses the method of dynamic stochastic synthesis (Xenakis 1992), which models the Brownian motion of microscopic particles. Video rendering displays the agent's movement as graphical line segments that interconnect previous agent positions. Several choreographical sequences are realised as random movements through sequences of previous dance gestures. A conceptual compatibility is established through the notion of gesture as an element of expressivity. This notion provides the means to metaphorically relate the simulation-based processes to performance activities. An additional emphasis of the piece lies on treatment of the stage as a synergistic environment. The term "synergy" refers to the cooperative activities of several elements of a system, which give rise to a property or behaviour that is unachievable by each component alone (Fuller 1979). The term "synergistic space" emphasises the fact that the appearance and behaviour within the performance space is not dominated by individual activities but rather is the result of the relationship and feedback mechanisms among the activities of the dancers, the simulation-based entities, and the generative music and image processes. In this sense, the presence of the dancers becomes an indispensable element of the space and adds the human involvement into the interactive environment (Spagnolli and Gamberini 2005).

[Figure 6 about here.]

In *Stocos*, the stage is inhabited by human dancers and simulated entities, both of which possess a behavioural repertoire and the capability to perceive and respond to each other. The perceptual capabilities of the agents rely on computer vision in order to detect the dancer's positions, contours and movements. The video-tracking information is subsequently transformed into spatial data-structures that manifest themselves within the simulation, such as force fields or polygonal chains. The agents are able to perceive these structures through distance-limited neighbourhood calculations between agent positions and geometrical objects. The dancers are able to perceive the agents' activities through the simulation's influence on the generation of music and visuals.

The piece uses two different levels of behavioural relationships among dancers and simulated agents. The first level creates a gestural identity between choreography and simulation, which is based on a direct mapping of the dancers' movements on the agents' positions and velocities. The mapping of this remotely controlled swarm onto the rendering mechanisms enables the dancers to gain direct control over the video and sound generation. The second level is based on an indirect behavioural relationship between dancers and agents: the agents possess a variety of behaviours, some of which cause them to move autonomously, while others allow them to respond to elements in the simulation space. These elements either represent other agents or are the result of a geometrical mapping of tracking data. The characteristics and diversity of these behaviours change throughout the performance. If the agents respond predominantly to tracking-based spatial objects, then their behaviour resembles that of a physical system reacting passively to the movements of the dancers (see figure 6). If the behavioural repertoire of the agents is bigger and encompasses behaviours that respond to inter-agent relationships, then the simulation exhibits a higher degree of behavioural complexity and independence. This gives rise to an improvisational form of interaction between dancers and simulation.

The appearance of the performance is characterised by an acoustic and visual merging of the physical and the simulation space. The stage setup consists of two white projection surfaces, one horizontal and one vertical, which delineate the performance space and an octophonic speaker array that surrounds the stage and audience. The stage is divided into distinct regions, each of which is associated with a particular set of sound synthesis control parameters. By relating the dancers' positions to this space, their movements become perceivable as acoustic trajectories. The projection of the generative video image covers the stage floor, the stage background, and the dancers' bodies. Through this projection the spatial relationships are translated into visual elements. As a projection on the entire stage, the images create a visual environment that supersedes the appearance of the physical space and the dancers. As a projection within the vicinity of the dancers, the images coalesce into clearly confined shapes that appear as visual counterparts to the dancers. By aligning simulation space and corporeal space, the video image can be projected solely on the dancers' bodies. In this configuration, video images and the dancers' physical bodies merge into a single entity whose appearance possesses both natural and artificial properties.

A variety of formal mapping categories can be identified in the realisation of *Stocos*. The identification of a gestural connection between dancers, simulation, music, and image constitutes a *Conceptual Relationship*. The notion of a synergistic space that is shared by dancers and simulated entities represents an *Ecological Relationship*. The connection between swarm simulation and dynamic stochastic synthesis implements a *Formal Numerical Relationship*. The swarm-based control of the visual rendering mechanism represents a simple form of an *Ontogenetic Relationship* based on the fact that both agents and visual elements share the same position. The activities of the dancers are related to the generation of synthetic sound and images through several *Interaction Relationships*. The assignment of the dancer's position to spatial regions of sound synthesis control parameters implements a *Formal Proximity Relationship*. The camera-based analysis of the dancer's contours and movements as forms in physical space and their subsequent transformation into forms within the simulation space constitutes an *Ontogenetic Relationship*. Finally, the response of the agents to the presence of these forms adds an additional mapping layer, which represents a *Formal Proximity Relationship*.

Conclusion

The usage of flocking algorithms as mechanisms for mapping tasks in computer music presents a number of advantages. Thanks to the emergent nature of swarm behaviours, relationships can be established that offer rich and varied results, which are less predetermined than traditional "connectivistic" mapping strategies. Based on a reflection of the different roles of flocking algorithms in mapping tasks and the variety of situations for the application of these mappings, we have presented what we believe to be fundamental categories of relationships that occur when translating between these domains. The application of flocks in generative and performance-oriented composition situations is reflected in these categories. But these relationships may also extend beyond the domain of pure mapping or the application of flocking algorithms. They describe underlying principles that are useful for organising heterogeneous materials and processes in computer music and generative art in general. By using a flocking algorithm and its simulation space as a blended space, control inputs with few elements can easily be converted to complex effects in the target process. Inversely, a swarm can translate a complex control situation into a few salient parameters in the output medium. Some of the common strategies for the application of swarms, such as spatialisation are obvious. But swarms also offer simple control over highly parallel polyphonic processes such as granular or additive synthesis or as simulation equivalence to physical models, with abstract entities that directly reflect the synthesis algorithm. The methods and toolset we present here are intended for the exploration of swarm algorithms in many different scenarios. The swarm and its 'scientific visualisation' can be regarded as an extended graphical user interface (GUI), and the flock may be regarded as a complex generator for structured events. Flocking algorithms can also be considered from a systemic or even metaphorical perspective. In particular, when translating musical ideas through such conceptual relationships, the mapping task is brought into the artistic domain and may occur at a moment in the creation process, which precedes the establishment of parametric connections. The pieces that we have shown in this article demonstrate only a fraction of the potential of using swarms as mapping methods, yet they hopefully manage to convey the appeal that such behaviour-driven forms can have. In conclusion, it becomes apparent that life-like behaviours of simulated flocks represent an attractive addition to the mapping strategies commonly used in computer music. Through their emergent qualities they can make mapping relationships less predictable and give the pieces a more autonomous evolution and organic feeling.

Online Resources

«« Layout note: this section including the thumbnail-strips should be separated from the text, and laid out as an independent text-box, an appendix or similar. »»

The website dedicated to the artistic projects and software described in this article is located here: http://swarms.cc

Videos depicting the art works are available online to complement the descriptions in this article.

Flowspace videos:

[Figure 7 about here.]

http://vimeo.com/20158277
http://vimeo.com/15294032
http://vimeo.com/14816324

Stocos videos:

[Figure 8 about here.]

http://vimeo.com/39332770
http://vimeo.com/14836862
http://vimeo.com/39769944

(all URIs were verified in January 2014.)

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List of Figures

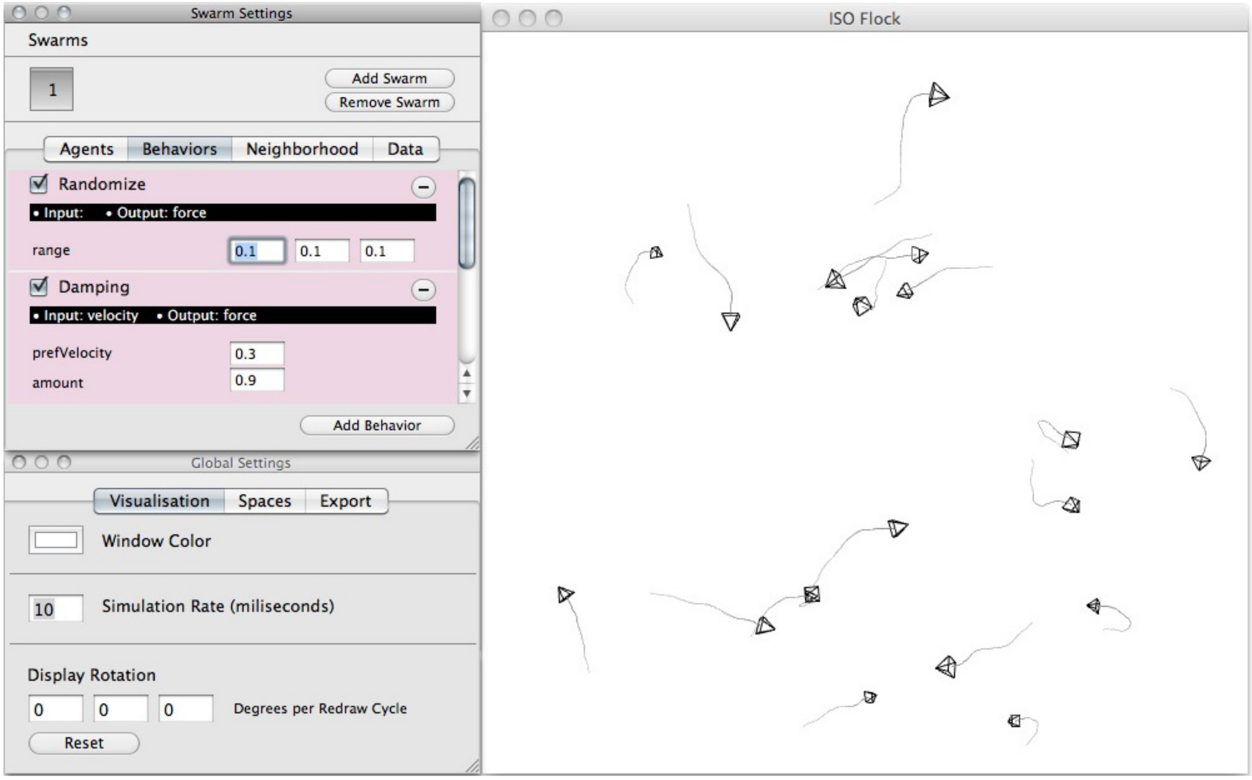

Figure 1. Software tools: the swarm visualisation of ISO-flock *together with the graphical user interface.*

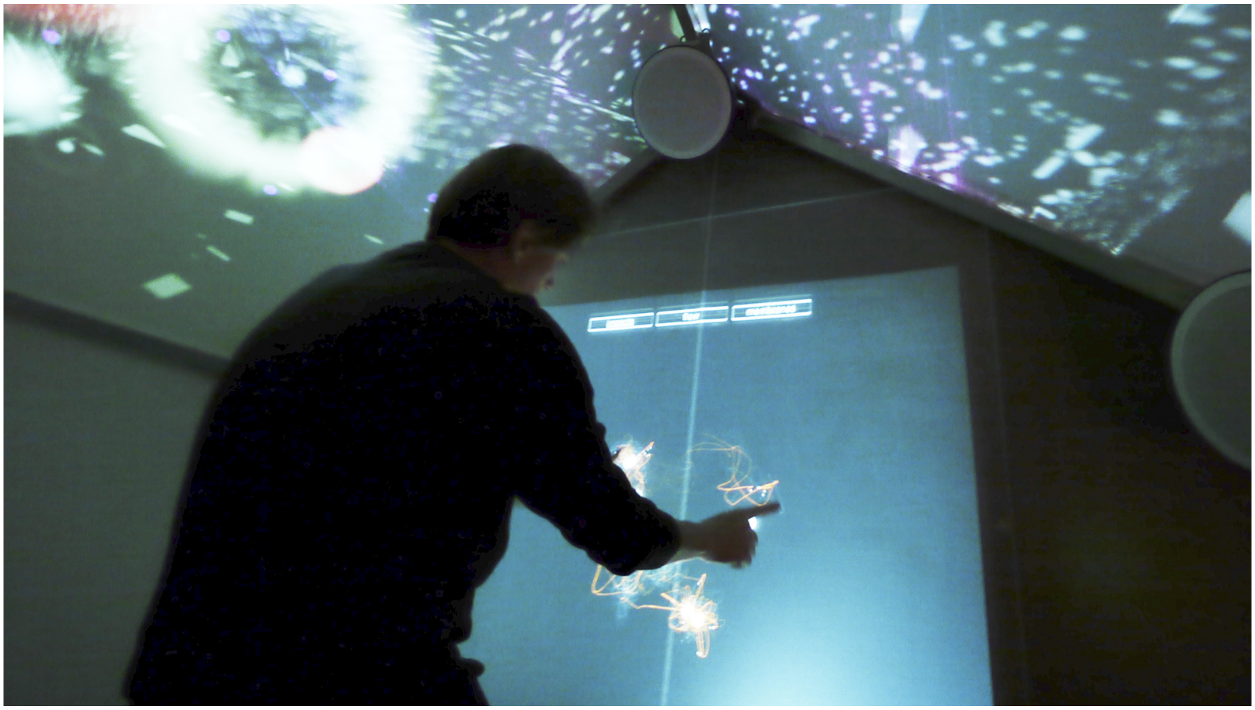

Figure 2. A partial view of the Flowspace *installation. The touch-based interaction surface displays a 'scientific visualisation' of the simulation. The rear-projected images above represent an artistic interpretation of the swarm. The visitor is surrounded by a 20 channel audio system.*

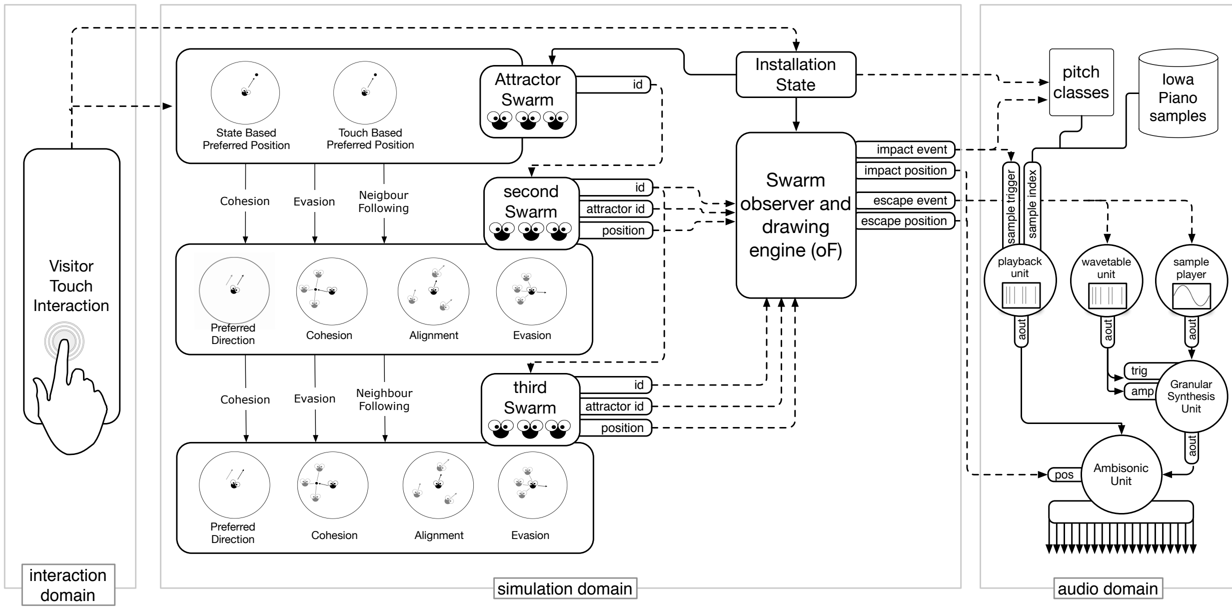

Figure 3. Schema for the swarm simulation of the piece Impacts. *Here, the three swarms are in a hierarchical relationship. Their continuous state change is analysed in order to generate discrete events in the audio domain. The simulation-domain decouples the interaction from the visual and sound output of the piece.*

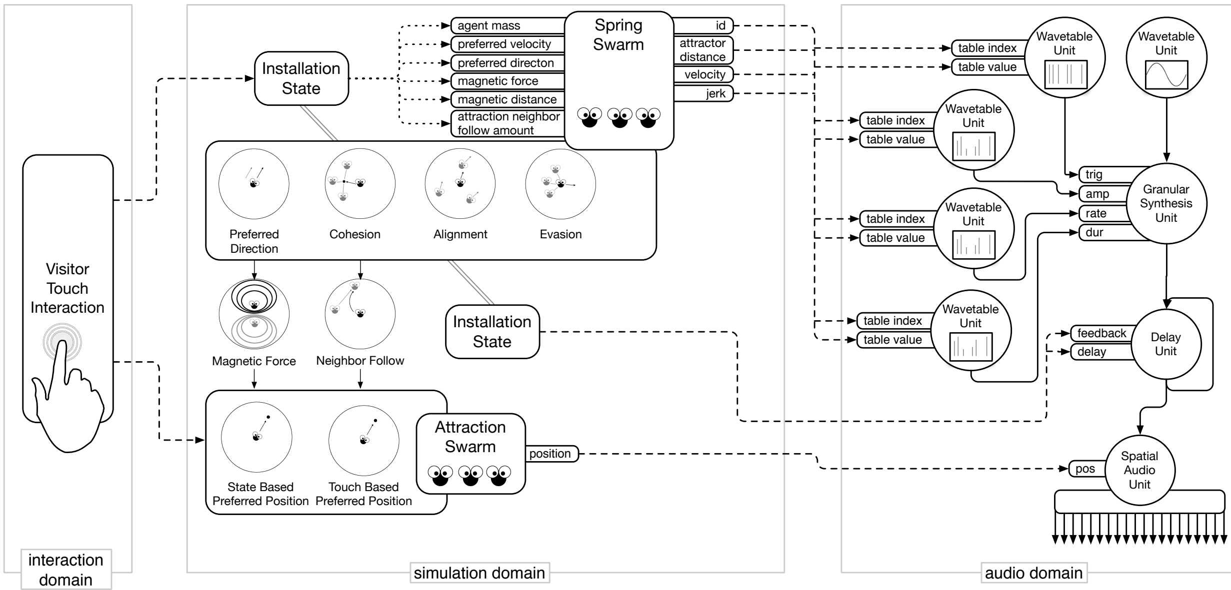

Figure 4. Schema for the swarm simulation of the piece Flow*. Here, the swarm simulation fulfils the role of an intermediate mapping space and is bordered by connection layers between the user's interaction and the audio-producing processes.*

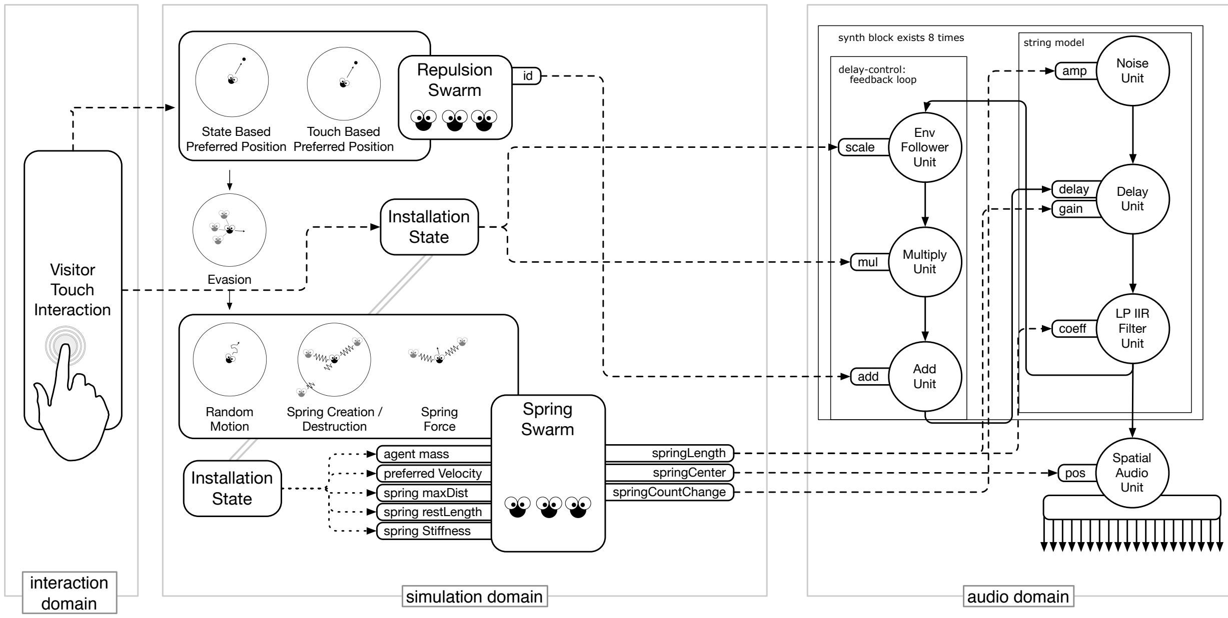

Figure 5. Schema for the swarm simulation of the piece Membranes*. The swarm simulation consists of two types of flocks. The secondary flock implements a mass-spring system, which is directly connected to the physical model that produces sound.*

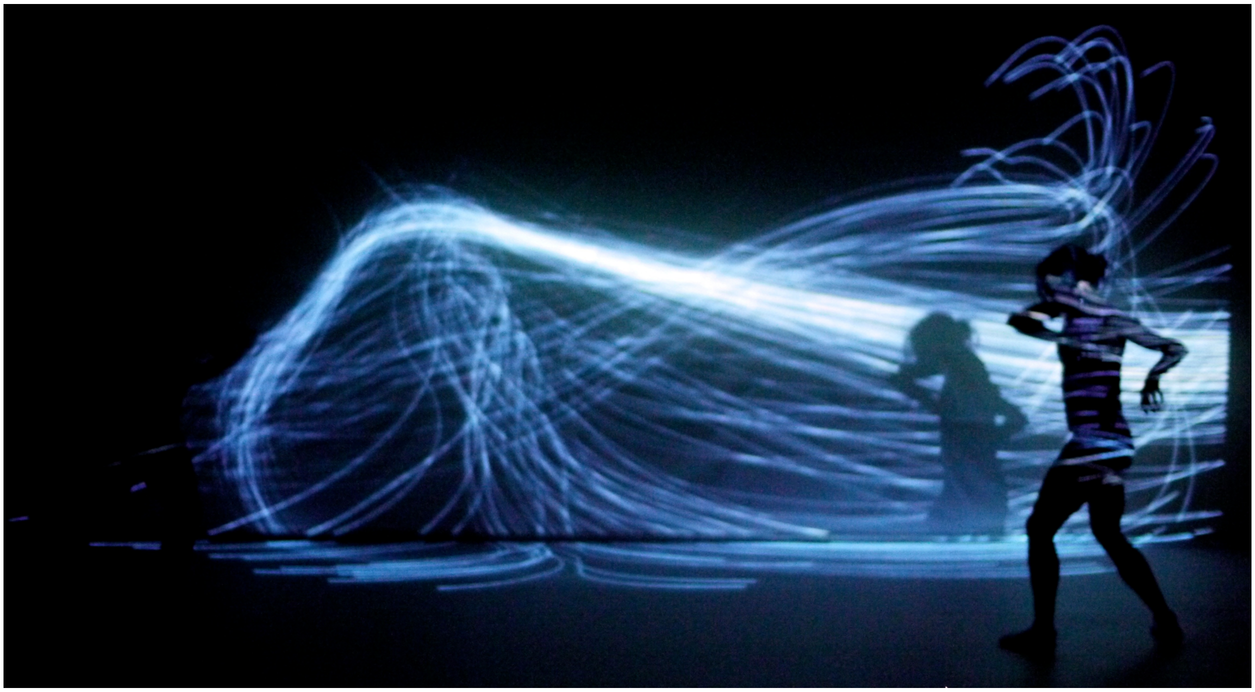

Figure 6. A scene from Stocos*. The swarm becomes visible through the blue traces and is attracted to the dancer's movements.*