Phantom Limb – Hybrid Embodiments for Dance

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Abstract

Phantom Limb is a dance project that employs simulation-based techniques to extend and alter a dancer's bodily characteristics and movement capabilities. It does so by representing physical and virtual bodies and their movements as actuated mass-spring systems and artificial neural networks. This unified representation of dancers and generative artefacts permits the creation of hybrid embodiments whose morphological, behavioral, perceptual and aesthetic aspects manifest on stage as acoustic and visual co-presence. This publication describes the conceptual motivation, preliminary technical implementation, and initial experiments in designing relationships between natural and synthetic forms of corporality.

1. Introduction

The project Phantom Limb is a collaboration between the two authors and the choreographer Muriel Romero. The project forms part of an ongoing research initiative entitled Metabody [1]. This initiative deals with the development of creative technologies and artistic productions that exemplify strategies for promoting cultural diversity and idiosyncrasies. Phantom Limb specifically addresses this thematic context by experimenting with simulation-based technologies that allow dancers to modify their morphological appearance and behavioral capabilities. This modification is based on the representation of a dancer's natural bodily properties via the same computational abstractions that are employed for the simulation of artificial bodily structures. This abstraction integrates the structural and behavioral properties of natural and simulated body parts into a unified form of hybrid embodiment. The idiosyncratic qualities and capabilities of a particular hybrid embodiment is then as much the result of the dancer's subjective properties and activities as it is of the peculiarities of the simulated body parts.

2. Background

The realization of Phantom Limb is inspired by a long standing tradition within performance art. Historical precedents include the artists Loïe Fuller, Oskar Schlemmer and Alwin Nikolais. Loïe Fuller became famous through works such as the *Serpentine Dance* [2]. A central element of these works are very wide costumes whose flowing movements extend and amplify the activities of the dancers (Fig. 1, left). Oskar Schlemmer's *Triadic Ballet* treats the human body as an artistic medium that is transformed by the costume into a geometric object [3] (Fig. 1, middle). Alwin Nikolais explored in works such as *Imago* or *Kaleidoscope* how costume-based distortions or extensions of a human body structure affect the dancers movement possibilities [4] (Fig. 1, right).

Figure 1. Examples of Costume-Based Body Modifications in Performance. Form left to right: Serpentine Dance by Loïe Fuller (1891), Triadic Ballet by Oskar Schlemmer (1922), Imago by Alwin Nikolais (1963)

Figure 2. Examples of Robotic Body Extensions in Performance. From left to right: Third Hand by Stelarc (1980), Connected by Gideon Obarzanek (2011), Exoskeletal by Christiaan Zwanikken (2014)

Among the more recent examples that are relevant in the context of this publication are works by Stelarc, Gideon Obarzanek, and Christiaan Zwanikken to name just a few. Those works employ robotic structures as actuated mechanisms that extend a human body. Stelarc is famous for his often drastically invasive body modifications. In his *Third Hand* project, a mechanical hand is attached to the artist's right arm and controlled via EMG signals from various muscles in his body [5] (Fig. 2, left). In *Connected* by Gideon Obarzanek, a dancer is connected via strings to a grid-like sculpture that has been built by Reuben Margolin [6] (Fig. 2, middle). The structure transforms the dancer's activities into undulating movements and contortions. The work *Exoskeletal* by Christiaan Zwanikken employs a robotic body-extension suit that comprises a mechanically actuated boar skull [7] (Fig. 2, right).

Within the field of Artificial Life, those projects that model morphological and behavioral properties of life-like entities via integrated simulation-based approaches are highly relevant for this project. For the sake of brevity, we describe only three by now classical examples. In the *Evolved Creatures* project by Karl Sims, bodily topology and control algorithms of artificial creatures are evolved concurrently in order to improve their capabilities for locomotion or for competing for food sources [8] (Fig. 3, left). The focus of the *Artificial Fishes* project by Xiaoyuan Tu and Demetri Terzopoulos lies on the realistic simulation of the fishes' appearance, movement and behavior. A high level of realism is achieved via a combined modelling approach that simulates the hydrodynamic properties of water, the animals' muscular structure, as well as their perceptual and cognitive capabilities [9] (Fig. 3, middle). In the art context, the *A-Volve* project by Christa Sommerer and Laurent Mignonneau is interesting in that it realizes an artificial ecosystem, whose creatures can be interactively created and shaped by visitors. The movement and behavior of these creatures is automatically derived from their shape properties [10] (Fig. 3, right).

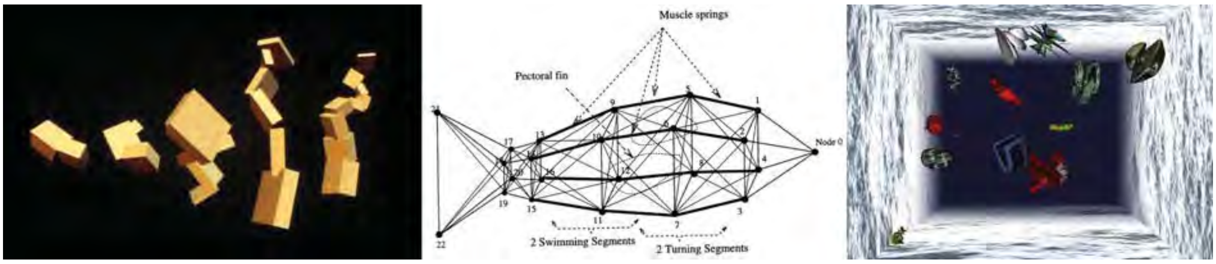

Figure 3. Examples of Artificial Life Simulations of Life-Like Creatures. From left to right: Evolved Creatures by Karl Sims (1994), Artificial Fish by Xiaoyuan Tu and Demetri Terzopoulos (1994), A-Volve by Christa Sommerer and Laurent Mignonneau (1997)

3. Software

The software environment for Phantom Limb consists of several applications for simulation, video tracking, visual rendering, video mapping, sound synthesis, and audio spatialization. These application run in parallel and exchange information and control data with each other via the open sound control protocol (OSC).

3.1 Simulation

The simulation software which has been custom developed in C++ is responsible for modelling the actuated virtual body extensions. The simulation functionality is divided into several parts: body architecture, mass-spring simulation, propulsion simulation, collision detection and resolution, numerical integration, neural network simulation, sensing and actuation.

3.1.1 Body Architecture

The body architecture part of the simulation manages the topology of the virtual body extensions. Each extension consists of one or several so-called body segments that are organized into tree like structures. Both the computational representations of the dancers' physical bodies that are derived from video tracking and the virtual body extensions are structured in such a way. The simulation takes care of translating the various body segments into corresponding mass-spring systems and of preserving their connectivity and directional constraints (Fig. 4, left).

3.1.2 Mass Spring Simulation

The mass-spring simulation (Fig. 4, middle) models spring tensions forces according to Hooke's law. In addition, it also simulates a directional restitution force that pushes springs towards a preferred rest direction which is relative to the direction of the preceding spring. Finally, all the mass points experience a damping force that is proportional and opposite to their velocity. The body architecture is represented within the mass-spring simulation as linear or branching sequences of springs. Successive springs within a sequence share their respective mass points (Fig. 4, left).

3.1.3 Propulsion Simulation

The propulsion simulation implements a physically rather contrived way of calculating forces that cause body segments to propagate through space. These forces are derived from the mass points' relative velocity with respect to the direction of their corresponding springs (Fig. 4, right). The propulsion force points in a direction opposite to the spring and its length is proportional to the dot product between the velocity difference between mass point 1 and 2 and a vector that is perpendicular to the spring's direction. Furthermore, a damping force is calculated that opposes the movement of a body segment and thereby imitated the viscosity of a surrounding medium. The damping force is the sum of two vectors. The first vector points into the direction of the spring. The second vector points is a direction that is perpendicular to the spring. The length of both vectors is proportional to the dot product between the velocity of mass point 1 and the vector perpendicular to the spring.

3.1.4 Neural Network Simulation

The simulation software allows the construction of time-delayed recurrent neural networks. The characteristics of these networks is as follows. Signals and activity levels are represented as continuous values whereas time is discrete. Signals propagate with a time delay and attenuation factor in between interconnected nodes. Signals that arrive concurrently at a node are passed through a transfer function that adds the node's gain and decay values to the sum of the incoming signals. The output of this function determines the node's activity level. This value is then passed through a step function that serves as threshold in order to determine if the node should produce an activity spike. If the node's activity level exceeds this threshold, the node fires, its activity is reduced by a preset amount, and the node enters a refractory period during which it cannot fire again (Fig. 5).

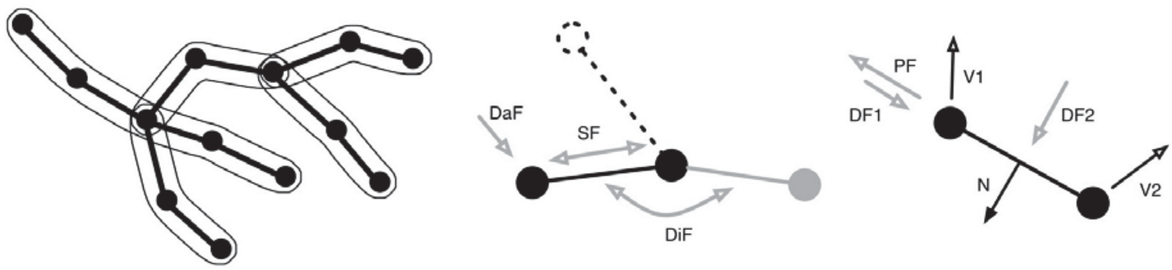

Figure 4. Body Architecture, Mass-Spring and Propulsion Simulation. Left: Schematic depiction of a corporeal structure consisting of multiple branching body segments and its corresponding mass-spring representation. The mass-spring system is depicted as black lines (springs) and black circles (mass points). The body segments are depicted as black outlines. Middle: Depiction of mass-spring forces. Forces are shown as grey outlined arrows (DaF: damping force, SF: spring force, DiF: directional force). The currently evaluated spring and its mass points are depicted in solid black. The preceding spring is depicted in solid grey. The current spring's rest direction and length is depicted as dashed black line. Right: Depiction of propulsion forces. Forces (PF: propulsion force, DF1: damping force vector 1, DF2: damping force vector 2) are shown as grey arrows. mass point velocities (V1: mass point 1 velocity, V2: mass point 2 velocity) are shown as black outlined arrows. The spring normal direction (N) is depicted as black filled arrow.

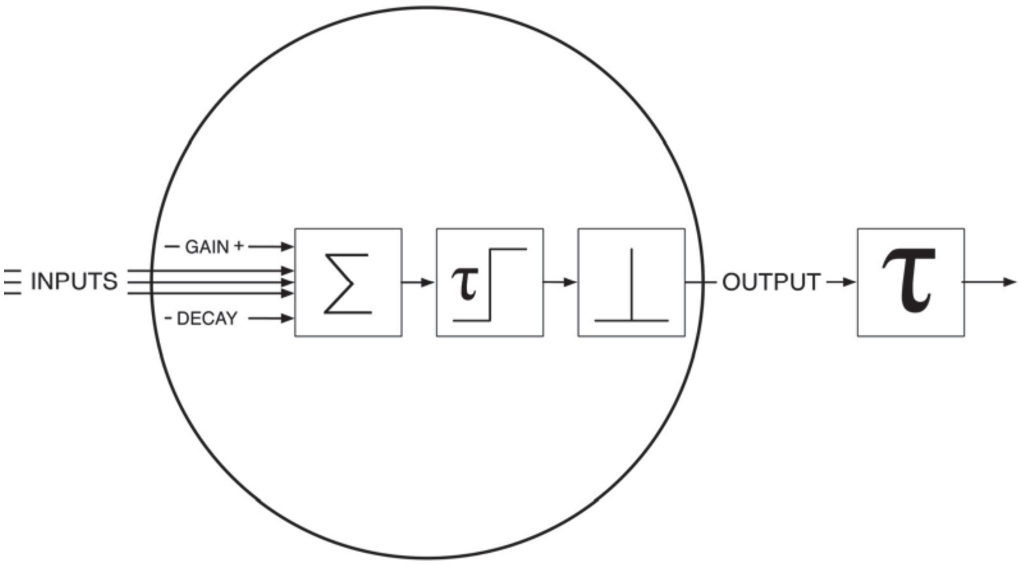

Figure 5. Neural Network Simulation. The graphical symbols in the schematic depiction of a neural node are (from left to right): Summation of input signals, gain

and decay, refractory period limit and activity threshold, output signal spike, signal propagation time delay.

3.1.5 Sensing and Actuation

The activity of the neural network can affect the properties of the mass-spring system and vice versa. This functionality is realized via the implementation of sensing and actuating elements. Each of these element is associated with a spring and a neural node. A sensing element maps a property of its spring into an activity value of its neural node (Fig. 6, left). An actuating element maps the activity of its neural node into a property of its spring (Fig. 6, middle). At the moment, the following sensing and actuation elements exist: Length sensors map the deviation of a spring's length from its rest length into a neural activity. Directional sensors do the same for the deviation of a spring's direction from its rest direction. Length motors map neural activity into a new rest length for a spring. Directional motors map neural activity into a new rest direction for a spring. An example body extension with its neural network, sensors and actuators is shown in Fig. 6, right.

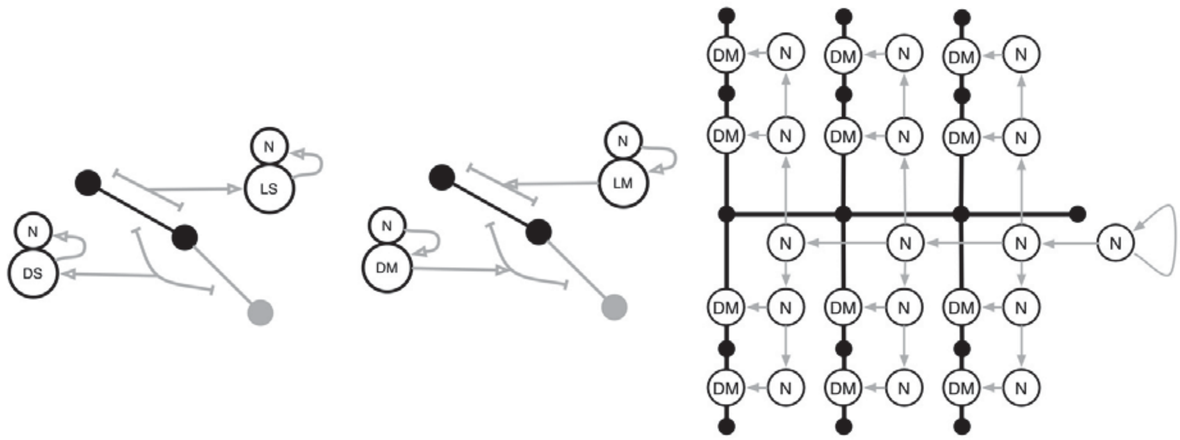

Figure 6. Left: schematic depiction of sensors. A directional sensor (DS) maps a spring's directional deviation into an activity level of a neuron (N). A length sensor (DS) maps a spring's length deviation in a neuronal activity level. Middle: schematic depiction of motors. A directional motor (DM) maps a neuronal activity into a spring's rest direction. A length motor (LM) maps a neuronal activity into a spring's rest length. Right: manually designed neural network and directional actuator system for a multi-arm body extension.

3.1.6 Collision Detection and Resolution

The simulation provides means to define bounding volumes to which individual body segments can be assigned. These volumes are constructed from 2D contours that are extruded into the Z-direction. A volume consists both of a hard limit surface and a soft limit region. In addition, a volume can act as an outer boundary, preventing body segments from leaving a particular region, or it can act as inner boundary, preventing body segments from entering a particular region. Bounding volumes can either be hand designed or automatically derived from the video tracked contours of one or several dancers (Fig. 7). The collision detection and resolution mechanism applies to mass points that try to traverse a hard limit surface. If such a collision is detected, the corresponding mass points are instantaneously repositioned onto the limit surface. If the mass points enter a soft limit region, a force is applied to gradually push to them back. This force is proportional to the depth of the mass point's penetration into the soft limit region.

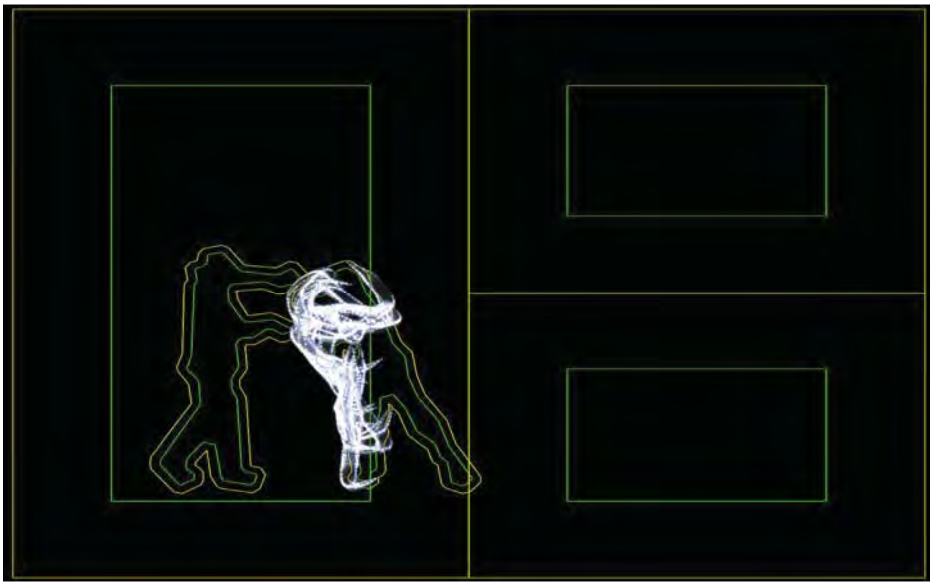

Figure 7. Bounding Volumes. Multiple bounding volumes can delimit the simulation space. Here, two of the volumes are derived from the tracked contours of the dancers. The other three volumes are static and aligned to screen regions on stage. A simulated body extension is constrained within one of the dancer's body contour. The hard limit surface is depicted as yellow outline. The soft limit region extends from the green outline to the yellow outline.

3.2 Tracking

The interaction between dancers and simulated body structures is based entirely on video tracking. For this task, three different video tracking applications are running in parallel. A custom developed tracking software derives body contours of dancers from a distance image obtained from a Kinect camera. These body contours are used to create dynamic bounding volumes within the simulation. An Eyesweb-based software patch calculates body centroids of dancers from a distance image obtained from an additional Kinect camera. Based on these centroids, skeletal representations of the dancers' bodies are created and mapped into corresponding structures within the mass-spring simulation. The mapping is based on a spatial transformation of the skeletons' joint positions from tracking space into mass point positions within simulation space A proprietary tracking software that forms part of the Motion Composer System [11] is used in combination with a Asus depth camera and an industrial gigabit ethernet camera. The combination of the very low latency response of the ethernet camera with the depth image of the Asus camera allows for fast interaction with the sound material and the simulated creatures. This tracking software detects higher level expressive features as well as low level features. The high level features include a set of gesture, the low level features consist of width, height and activity. The output of the tracking software is used to control the properties of the body extensions and the medium within which they move.

3.3 Hybrid Embodiment

The representation of the dancers' bodies as mass-spring structures within the simulation environment plays a central role for the integration of simulated and natural bodies into a hybrid form of embodiment. On a purely mechanical level, the springs constituting the virtual body elements can be interconnected with the springs representing a dancer's skeletal structure by assigning some of the former springs to mass points that are directly controlled via the dancer's tracked body centroids. Based on this purely physical connection, the dancer's movements propagate mechanically through the mass-spring system and thereby cause a movement of the simulated body structure. An additional and more elaborate level of behavioral relationship between dancers and their virtual body extensions can be realized by creating shared neural networks. For each of the springs that correspond to a skeletal representation of a dancer's body, a directional sensor can be added. These sensors control the activities of their associated neurons which then propagates through the neural network. If some of the neurons within this network are part of actuators that control the rest length and rest direction of the springs in a virtual body extension, then the dancer's movements translate into behavioral changes of the virtual body extension. Figure 8 depicts two examples of a neural network that is associated with a dancer's mass-spring representation and a virtual body extension. The image on the left depicts a branching body extension that is mechanically attached to the left hand of the dancer's skeleton. Here, the neural network is extremely simple and therefore, its parameters can be easily tuned by hand. The image on the right depicts a short linear body extension that is not physically attached to a skeleton. Here, the neural network consists of multiple neurons, sensors and actuators which are organized into several fully interconnected layers. While this network has a much greater potential of generating interesting behavioral relationships between dancers and body extensions, the large number of parameters render a manual configuration unfeasible. For this reason, these types of networks have been automatically configured via evolutionary adaptation.

3.4 Video Rendering and Mapping

The simulated body extensions are transformed into polygon meshes by extruding a circular circumference along a three dimensional Bezier spline whose control points are derived from the body segments' mass point positions. These polygon meshes are then rendered both as wireframe structures and texturised surfaces that are then composited into a final video image. This image is passed via the Syphon texture sharing mechanisms [12] to a custom developed video mapping software. The mapping software provides the means to subdivide and align different image sections to physical screen locations on stage.

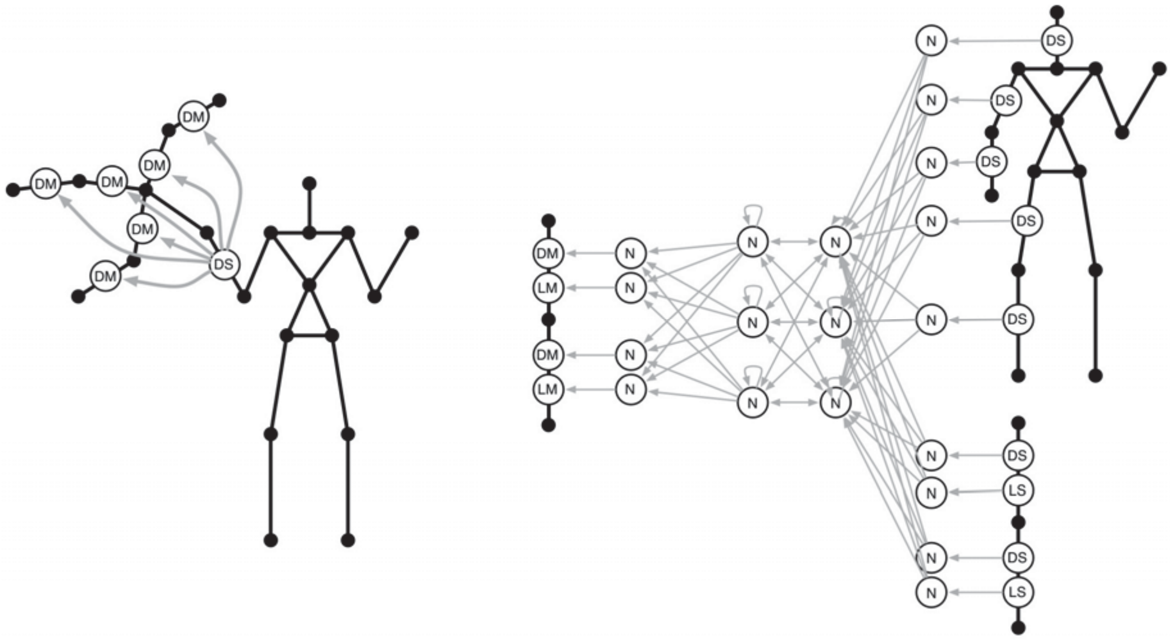

Figure 8. Combination of a Dancer's Skeletal Representation with a Virtual Body Extension. The schematic representation depicts the mass-spring system of the dancer's skeletal structure and the virtual body extension as filled black circles (mass points) and black lines (springs). The directional sensors (DS), neurons (N), length motors (LM), and directional motors (DM) are depicted as black outlined circles. The neural connections are depicted as grey outlined arrows. In the right image, the body extension is depicted twice (once as providing sensory input only and once as receiving motor output only) in order to achieve a cleaner representation of the neural network.

3.5 Sound Synthesis and Spatialization

Four types of sound synthesis approaches are used: an original extended form of dynamic stochastic synthesis, subtractive synthesis, additive synthesis, and granular synthesis. The sound synthesis as well the generation of the musical structures are implemented in the programming environment Supercollider. Some of the dynamics between the virtual body extensions and the dancers are also controlled from within Supercollider using stochastic patters that introduce mutations in the configurations of the body extensions and their attachment to the skeletal representation of the dancers. The synthesis algorithms are controlled by the simulated body structures in a variety of ways. A straightforward approach is to map the vertical and horizontal position of each mass point that make up a body segment to the frequency and spatial position of the resulting sound. The mapping of the coordinates movement of the mass points results in interesting musical phenomena that range from unisons to highly complex clusters. This approach of translating branching graphical elements into musical structures has a famous historical predecessor in Iannis Xenakis *arborescences* [13]. A more sophisticated mapping approach is used in the case of dynamic stochastic concatenation synthesis [14]. In this model, several waveforms generated by stochastic functions (the so-called *gendys*) are juxtaposed. This results in sounds of a more granular quality. The structure of each gendy is connected to the structure of each spring within a body segment, thereby mirroring the spring's shrinking and expanding. Of particular musical interest are the harmonic structures that emerge from those springs which are connected to joint positions of the dancer's skeletal representations. In this situation, the dancer's human body proportions generate waving chords that are transformed according to the choreography of both the natural and virtual bodies.

4. Performance

4.1 Stage Setup

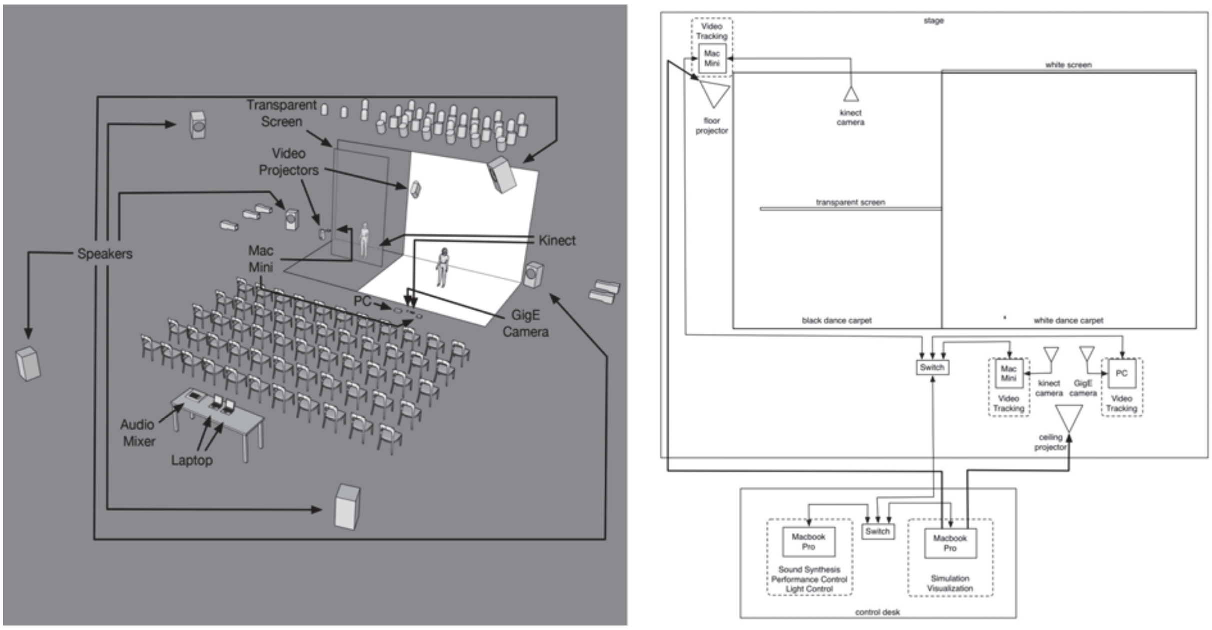

Figure 9. Stage Setup. The image on the left depicts a 3D representation of the stage. The image on the right show a schematic depiction of the hardware used on stage.

So far, the Phantom Limb project has resulted in two dance performances that were shown at La Casa Encendida in Madrid. For these performances, the stage setup was designed to emphasize from the audience's point of view our concept of hybrid embodiment. An acoustic and visual setting was created that allowed the appearance of the dancers to be overlapped with a rendering of the virtual body extensions. A central element of this setup is a transparent video rear projection screen [15] which hangs from the ceiling in front of a dancer. The dancer is tracked by a Kinect camera that is situated behind her. The visual rendering of the simulation is projected from a video projector that is placed at an acute angle onto the screen in front of the dancer. The dancer's tracked skeleton and the graphical rendering of the virtual body extensions are aligned in such a way that they match in position in size from the point of view of the audience. By controlling the intensity of the projected image and the illumination of the dancer, the combined visibility of the dancer and the virtual body extensions can be adjusted to give raise to a mixed appearance.

The right half of the stage consists of a vertical front projection screen that is placed at the back of the stage and a white dance floor in front of it. Both the screen and the floor are projected on via a ceiling mounted video projector. Additional tracking cameras are placed at the center in the front of stage. The audio setup consists of six speakers. Two of them are placed in the back corners of the stage. An additional two are hanging on each side above the audience. And the last two speakers are placed on the side behind the audience. A 3D rendering of the stage setup and a schematic representation of the stage hardware setup are depicted in Figure 9.

4.2 Choreographic Scenes

The choreography for the Madrid performance is divided into several scenes, each of which highlights a particular idea how to relate the dancers' bodies and behaviors to the simulated body extensions. In the following text, six of these scenes are briefly presented.

In scene 1 (Fig. 10, left), a hand-like structure is projected on a transparent screen in front of the dancer. The structure is physically attached to a dancer's skeletal representation. In addition, a simple neural network (Fig. 8, left) allows the dancer to control some of the structure's shape properties. Throughout the scene, the number and position of the body attachments changes.

In scene 2 (Fig. 10, right), a multi-segment structure (Fig. 8, right) is projected in front of the dancer. Depending on the movement of the dancer, the structure fractures and dissociates into multiple freely moving fragments or re-coalesces and re-attaches to the dancers body.

In scene 3 (Fig. 11, left), the same multi-segment structure is projected on the transparent screen. But this time, the creature is physically and visually dissociated from the position and skeletal structure of the dancer. The connection between dancer and the simulated segments is based on relating the degree of opening and contraction of the two body structures.

In scene 4 (Fig. 11, right), a large multi-segmented structure is projected on the white screen in the background of the dancers. The structure is not attached to the dancers' skeletal representations but envelops their body contours. The enveloping effect is temporarily interrupted when the dancers quickly move away from the structure.

In scene 5 (Fig. 12, left), another large multi-segmented structure is projected on the white screen. Contrary to the previous scenes, the structure is not associated with any dancer and behaves as an autonomously moving creature.

In scene 6 (Fig. 12, right), a large number of smaller structures are projected on the white screen. These structures are dynamically created by the dancer whenever she accelerates very quickly. After a certain time, the structures disappear. While the structures exist, they move freely across the screen but the rhythmicity of their movement is coordinated with the dancers' movements.

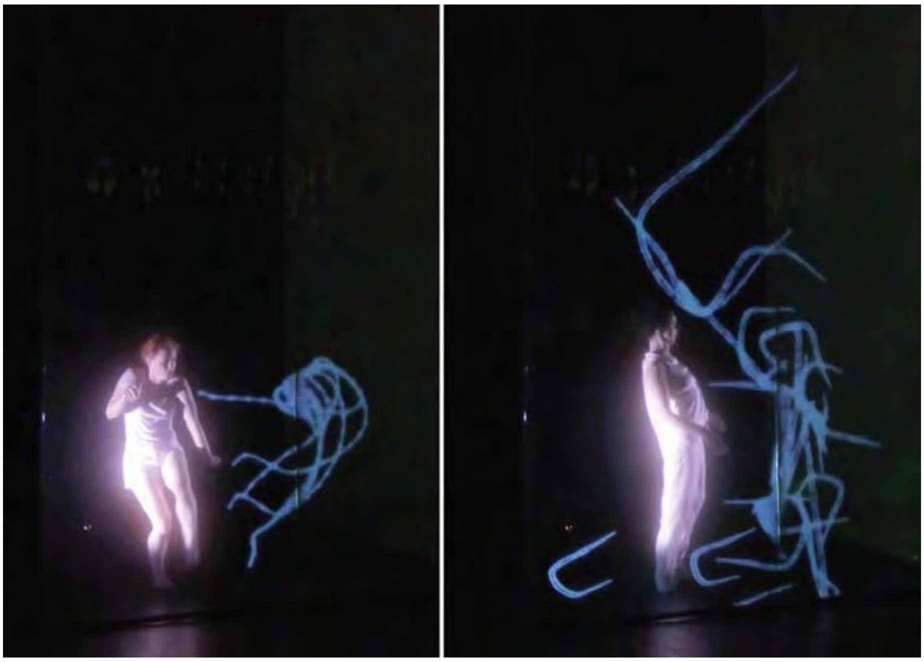

Figure 10. Scenes from a Dance Performance. Left image: Scene 1. Right image: scene 2.

Figure 11. Scenes from a Dance Performance. Left: Scene 3. Right: scene 4.

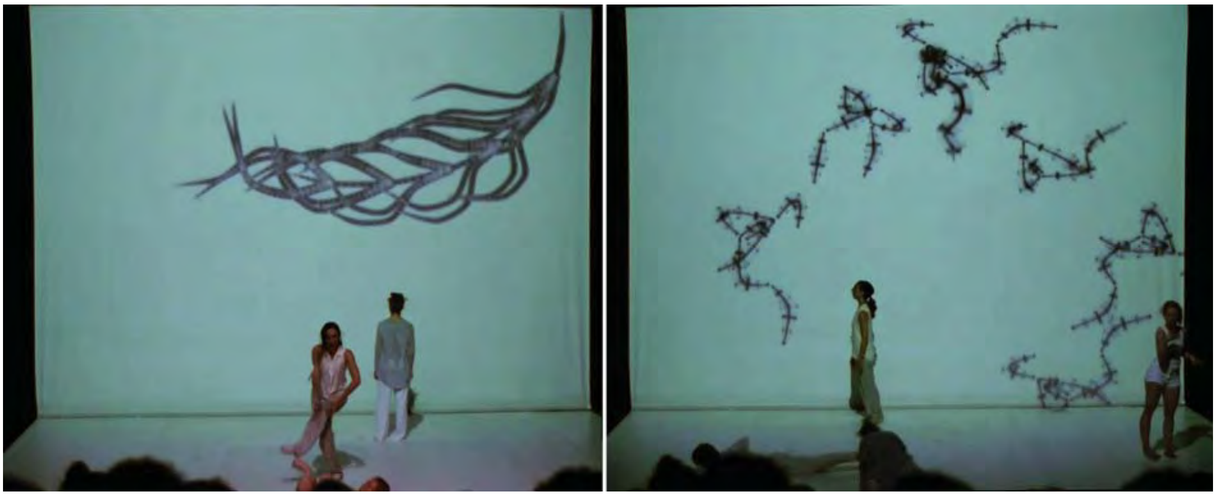

Figure 12. Scenes from a Dance Performance. Left: scene 5. Right: scene 6.

4. Conclusion and Outlook

The main goal of the Phantom Limb project is to experiment with hybrid forms of embodiment in dance. Our approach consists of establishing a simulation-based augmented reality situation on stage. This situation allows virtual body extensions and the dancers' physical bodies to merge into composite corporeal structures whose morphological and behavioral properties deviate significantly from a normal human body. As part of this project, a set of technical tools has been developed that comprises custom developed simulation software, several video tracking systems, audio and video synthesis and spatialization tools, and video screen setups. These tools have allowed us to develop and present some initial performance ideas in the form of a dance piece. The piece has served as a valuable testbed for our ideas and technologies and helped us to outline future improvements and research directions. One of the issues that we would like to address in the short term concerns a certain lack of complexity in the behavioral relationships between dancers and their virtual body extensions. So far, most body extensions respond to the dancers' movements via simple reflex type reactions. In order to achieve less direct and more diverse forms of behavioral relationships, it might be useful to modify the fitness functions that control the artificial evolution of the body extensions. Rather than to reward simple activity synchronization or movement distance, the fitness function could be based on Laban Movement Analysis [16]. Some possibly suitable quantifiers for this analysis system have been proposed by Antonio Camurri and his coworkers [17]. As a further goal, we would like to experiment with additional than purely visual and acoustic means of providing feedback to the dancers about the activities of the virtual body extensions. One possibility would be to employ wearable actuators that can generate tactile sensations. Such a sensation could for instance be triggered when a simulated body segment collides with the hard limit surface of a bounding volume. As part of a rather long term outlook, it would be interesting to combine our simulation-based approach with robotic means of extending a dancer's body with artificial body extensions.

To summarize, we believe that our research which combines ideas and methods from artificial life, generative art and dance provides ample opportunities to explore new forms of choreographing the human body. By creating and manipulating hybrid forms of embodiment, the performers bodily identity can be transformed into a plurality of morphological and behavioral differentiations and possibilities. The fluid transition between these various bodily manifestations creates a level of malleability that helps to transform a dancer's body characteristics into an expressive medium. As such, our approach continues a tradition of artistic works that experiments with the construction and alteration of the human body.

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