Strings

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2 authors:

Daniel Bisig
Zürcher Hochschule der Künste
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Ephraim Wegner
Macromedia University of Applied Sciences & Hochschule Offenburg
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Strings

Daniel Bisig
daniel.bisig@zhdk.ch
Zurich University of the Arts, Switzerland

Ephraim Wegner
ephraim.wegner@hs-offenburg.de
Offenburg University, Germany

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This article presents the currently ongoing development of an audio-visual performance work with the title *Strings*. This work provides an improvisation setting for a violinist, two laptop performers, and two generative systems. At the core of *Strings* lies an approach that establishes a strong correlation among all participants by means of a shared physical principle. The physical principle is that of a vibrating string. The article discusses how this principle is used in both natural and simulated forms as main interaction layer between all performers and as natural or generative principle for creating audio and video.

1. Introduction

This publication presents the currently ongoing development of a performance work with the title *Strings*. This work is realized in a collaboration between the two authors and violinist Harald Kimmig[1]. *Strings* will provide a performance setting for three instruments, an acoustic violin, a sound synthesis system, and a video synthesis system. The performance will follow an improvisational approach that emphasizes experimentation and exploration while at the same time trying to maintain a strong aesthetic consistency between all performers. This consistency is achieved by sharing and interrelating the physical principle of vibrating strings among all three instruments. In case of the acoustic violin, this principle forms naturally part of the sound production mechanism of the instrument. In case of the sound and image synthesis systems, the principle is translated into computer simulations that operate as generative mechanisms.

So far, most of the development of *Strings* has been dedicated to the establishment of a strategy for integrating acoustic and digital instruments into a shared performance setting, the technical implementation of the generative systems, and the evaluation of systems' aesthetic output. For this reason, this publication focuses heavily on these aspects. This comes at the cost of a detailed discussion of the interaction between the violinist and the generative systems. The integration of generative systems into rehearsal situations with the violinist forms part of the planned future research. Because of this, the current description of the possible forms of engagement between the violinist and generative systems and the shape of the performance remains speculative. In a future publication, these essential aspects of *Strings* will be properly addressed and documented.

2. Background

The following section describes the academic and artistic contexts that inform the work. This section includes discussions about the integration of a complex interaction layers into an instrumental performance and about the translation of a generative system's output into a perceivable result.

2.1. Complexity and Interaction in Performance

Acoustic musical instruments represent physical systems that can exhibit simple or complex behaviours depending on how they are interacted with. Pushing an instrument into a complex behavioural regime is a musical practice that is frequently encountered in free improvisation and experimental music. Mudd (Mudd 2017) provides empirical findings about the motivations of musicians to employ this practice. This includes among others a desire to perform music in an exploratory manner and to encounter unusual sonic results.

[1] http://www.haraldkimmig.de/

Within the field of computer music, there exists two main and typically independent approaches to endow a synthetic musical instrument with the properties of a physical system. The more common approach is based on the technique of physical modelling synthesis. Here, the simulation of the sound producing properties of a physical system forms the foundation for creating synthetic sounds that mimic some of the characteristics of naturally produced sounds. The less common approach deals with the application of simulated physical systems as control layer for interacting with digital instruments. This technique is first proposed in a paper by Mulder and Fels (Mulder and Fels 1998). The authors conclude that a physical simulation can improve the naturalness and easiness of interaction with a digital instrument. A similarly focus on improving the naturalness of interaction with a digital instrument is also found in more recent publications. For example Castet (Castet 2012) argues that the presence of a simulated physical interaction layer establishes a direct relationship between perceptual parameters and physical parameters through which the latter ones gain perceptual significance. In a publication by Pirro and Eckel (Pirro and Eckel 2011) the authors promote the usage of a simulated physical interaction layer as a means to tap into the embodied knowledge of a performer and thereby to activate already acquired motor skills. Aspects of unpredictability and open-ended exploration that a simulated physical interaction layer could entail are more thoroughly addressed in the PhD dissertation by Johnston (Johnston 2009). Johnston distinguishes between three types of interaction with a simulated physical interaction layer: instrumental, ornamental, conversational. The latter two interaction types resonate well with the discussion by Mudd (Mudd 2017) in that they emphasize how a physical system that exhibits partially or fully unpredictable behaviours shifts the role of a performer from a position of control to one of accompaniment or collaboration. The possibility of a simulated physical interaction layer to escape external control and instead exhibit autonomous behaviours is also discussed by Alaoui and co-authors (Alaoui et al. 2014). This publication also lists in concise form some of the benefits of employing physical models as interactive generative systems. These benefits include among others: real-time control, expressive potential, intuitive and embodied interaction, plausible behaviours, digital partners, and coherence across different media.

2.2. Simulation-Based Media Correlation

The potential of a simulated physical system to control not only the creation of music but also other media is pointed out by several publications. Momeni and Henry (Momeni and Henry 2006) argue that one of the main benefits of using a simulation as generative mechanism is its capability to concurrently control the creation of several different media. These authors as well as Jonson (Jonson 2009) stress the importance of making the simulation perceivable in the visual domain. According to them, it is mainly through a visual representation that the operational principle of the simulation becomes understandable both for the performers and the audience. The creative aspects of combining visual and acoustic media through a common generative system and the collaborative approaches that are rendered possible by this are discussed by Alaiou (Alaoui et al. 2014) and Bisig and Kocher (Bisig and Kocher 2013).

The application of simulation-based interaction layers also opens up interesting possibilities for correlating media that form part of both the input and output channels of an interactive system. In such a setup, instead of using a gestural input to control the simulation layer, a medium acts as input to which the simulation responds and another medium is created as output through the behaviour of the simulation. This approach is for example employed by Jonson (Jonson 2009). In all his implementations, the physical interaction layer responds to the sounds produced by a musician and this sound alters the behaviour of the physical simulation.

3. Implementation

This chapter provides an overview of the technical implementation of *Strings*.

In summary (see Figure 1, left side), the operation of *Strings* is as follows: An audio and video capture system records and analyses the visual and acoustic situation on stage. This analysis controls the creation and excitation of two physical simulations. Both simulations employ a model of a mass-spring-damper system [MSDS]. One of these simulations controls the generation of synthetic video, the other controls the generation of synthetic audio.

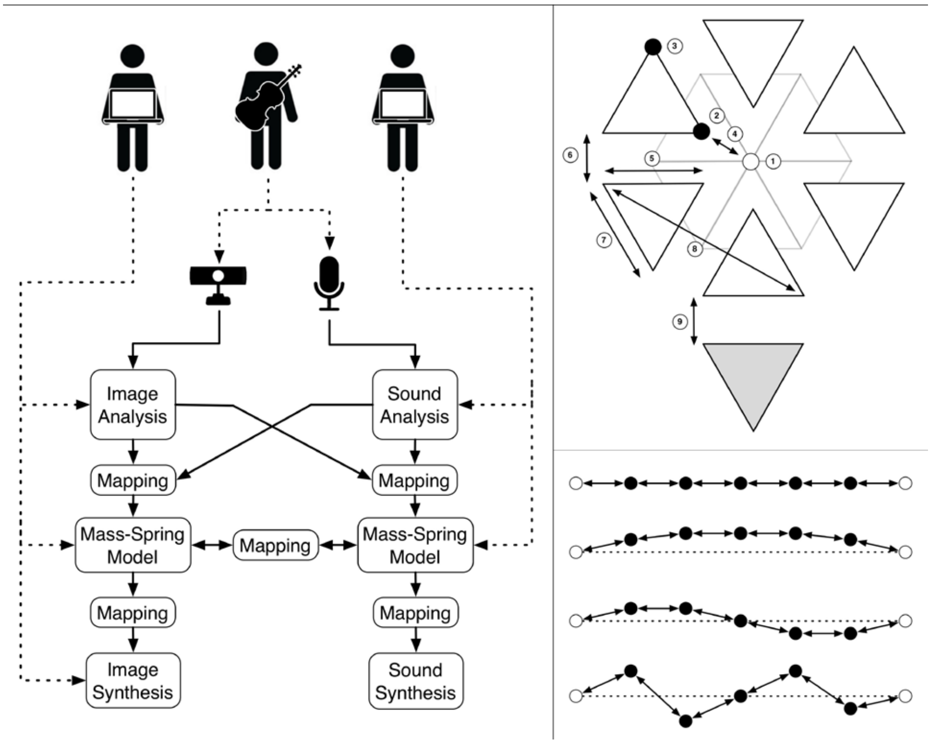

Fig. 1. Performance Elements and Mass-Spring-Damper Systems [MSDS].

The three figures present schematic depictions of the relations among all performance elements (left image), the different mass-point and spring types in the image generating MSDS (top right image), and the four sequential spring arrangements in the sound generating MSDS (bottom right image). In the image showing the performance elements, continuous lines represent the exchange of data between software and hardware components, dashed lines represent interactive controls by performers. In the schematic depiction of the MSDS, black circles represent mobile mass-points, outlined circles represent stationary mass-points, lines with arrowheads represent springs. In the schematic depiction of the image generating MSDS, the light grey elements represent triangulated feature points in the camera image from which the MSDS is constructed. Here, the labels are as follows. 1: stationary mass-point at the origin of a camera image feature point, 2: mobile mass-point in the interior of a region, 3: mobile mass-point at the periphery of an image, 4 :*Origin* springs, 5: *Triangle* springs, 6: *InterTriangle* springs, 7: *Region* springs, 8: *Structural* springs, 9 *InterRegion* springs. In the graphical depiction of the sound generating MSDS, the four horizontal structures represent four individual MSDS. Here, dashed lines represents the rest heights of mass-points from which they are vertically deflected upon excitation.

3.1. Mass-Spring-Damper Systems

Strings combines three different MSDS as layers of interaction and as mechanism for media generation. One of the MSDS is of natural origin and represents the set of strings on an acoustic violin. The other two MSDS are implemented as computer simulations.

The modelling of the MSDS follows standard conventions. The MSDS consists of mass-points and springs. Each spring creates an elastic connection between two mass points. Mass-points are characterised by their mass, springs are characterised by their stiffness and damping. Spring tension forces arise when springs deviate from their rest lengths. These tension forces are calculated according to Hooke's law. Damping forces arise when mass-points move and oppose this movement. These damping forces are proportional in their strength to the velocities of the mass-points and the forces point into the opposite directions of the velocities.

3.1.1. Image MSDS

The MSDS for controlling image synthesis is implemented in the OpenFrameworks programming environment[2]. The MSDS consists of mass-points and springs that are interconnected with each other in a two-dimensional triangular lattice arrangement. The number of mass-points and springs in this lattice is dynamic and changes in response to a live-captured video image (see Section Mapping). The MSDS consists of three types of

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[2] https://openframeworks.cc/

mass-points and six types of springs. These types differ among each other in their physical properties and in the elements of the lattice they control (see Figure 1, top right side).

Mass-points of the first type are immobile. They are located at the same positions as feature points in a live-captured video image (see Section Capture) and serve as anchors for the lattice. The other two types of mass-points are mobile. One type of mobile mass-points is located within the interior of lattice regions, the other type is located at the periphery of lattice regions.

The different types of springs are as follows: *Origin* springs connect non-mobile and mobile mass-points with each other. Their purpose consists in pulling the lattice back into its initial position defined by features in the video image. *Triangle* springs follows the circumference of lattice triangles. *InterTriangle* springs connects neighbouring lattice triangles. *Region* springs follows the circumference of all regions within the lattice. *Structural* spring connect mass-points that lie at the opposing ends of two neighbouring triangles. *InterRegion* springs connect neighbouring regions.

3.1.2. Sound MSDS

The MSDS for controlling sound synthesis has been implemented in the CSound programming environment[3] and follows the implementation described by Comajuncosas (Comajuncosas 2000). The MSDS consists of a total of 28 mass-points and 24 springs (see Figure 1, bottom right side). All mass-points and springs possess their own physical parameters. The MSDS is organized into 4 groups, each combining 7 mass-points and 6 springs. Within each group, the mass-points are arranged on a line and equally spaced. The two mass-points located at the periphery of this arrangement are immobile whereas the mass-points located in between are mobile. All mass-points within a group are linearly connected by six springs. When this MSDS is excited, the mass-points move vertically away from their original arrangement.

3.2. Input Media for Interaction

While certain physical aspects of the MSDS used for image and sound synthesis are controlled through graphical user interfaces, the main form interaction is based on the live capture and analysis of the violinist's activities on stage. The capture and analysis is performed both in the visual and acoustic domain.

A camera[4] that is placed at the front edge of the stage captures the position and appearance of the violinist on stage. Video analysis serves the purpose of identifying salient positions within the camera image. The analysis involves the following processing steps: image blurring, edge detection, edge simplification, and edge point extraction. The extracted points form the basis for constructing the image MSDS.

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3. https://csound.com/

4. Intel Realsense D435

Sounds produced by the violinist are recorded with a microphone that is mounted on the instrument. Sound analysis serves the purpose of detecting prominent frequencies in the timbre of the violin sounds as well as moments of silence. Identified frequencies and their amplitudes are used to control the excitation of both the image and sound MSDS. Moments of silence are used as windows of opportunity to apply large modifications to the MSDS while minimizing audible and visible discontinuities. Sound analysis involves the following processing steps: Fast Fourier transform, amplitude-based frequency sorting, identification of fundamental, and scaling and selection of partials according to consonance. The sorted and scaled frequencies and amplitudes are used for exciting the sound MSDS.

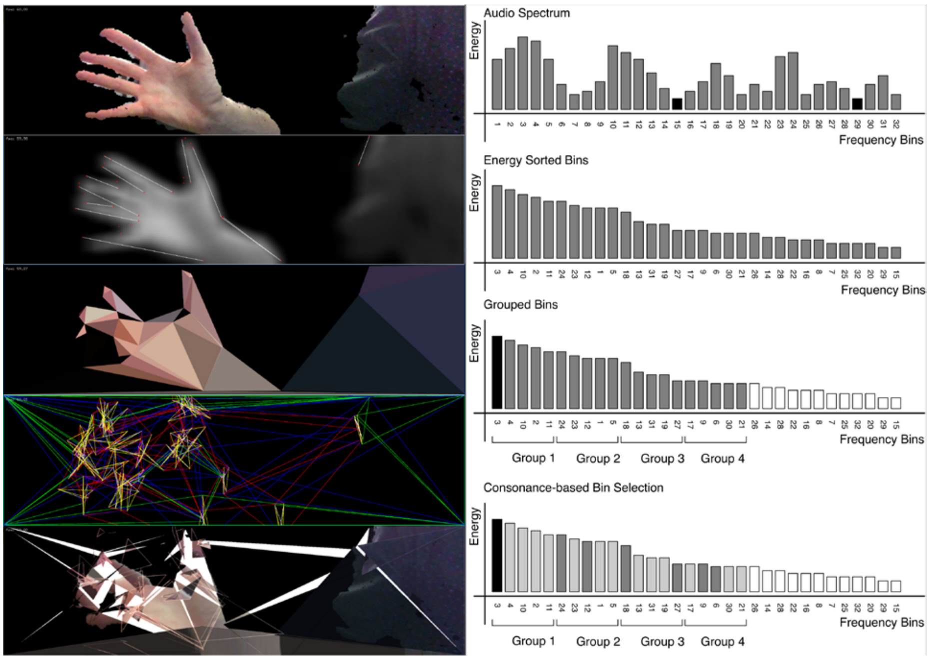

Fig. 2. Sound and Image Analysis and Generation.

The image on the left depicts the creation of a synthetic image from a live captured camera image. From top to bottom, the processing stages are as follows: The camera image, salient contours and feature points in the camera image, Delaunay triangulation derived from feature points and coloured according to the camera image, a MSDS created from the triangulation, and the final rendering of the MSDS as a synthetic image. The image on the right shows the process of analysing the acoustic spectrum of the live microphone input. From top to bottom, the processing stages are as follows: frequency bins obtained by Fast Fourier analysis, frequency bins sorted by amplitude levels, identification of fundamental and assignment of frequency bins to four groups for later use for the excitation of the four sound producing MSDS, and identification of consonant partials.

3.3. Media Generation

The previously described MSDS control the generation of both synthetic video and audio. These media form together with the violinist's performance the perceivable content of *Strings*.

The video image is constructed by drawing a triangulated mesh. The shapes and positions of the mesh's triangles is directly derived from the lattice triangles present in the image MSDS. The triangles are coloured by either using the captured video image as texture or by interpolating between colours that are sampled in the captured video image at the corner positions of the triangles. The outline of the triangles can be drawn as lines in an arbitrary but constant colour or the outline can be hidden. The rendered mesh can further be post-processed by applying horizontal and vertical blurring and by cropping and re-scaling the colour histogram. Two triangulated meshes are drawn on top of each other with each one being controlled by a different image MSDS and rendered with individual settings. Subsequently, the blending between these two rendered meshes can be controlled by varying the addition and multiplication factors of the blending. The blended output is then composed on top of the previously rendered frames.

The sound MSDS whose simulation is updated at audio rate is used as sound synthesis system. The sonification is based on a direct audification (Surges et al. 2015) technique: the deflection of a selected mass-point in each MDSD group is directly translated into an audible audio waveform. Four of these waveforms are created in parallel from the four MDSD. They create individual voices in the musical output.

3.4. Mapping

Different mapping layers form part of the implementation. Mapping layers exist for the translation of the output from video and sound analysis into the creation and control of the respective MSDS. A further mapping layer connects the two MSDS with each other. And two additional mapping layers connect the two MSDS to the image and sound synthesis systems.

3.4.1. Video Analysis to MSDS

A Delaunay triangulation is applied to the feature points in the camera image. The triangles are colourized based on colours taken from the camera image. Depending on colour similarity and spatial proximity, triangles are assigned to identical or different regions. Each region is transformed into a preliminary MSDS. In this preliminary MSDS, mass-points correspond to triangle corners and springs correspond to triangle edges. These preliminary MDSD are then combined and their mass-points and springs diversified into different types in order to create the final image MSDS.

The number of camera image feature points also affects the excitation of the sound MSDS. The number of feature points is mapped on the maximum number of frequency bins that can be used for exciting the sound MSDS. As a result, the amount of detail present in the captured video will affect the level of detail of both the synthetic sound and the synthetic image in a similar manner.

3.4.2. Sound Analysis to MSDS

In case of the image MSDS, springs are assigned based on their rest-length to the different frequency bins obtained from sound analysis. Springs with shorter rest-lengths are assigned to higher bins and springs with longer rest-lengths are assigned to lower bins. If the frequency exceeds an amplitude threshold, the assigned springs are made to oscillate with an amplitude and frequency that is proportional to the amplitude and frequency of the bin.

In the case of the sound MSDS, the amplitudes from the sorted and grouped frequency bins are used for the mapping. The bins' frequencies control the stiffness of the springs which in turn affects the spectral energy distribution that is generated by the excited MSDS. The amount of excitation that is applied is proportional to the bins' amplitudes.

Based on moments of silence that are detected by sound analysis, an average duration of the violinist's sound production is calculated. These durations are used to control the spring damping of the sound and image MSDS. The damping values are inversely proportional to the sound durations. In case of the sound MSDS, damping controls how quickly the acoustic output of the sound synthesis system falls to silence once the MSDS is no longer excited. In case of the image MSDS, the velocity of the mass-points is mapped to the transparency value of the rendered meshes with the transparency values being inversely proportional to the mass-point velocities. Since damping affects how quickly the velocities of the mass-points decay to zero, changing the damping value has a perceptually similar effect on the synthetic image as on the synthetic sound in that it affects how quickly both disappear.

3.4.3. MSDS to MSDS Mapping

The image and sound MSDS can be related to each other by exchanging mean values for physical parameters such as the mass of mass-points and the stiffness and damping of springs. The strength of this exchange can be controlled by the performers. Furthermore, the positions of the excitation signal pickup up by the sound MSDS is spatially mapped onto the image MSDS. This mapping controls the strength of the sound induced spring oscillations in the image MSDS with the oscillations being strongest at the centre of the mapped position and then gradually falling off towards more distant springs.

3.4.4. MSDS to Image and Sound Synthesis

In both cases, the mapping from MSDS to media generation is trivial since the image and sound generation principles are closely related to the structural and functional properties of the MSDS. In case of the image MSDS, the mapping controls the creation of a triangulated mesh. This mapping applies a spatial transformation that preserves in the resulting image the topology of the spring lattice and its spatial arrangement. In case of the sound MSDS, the mapping scales the deflection of the mass-points to an amplitude value that lies within a range suitable for creating an audio waveform.

4. Interaction and Improvisation

The violinist's activities shape the visual and acoustic content of *Strings*. It is through the recording and analysis of his performance that he profoundly affects the properties and behaviour of the two MSDS. His visual appearance controls the structure of the image MSDS and it is musical output excites the two MSDS into producing a visible and audible output.

The laptop performers will predominantly interact with the two MSDS by controlling those physical aspects that are not influenced by the violinist. This includes altering the rest lengths of springs in the image MSDS and altering the masses of the mass-points in both MSDS.

A particularly important physical parameter to interact with is that of the springs's damping factor. Depending on the value of this parameter, the two MSDS will either quickly return to rest after having been excited by the violinist or they will continue to oscillate. If the damping factor is particularly low, these oscillations quickly become unstable and result in self-sustained and chaotic behaviours. In this situation, the two MSDS are barely controllable and can therefore be considered to behave as autonomous and self-improvising entities. On the other hand, if the damping value is very large, the two MSDS depend in their activities on a continued energy input that is provided by the violinist. Under these conditions, the MSDS possess very little autonomy and operate more akin to a digital extension of the acoustic violin.

5. Results

The results presented here are preliminary since *Strings* is still under development and the main rehearsals have yet to take place. The following section presents first insights into the capability of the MSDS to produce acoustic and visual outputs and the characteristics of these outputs.

5.1. Visual Output

In general, the visual output of the image synthesis system takes the form of a minimalistic polygon-rendering of the visual situation on stage. The rendered image varies in its appearance and dynamic change between mirroring and abstracting the violinist's appearance and movements. The balance between mirroring and abstraction depends mainly on the following aspects: texturing versus interpolation of colours, reconstruction frequency of the MSDS from camera image feature points, deviation of the spring rest-lengths from the distances between camera image feature points, and the amount of spring damping.

When texturing the mesh triangles with the camera image, the rendering results in a visual appearance that is reminiscent of shards of a fractured mirror that reflect their surroundings. If instead the colours are interpolated from individually sampled positions in the camera image, the rendering resembles a mosaic consisting of differently sized and coloured tiles.

The MSDS can either be reconstructed for every new camera frame or it can be reconstructed only occasionally. In the former case, the rendered mesh continuously align with the visual appearance of the violinist, creating a more or less faithful image of him. In this setting, the movement of the MSDS is of lesser importance compared to the movements of the violinists that dominate the dynamics of the synthetic image. Contrary to this, when the MSDS is only rarely updated from the camera image, the movements of the MSDS dominate visually and they cause an earlier depiction of the violinist to move in a manner that is unrelated to the violinist's own movements.

Changing the rest-lengths [RL] of springs in the MSDS causes a distortion of the synthetic image whose characteristics depends on the particular spring types that are being affected. Changing the RL of *Origin* springs pushes all triangles towards the periphery. Changing the RL of *Triangle* springs causes the triangles to shrink or expand. Changing the RL of *InterTriangle* springs causes gaps to appear or disappear between the triangles. Changing the RL of *Region* springs leads to a compaction or expansion of similarly coloured parts within the mesh. Changing the RL of *InterRegion* springs causes dissimilarly coloured parts to separate from each other. Changing *Structural* springs causes a more or less equal distortion of all triangles.

Changing the amount of spring damping affects the oscillatory movements that the synthetic image exhibits in response to exciting stimuli received from the acoustic output of the violinist. These oscillatory movements translate into visual form the principle of acoustic vibrations. This visual analogy is emphasized by relating the transparency of the triangles to the velocities of the mass-points. As result, strongly oscillating parts in the synthetic image become visually dominant whereas non-oscillating parts disappear. When choosing very low spring damping parameters, the oscillations of the MSDS start to supersede and disrupt the former spatial relationships that existed among the feature points in the camera image. Such a heavily oscillating synthetic image loses its visual relationship to the original camera image and appears as a fast flickering mass of colours.

Videos are available online that showcase the following aspects of image synthesis: varying the rendering of the triangulated mesh[5], varying the

[5] https://vimeo.com/391715587/fcb605725f

reconstruction rate of the MSDS[6], varying the rest-length of springs[7], externally controlling the oscillations of springs[8].

5.2. Acoustic Output

By mapping selected amplitudes and frequencies from the analysis of the sound produced by the violinist to the vertical deflection of mass-points and the stiffness of springs, the violinist is able to affect the timing, duration, amplitude, pitch and spectrum of the synthetic sounds. Apart from spring stiffness, the mass of mass-points also influences the pitch of the synthetic sounds. What can also be varied are the positions within each of the four sequentially arranged MSDS at which the MSDS is excited and at which the response to this excitement is picked up. Changing these positions affects the amplitude and spectrum of the synthetic sounds. The closer the excitation and pickup positions are to each other, the more the acoustic characteristics of the excitation signal is still present in the synthetic sounds. When this distance is increased, the amplitude dynamics of the excitation signal is smoothed out and the resonant frequencies of the MSDS are dominating the audible result.

Audio files are available online that showcase the following aspects of sound synthesis: varying spring stiffness causes pitch variations[9], varying mass-point mass causes pitch variations[10], varying positions for excitement and response affects amplitude dynamics and resonant frequencies[11], varying spring damping moves the system between stable to unstable regimes[12].

6. Next Steps

Up to now, *Strings* has been developed with only an occasional involvement of the violinist. Accordingly, the main tasks of integrating the MSDS and synthesis systems into an improvisational setting are still ahead of us. In particular, we have to verify whether the violinist is at ease with a situation in which his musical performance is the main factor influencing the generation of synthetic video and audio. This being at ease not only requires the violinist to be willing to cope with the challenge of improvising together with two partially autonomous generative systems. It also requires that the violonist's playing doesn't cause a flurry of audio-visual consequences that is difficult for him to control and that interfere with his own aesthetic intentions. The authors anticipate that during the first phases of extensive rehearsals, some of the mappings that translate the violinist's performance into the structure and behaviour of MSDS will need to be tuned or redesigned. In addition, it is also likely that a pre-defined performance sequence will need to be established that organises the improvisation into multiple sections. These sections will differ from each other with respect to the level of interdependence among all participating systems and performers.

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6. https://vimeo.com/391715750/1b64bb3355

7. https://vimeo.com/391716174/472eb3585e

8. https://vimeo.com/391716466/131276ce8b

9. http://e-wegner.net/data/strings_example_01.wav

10. http://e-wegner.net/data/strings_example_02.wav

11. http://e-wegner.net/data/strings_example_03.wav

12. http://e-wegner.net/data/strings_example_04.wav

7. Conclusion

The project is motivated by the author's desire to integrate both human performers and generative systems into a shared improvisation setting. The sharing of this setting is enabled through the adoption of a particular physical principle and its establishment as common principle for the creation of music and video. By choosing the phenomena of an oscillating string as this physical principle, it becomes possible to directly relate the sound producing principle of an acoustic string instrument to simulated abstractions of this principle which in turn drive the generative creation of synthetic video and audio. Based on such a direct and consistent relationship between natural and simulated forms of string oscillations, several levels of correspondence can be established between the acoustic instrument and the generative systems.

On the level of physical correspondence, the principle of excitation can be employed to transfer the acoustic output resulting from vibrations of violin strings into actuations of simulated strings.

On the level of interaction correspondence, the previously mentioned physical principle allows effective gestures (Cadoz and Wanderley 2000) for controlling the violin to also serve as effective gestures for interacting with the generative systems. The capturing of the effective gestures by means of a camera extends the range of responses that the generative systems can exhibit while still staying consistent with the principle of gestural interaction.

On the level of aesthetic correspondence, the equivalence of the relationship between physical parameters and acoustic result can be exploited to establish an aesthetic proximity between the musical output of the acoustic and digital instrument. Such a similarity can be approximated in the synthetic image by displaying oscillations as periodic spatial perturbations and by linking the oscillation's amplitude to the visibility of said perturbation.

On the level of autonomy and control, a correspondence can be established in which both the natural and simulated physical behaviour of oscillating strings can gradually vary between predictable and chaotic regimes. As such, both the acoustic instrument and generative system lend themselves to exploration and experimental forms of performance.

To summarize, *Strings* unifies several formerly disparate approaches for integrating physical simulations into performance settings. Rather than employing a physical model solely for sound synthesis or for establishing an interaction layer, the employed approach combines sound synthesis, image synthesis, and interaction through the use of a common physical model. Also, the proposed work uses a physical model for correlating audio-visual media both as input modalities for the simulated physical interaction layer and as synthetically generated outputs. The authors believe that such a combined approach is novel and original.

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