Pendulum — Exploiting Simple Physics for Generative Art

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Abstract

Pendulum is a kinetic audio installation that directly relates physical movement with musical output. The installation consists of four free hanging pendulums that are actuated by computer controlled propellers. Each pendulum houses either a microphone or loudspeaker at its bottom. As the loudspeakers and microphones travel along quasi-periodic trajectories, their changing spatial relationships manifest sonically through continuously changing acoustic feedback.

This installation represents an attempt to exploit the interplay between simple physical and computational processes as main constituents for establishing the generative and interactive characteristics of an artwork. It is through this interplay, that the generative processes become perceivable and are rendered responsive to the surrounding environment and the presence and activities of visitors.

This work highlights how natural and computational principles can be employed in a complementary manner for establishing consistency between the perceptual, behavioural and interactive aspects of an artwork while at the same time relinquish the need for devising complicated mapping, sensing, and interaction mechanisms.

1. Introduction

Pendulum is a kinetic audio installation that has been realised by the authors of this article. The installation consists of four pendulums whose movements result from a combination of passive physical dynamics and motorised actuation. Each pendulum houses either a loudspeaker or microphone at its end. The pendulums' movements cause the orientations and distances among the microphones and loudspeakers to continuously change. This gives rise to a variety of acoustic feedback effects. Simple computational algorithms are employed to control the motorised actuation of the pendulums and the attenuation and routing of the acoustic feedback. The musical content of the work emerges from the interplay between physical movement, acoustic feedback, and computational control.

Pendulum constitutes to some degree a continuation of one the author’s previous experiments that dealt with the combination and blending of a generative system with the spatial and perceptual characteristics of its physical environment [1-3]. But *Pendulum* differentiates itself from these previous activities in that it exploits physical principles as integral constituents of the generative characteristics of the work. By doing so, the work connects with a tradition that is more firmly rooted within the field of sound art and electroacoustic music than it is within generative art.

2. Background

Artistic approaches that place their creative focus on the establishment of a close relationship between the physical characteristics of an electromechanical system and the musical content have started to emerge in between 1960 and 1970. These approaches took place as part of an avant-garde movement that formed in order to counter an increasing tendency in electronic music that aimed to liberate the perception of musical material from its sound producing origin. Several artists around that time experimented with the physical principles of loudspeakers. These artists treated loudspeakers not as hidden technical black boxes but rather as musical instruments in their own right. Famous pieces that were created through this approach are for example *Music on a Long Thin Wire* (1977) by Alvin Lucier [4] and *Rainforest* (1968) by David Tudor [5]. *Music on a Long Thin Wire* employs a deconstructed loudspeaker that consists of a long and exposed metal wire. The wire is mechanically excited by passing alternating current though it which is supplied by a signal generator. This causes complex vibrations and resonances that are amplified using contact microphones placed at either end of the wire. The piece *Rainforest* also exploits the resonant characteristics of physical materials. Here, several different customised loudspeakers are used. These loudspeakers consist of objects such as cartwheels, bedsprings and oil drums which are made to resonate by electromechanical transduction elements.

Within the context of kinetic art, even more radical attempts have been undertaken to coalesce technical mechanisms and sonic results. These approaches typically combine kinetic movement and physical materials to create semi-industrial assemblages that produce sounds though the repeated striking of these materials. The resulting sonic output consists of the acoustic emissions of the motorised movements and the vibrational response of the excited objects and surfaces. Jean Tinguely is a famous representative of this approach. He has been realising kinetic audio installation since the 1950’s. Examples are the large industrial-sized assemblages that form part of the *Meta-Harmonie* series (1979-85) [6]. These assemblages consist of steel cogs, wheels, wires, belts and musical instruments that emit a cacophony of mechanical noises, as well as percussive and pitched sounds. This approach to kinetic sound art still enjoys some popularity among contemporary artists. One artist under the pseudonym of Zimoun has become well known for his room filling robotic installations which typically consists of a large number of small and simple motorised devices, each of them emitting sounds through mechanical collisions and movements [7].

Of particular interest among many sound artists who experiment with electromechanical principles is acoustic feedback. This phenomena results from a positive feedback loop that is established by routing an audio signal from a recording device to an emitting device whose output is then once again picked up by the recording device. This feedback gives rise to a variety of acoustic effects including sound colouring, pitch shifts, and volume alterations. The motivation to employ acoustic feedback as a means for creating sonic artefacts started to play an important role in the 1960's as part of this decade's general rebellious attitude towards established cultural, social and political norms [8]. Of bigger interest in the context of this publication is the artistic use of feedback as a source of unpredictability and instability. Since acoustic feedback is hard to control, it can be integrated as an element of improvisation in a musical performance. An early example of such an approach is the piece *Quintet* (1968) by Hugh Davies. In this piece, five performers carry microphones in their hands and walk towards and away from loudspeakers that are situated in the corners and the center of a stage. The performers follow clear instructions as to what kinds of sounds they should produce through feedback. As the piece progresses, the routing of microphones and speakers changes and forces the performers to rediscover the positions and movements that are necessary for creating the desired musical results.

The sensitivity of acoustic feedback to changes of distance between sound recording and emitting devices can be exploited to drive musical changes and developments throughout a piece. By moving loudspeakers and/or microphones, the sonic output continuously varies due to changes in sound volume, signal phase, acoustic reflections and doppler effects. And also, through movement, the loudspeakers and/or microphones gain prominence on stage both as sounding and performative objects that draw the focus of the audience's attention. Accordingly, working with the combination of movement and acoustic feedback draws from artistic methods and offers creative opportunities that are of interest for musicians and kinetic artists alike.

The piece *Pendulum Music* (1968) by Steve Reich [9] illustrates very well how installation-based and performative approaches can be combined. In this piece, several microphones hang above an equal number of loudspeakers. At the beginning of the piece, the microphones are pulled by performers and then released to swing directly above the loudspeakers. From then on, the performers no longer interfere and its only through the gradually decreasing amplitude of the pendulum movements that the music of the piece transitions from brief and intermitted bursts to longer sounds that vary in pitch and colour until eventually the microphones comes to rest and the musical output settles into a continuous sound.

This piece is relevant in the context of this publication for an additional reason. It exemplifies how the autonomous behaviour of physical objects can form an integral element of a musical process. And it also shows how feedback can be exploited as mechanism that establishes an intricate and complex network of interdependencies between all elements on stage and the musical output. The piece contains in itself the transition from a conventional concert setting that centres on the activity of human performers to a situation in which the human performers relinquish control to allow non-human entities to play their own role in the unfolding of the work. Depending on the complexity of the behavioural relationships among all non-human entities, this unfolding takes place in an unpredictable manner that can lead to an emergent musical result. David Toop describes this kind of unfolding as the *drama of natural emergent phenomena* [10]. This focus on process and potentially open ended results is related to the notion of the *open work* by Umberto Eco [11]. But in contrast to Umberto Eco, Steve Reich makes a clear distinction between process-based musical works for which the autonomous processes took place prior to a performance and those works in which, as is the case with *Pendulum Music*, the processes are ongoing in front of the audience. Its this latter approach that in combination with the presence and behaviours of physical objects can foreground the processual characteristics of an artistic work and therefore allows the audience to directly witness the processual unfolding of artwork's form.

3. Concept

The installation *Pendulum* has been realised in the context of a research project entitled *Feedback Audio Networks (FAUN)*. The goal of this research project is to explore the application of time-delay and feedback mechanisms as main principles for the generation of musical material [12]. But contrary to our previous experiments, *Pendulum* renounces the sole use of sound synthesis in favour of an approach that integrates both physical and computational processes.

The realisation of *Pendulum* is based on the establishment of a mutual dependency between kinetic movement and musical result. By creating a situation in which the musical output is almost exclusively dependent from and shaped by physical movement, the role of the composer and the methods of creation are drastically altered. As consequence, the composer needs to develop his or her musical ideas by working in the domain of physical movement. But even more importantly, the characteristics of this physical movement and its connection to the resulting sound underlie constraints and possibilities that are often outside of the composer's control. Therefore, composition becomes an exploratory endeavour throughout which an understanding and appreciation needs to be developed for the partially autonomous processes at play.

This creative technique is of course shared by many generative approaches. But what is more unusual is the fact that the autonomous processes result predominately from the interplay of physical phenomena whereas computational principles are relegated into a secondary role. In this secondary role, computation serves to allow a composer to exert a larger and more nuanced degree of control over the physical phenomena than would be possible otherwise. It is important to note, that in *Pendulum*, computational processes don’t contribute any acoustic material on their own. Rather, it is through computation that the diversity of the physically created musical material is expanded.

Working with kinetic movement and acoustic feedback directly rather than through a computer simulation offers several opportunities and benefits. First and foremost, the physical system creates interesting feedback and time-delay effects naturally, that is for free, without the need for developing an elaborate computational signal processing system. And the diversity of acoustic effects that originate from a physical system is likely larger that it would be from a simulation. This is owed to the fact that all physical and technical components involved add through their inherent imperfections and variations to the diversity of the musical output. Most of these effects would be very hard or at least time consuming to mimic in simulation. The surrounding space of the installation forms part of this network of interdependencies through its capability to alter the absorption, reflection and resonances of acoustic waves. For this reason, an installation whose musical output is produced through acoustic feedback effects naturally becomes site specific. The employment of physical principles as basis for creating music can have a beneficial impact on the audience. Since both kinetic movements and acoustic feedback are familiar phenomena, they can render the artistic intent and the musical result readily apparent for the audience. Furthermore, people’s intuition about everyday physics creates ideal prerequisites for interactivity. The physical behaviour of the installation invites the audience to intervene through physical activities. And the installation’s response to interaction is again readily understandable due to its grounding in physical principles. This provides the unique opportunity to provide a playful and rewarding setting for audience engagement without the necessity to sacrifice the processual complexity of an artwork for the sake of clarity and intuition.

4. Implementation

This section provides a technical overview of the *Pendulum* installation. This includes a description of the hardware and software components that were specifically developed for the installation.

4.1 Hardware

The installation consists of four free hanging pendulums. Two of the pendulums are equipped with a loudspeaker and two with a microphone each. The microphones have a hypercardiod characteristics and record sounds in a highly directional manner. The loudspeakers consist of a broad band speaker driver and is used without casing. The main length of a pendulum is made from a hollow aluminium rod that is either two or four meters in length. These different lengths have been chosen in order for the pendulums to exhibit more diverse kinetic movements and to provide for the audience different listening and interaction situations. The upper end of an aluminium rod is connected with a steel wire to an electrical slip ring that in turn is fixed with a mechanical clamp to a support structure. The bottom part of a pendulum consists of a horizontal boom construction to which two propellers and either a loudspeaker or a microphone are mounted (see Figures 1 and 2). Each propeller is actuated by a brushless motor. The propeller-motor combination sits in a wooden cage that can be rotated about 180 degrees around its vertical axis. This rotation is controlled by a servo motor that is connected by a pulley with the cage’s rotational joint. The loudspeakers and microphones are mounted underneath the propeller cages and point in a horizontal direction.

Three RGB light emitting diodes (LED) are attached to each pendulum. Two LEDs are fixed on top of the cages' rotational joints and follow their rotation. These LEDs emit their light through the cages and on the propellers. One LED is fixed to the aluminium rod just above the mechanical construction at the bottom of the pendulum. This LED points downwards and illuminates this construction. An absolute orientation inertial movement unit (IMU) that provides nine degrees of freedom (acceleration, gyroscope, compass) is mounted onto a horizontal section of the boom segment. Also mounted to the boom segment are two ESC brushless motor controllers.

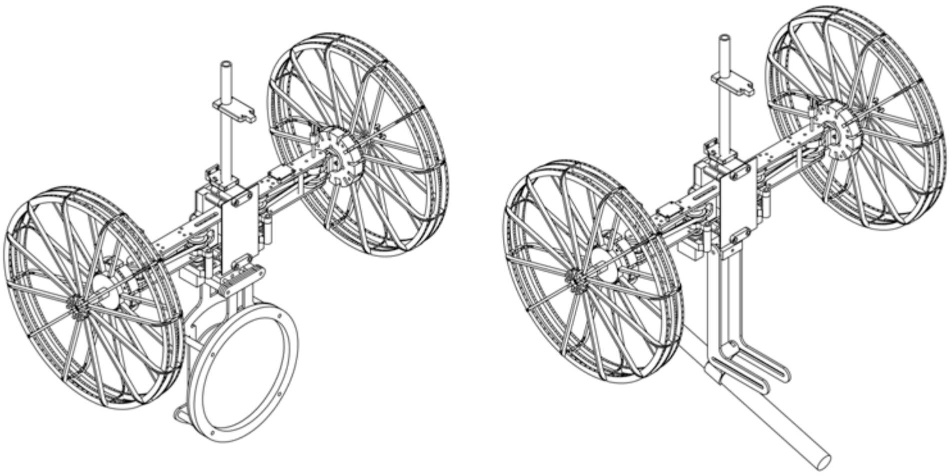

Figure 1: Loudspeaker and Microphone Pendulum. The two schematic images show on the left side a pendulum that houses a loudspeaker and on the right side a pendulum that houses a microphone.

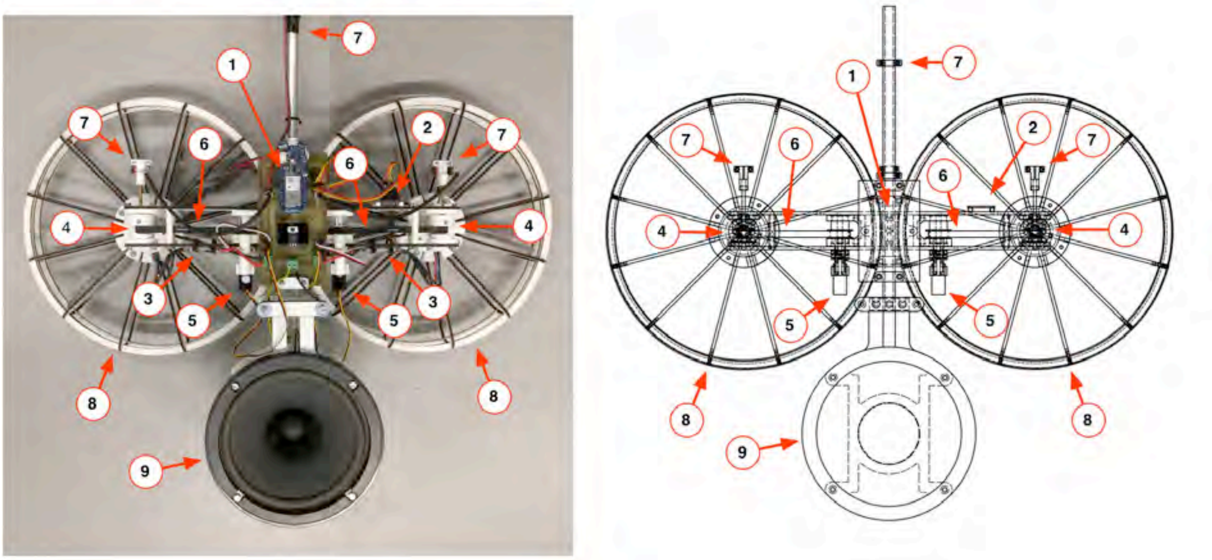

Figure 2: Pendulum Hardware. Both the schematic depiction (left side) and the photograph (right side) provide the same detailed view off the construction that is attached to the bottom of a pendulum. The following components are highlighted: 1) Arduino micro controller, 2) IMU, 3) ESC brushless motor controller (missing in the schematic depiction), 4) brushless motor, 5) servo motor 6) pulley 7) RGB LED, 8) propeller cage, 9) loudspeaker.

Placed vertically in the middle of the boom is a PCB board that contains the power conditioning electronics, control lines, and a Wifi-enabled Arduino micro controller. One 60 Watt power supply provides electrical power for each pendulum. The loudspeakers are driven by a mono audio amplifier. The power supply and audio amplifiers are mounted on a plate above each pendulum. The electrical power lines and the audio signal lines are passed first through a slip ring and then through a five core cable. This cable runs along the interior of the pendulum’s hollow aluminum rod which it exits underneath the loudspeaker or microphone. The only additional hardware involved is an USB audio interface, a Wifi router, and a Mac Mini computer. The audio signals from the microphones and to the loudspeakers run through balanced XLR cables which are connected to the audio interface. The audio interface provides phantom power for the microphones. All control signals that are exchanged between the Arduino micro controller and a Mac Mini computer as sent via Wifi. An overview of the entire installation setup is provided in Figure 3.

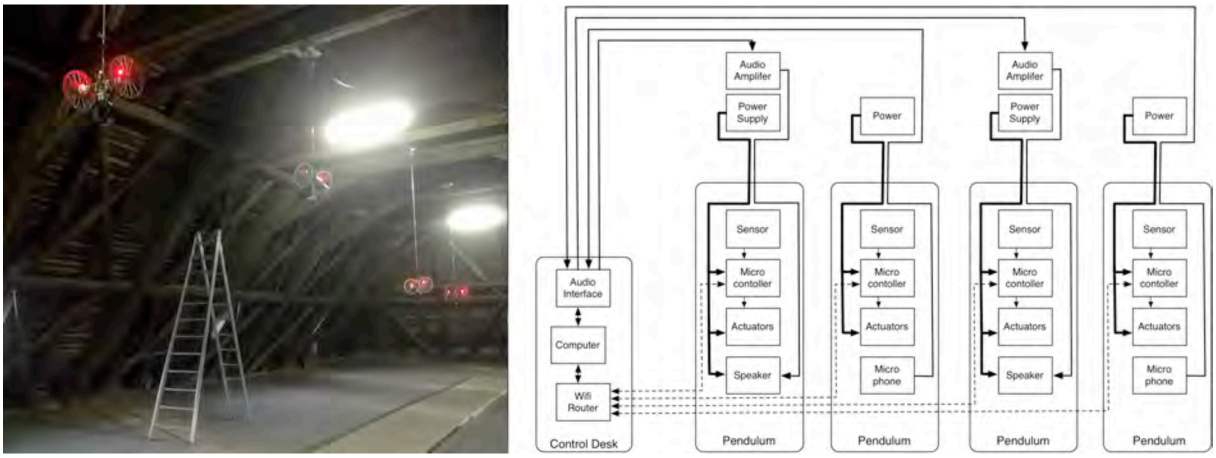

Figure 3: Installation Setup. The left photograph shows the setup of the four pendulums underneath the roof of the exhibition venue in Brugg, Switzerland. The pendulums were arranged in such a way that the two long pendulums and the two short pendulums were hanging pairwise and close to each other whereas the distance in between the pairs was larger. The pendulums carrying a loudspeaker and those carrying a microphone were placed in an alternating sequence. The graphics on the right shows the connectivity and power distribution among all hardware components. Different connection types are depicted by lines of different thickness. From thick to thin, these lines represent: power cords, audio cables, USB cables, PCB control lines. The dashed lines indicate Wifi-based communication.

4.2 Software

The software that controls the installation consists of two parts. One part runs on the Arduino micro controller and the other on a Mac Mini computer.

4.2.1 Micro Controller Software

The functionality of the micro controller software is very simple and only provides the means for remote controlling each pendulum. The micro controller operates as slave and the computer as master. Computer and micro controller exchange messages in the *Open Sound Control (OSC)* format over Wifi. These messages operate bidirectionally. Messages sent from the computer to the micro controller control the speed of the brushless motors, the rotation of the servo motors, and the colour and intensity of the RGB LED’s. Messages sent from the micro controller to the computer provide sensorial information that has been acquired from the IMUs.

4.2.2 Computer Software

The functionality of the software that runs on the computer is more sophisticated. This software has been programmed in the Max/MSP environment and controls the kinetic, visual and acoustic behaviours of the installation. The software’s functionality is organised hierarchically.

At the top level is a scene progression mechanism that controls long term changes in the installation’s behaviour. Each scene consists of a particular combination of kinetic movements, LED settings, and audio signal processing configurations.

Located underneath the top level are software modules that group particular combinations of control and processing settings and procedures into behavioural primitives. There exist different categories of primitives: those defining kinetic movement, those specifying light emission, and those controlling digital audio processing. Some of the primitives simply define fixed parameterisations, other comprise internal mechanisms that operate either in a closed or open loop. In case of the closed loop mechanisms, the sensorial information retrieved from the IMUs and/or from analysis of the acoustic signal is used to alter the operation of the mechanism. All primitives in each category can be independently chosen and combined arbitrarily with any other primitives from the other categories.

Finally, the lowest hierarchical level provides functionality that directly configures and controls the installation hardware. This includes calibration values, speed limits, and communication settings for the brushless motors and servo motors. It also includes intensity gain curves and communication settings for the RGB LED’s. And it includes audio signal analysis, processing, and routing mechanisms for controlling acoustic feedback. This latter functionality will be explained in more detail.

4.2.3 Audio Processing

The purpose of audio signal processing is to provide more control over and increase the sonic diversity of the acoustic feedback effects. An overview over the audio signal processing chain is provided in Figure 4. The chain consists of two branches that are identical and run in parallel. Each branch is associated with one microphone. The outputs of the branches are then passed though a matrix that routes them to the two loudspeakers. This routing is not fixed and can be changed on the fly. Altering the routing strongly affects the feedback effects. If the routing passes the audio signal between pairs of microphones and loudspeakers that are closest to each other, the feedback effect will be strongest and the resonance frequencies will be highest, whereas a routing that involves those microphone loudspeaker pairs which are farthest from each other causes a faint feedback and low resonance frequencies or no feedback at all.

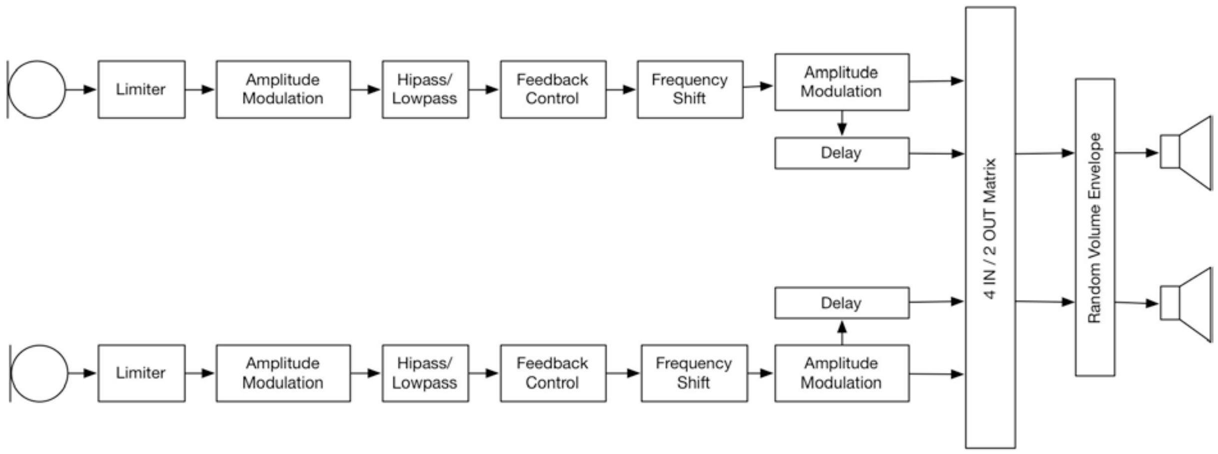

Figure 4: Audio Signal Processing Chain. The schematic figure depicts the digital signal processing chains that the two pre-amplifed microphone signals pass through before being rerouted through a matrix to the two loudspeakers.

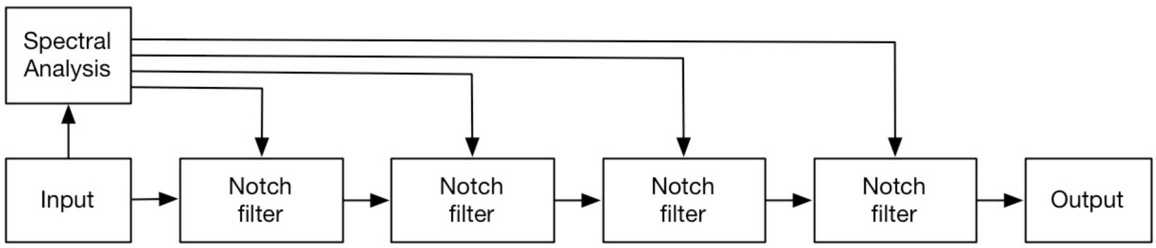

Figure 5: Feedback Control Mechanism. The schematic figure depicts the spectral analysis and filtering stages that form part of the feedback attenuation mechanism.

The signal processing units that from part of the chain between microphone and matrix operate sequentially. At first, the audio signal passes through a limiter unit that constrains the amplitude range. This unit prevents feedback from increasing the audio volume above a certain threshold. Next in the chain is an amplitude modulation unit that either creates a tremolo effect or enriches the sonic output by introducing spectral side bands. Then follows a high pass and lowpass filter that limit the range of frequencies that can be amplified through feedback. After that follows a feedback control mechanism that consists of multiple units. The purpose of this mechanism is to detect those four frequencies that dominate the spectrum of the incoming signal and then specifically attenuate them by passing the signal through four notch filters whose center frequencies correspond to those spectral peaks (see figure 5). The duration for the filters to move their center frequencies can be varied in order to alter the velocity with which the resonance effects are attenuated. Subsequent to the feedback control mechanism is a frequency shift unit. This unit offsets the incoming frequencies and reduces the strength of the feedback effect. This unit can also be used to create musical glissandi. After that, another amplitude modulation unit is employed. Before the audio signal is routed by the matrix, it is split into a direct signal and a delayed version of itself, both of which enter the matrix. The delay plays an important role for creating sonically interesting superposition and interference effects between an immediate and a delayed version of the feedback signal. A final signal processing step is applied after the signals leave the matrix. This step employs a volume envelope that is superimposed on the audio signals own dynamics. The envelope is created from a random walk that varies between zero and -two decibels. This effect is used to slightly and slowly vary the density of sounds during a scene.

5. Installation Behaviour

The following section describes the three types of behaviours that the installation can exhibit: kinetic movement behaviours, light emission behaviours, and musical behaviours. As previously described, kinetic and musical behaviours are inherently connected due to a physics-based dependency between acoustic feedback and movement. Therefore, the distinction between movement and music only serves the purpose of structuring this description. The movement dependency of the light behaviours is more trivial and more contrived. It is trivial since the emission of light from LED's obviously is affected by the orientation of and occlusion by the pendulums. And it is contrived in that several of the lights' behaviours are caused computationally by mapping the output of the IMU sensors to light parameters. Nevertheless, the lights play an important role in shaping the visual atmosphere of the installation and highlighting particular kinetic movements and musical changes.

5.1 Movement

Obviously, a pendulum is a very simple physical object that exhibits periodic movements. In case of our installation, each pendulum possesses three degrees of freedom: it can swing in any direction and rotate around its own axis. The propellers serve to initiate and modify the pendulums' movements. By adjusting the orientation and speed of the propellers, each pendulum can be made to follow simple or complicated spatial trajectories. These trajectories have been organised as a set of movement primitives that are schematically depicted in Figure 6. The *Oscillation* primitive is created by orienting the propellers in a perpendicular direction with respect to the pendulum's boom segment. Each propeller is turned on and off in alternation. This switching is triggered whenever the gyroscope sensor value reaches a minimum. The *Rocking* primitive is similar to the *Oscillation* primitive in that it causes the pendulum to swing back and forth. But contrary to the *Oscillation* primitive, the two propellers are oriented in parallel with the pendulum's boom segment facing into the same direction and they are turned on and off at the same time. To decide wether the propellers should turn off or on, not only the gyroscope sensor value is taken into account but also the compass sensor value along the X-axis. For positive orientations, the propellers are turned off, for negative orientations, they are turned on. The amplitude of the swinging movement is larger for the *Rocking* primitive than for the *Oscillation* primitive since both propellers contribute simultaneously to the propulsion. For the *Rotation* primitive, the propellers are oriented in parallel with the pendulum's boom segment but face into opposite directions. This causes the pendulum to rotate around its own axis without deviating from its vertical hanging position. In the *Circling* primitive, one propeller is oriented in a perpendicular direction with respect to the pendulum's boom segment and the other propeller is oriented more or less at 45 degrees. This orientation causes the pendulum to follow a circular path with the perpendicular propeller facing towards the center of the circle and the other propeller facing outwards. This movement primitive is difficult to achieve since small deviations of the propellers' orientations or small differences in the propellers' speeds will cause the pendulum to rotate around its own axis while still following the circular trajectory. This latter type of movement is aimed for as part of the *Looping* primitive. Here, the first propeller has the same orientation as in the *Circling* primitive but the second propeller is oriented in parallel to the pendulum's boom segment. For both the *Circling* and *Looping* primitives, the propellers' orientations are not fixed but slightly altered in response to the gyroscope sensor value in order to stabilise the pendulum's orientation and subsequently its trajectory. Finally, the *Stepping* primitive is somewhat unique in that the propellers are not rotating but rather the propellers' orientation is continuously changed. The propellers swing back and forth between the two orientations that puts them in parallel with the pendulum's boom segment. The overall pendulum movement is small and consist of a slight back and forth rotation around its own axis.

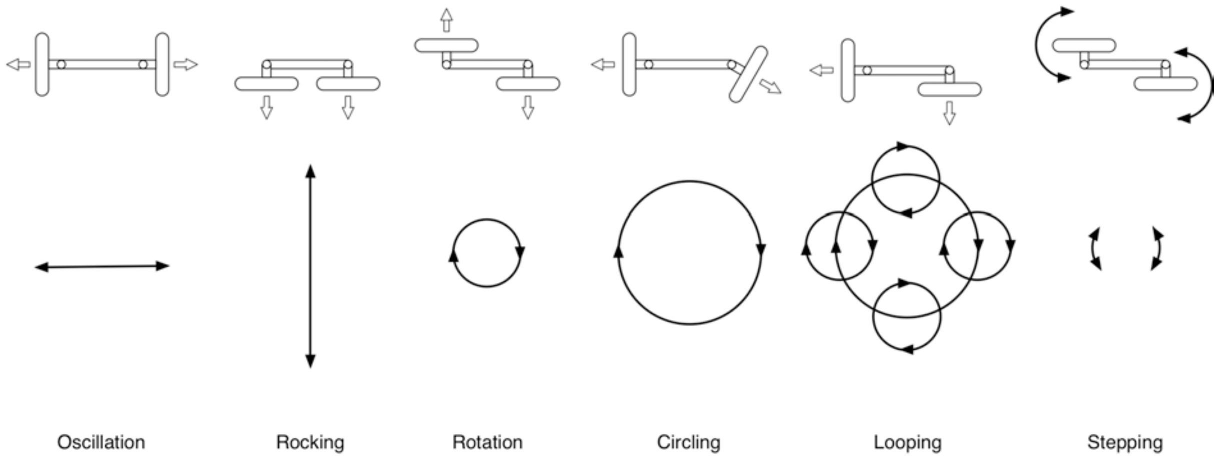

Figure 6: Movement Primitives. The schematic depiction shows all the movement primitives that have been used for the exhibition. The upper half of the image shows a top down representation of a pendulum and the lower half shows a top down view of the pendulum's movement trajectories. The outlined arrows represent air propulsion, the black arrows represent trajectories.

5.2 Light

A total of five light primitives have been created so far. These primitives are used to either highlight the pendulum's shape or to accentuate particular movements by synchronising light changes with these movements. The *Constant* primitive simply sets all LED's to a fixed colour. This primitive is mainly used to cause the mechanical parts of the pendulum, in particular the propeller cage, to cast shadows onto the walls and ground of the exhibition space. The *GyroBrightness* primitive turns the two side LED's off. The brightness of the center LED is changed depending on the gyroscope sensor value. The LED turns off when the pendulum passes through a vertical orientation and turned on when the pendulum reaches its maximum deflection. This light behaviour accentuates the pendulums' swinging motions. For the *OrientationBrightness* primitive, all three LEDs change their brightness at the same time in dependency of the compass sensor value. The rotation angle is subdivided into an even number of angular segments. Whenever the compass sensor indicates an orientation that lies within one of the even numbered segments, the LED's are turned on. And whenever the orientation lies within one of the odd numbered segments, the LED's are turned off. This light behaviour causes a stroboscopic effect that is synchronised with the pendulum's rotational movements. The *OrientationColor* primitive also makes use of all three LEDs but this time the hue value of the LEDs is changed in correspondence with the compass sensor value. One full rotation of the pendulum is mapped into the full range of hue values. This light behaviour is mostly used to enhance the visual effect of slow pendulum rotations. Finally, the *ServoBrightness* primitive makes use of the two side LEDs. The brightness of these LEDs is turned on and off whenever the servo motors that control the cages' orientations exceed an upper or lower threshold in their control value. This gives rise to brief light bursts that alternate with longer phases of darkness and thereby accentuate small non-translational movements of the pendulums.

5.3 Music

The musical primitives take the form of grouped parameter settings for the audio signal processing units. These settings were stored in a hash table from where they could be recalled through numerical indices. A total of ten musical primitives were created for the exhibition. Figure 7 provides an overview over the parameter settings for each of these primitives. Not all parameters are represented in this table but only those whose value changes between different primitives. It should be noted that the parameter settings are very similar for the two audio signal processing chains. The reason for this similarity is based on the aesthetic decision that all the pendulums should behave in a similar manner within each scene.

What follows is a brief description of each musical primitive. The *PureFeedback* primitive barely modifies the incoming microphone signal. It therefore renders the acoustic feedback effect audible in its immediate physical form. The *LocalAmplification* primitive is used in situations in which the microphones and loudspeakers are positioned at a large distance from each other. Accordingly, little feedback is audible. Rather, this preset amplifies local sounds that originate from the immediate vicinity of the microphones. The *AmpModResonance* primitive is one of only two primitives that employs amplitude modulation. This effect is controlled by the compass sensor value. This primitive is also rather unique in that it boosts instead of attenuates the resonance frequencies in case of microphone 1. Pitch shifting and a long delay gain is employed to create slow glissandos and acoustic interference. The *Resonance* primitive is the only other primitive that boosts resonance frequencies. In this primitive, the boosting effect is applied for both microphones. Furthermore, the spectral width of the feedback effect is limited to a narrow range between 53 and 500 Hz. This primitive employs a brief delay time. The *SlowAttenuation* primitive strongly attenuates feedback but only after a long delay. Similar to preset 1, this preset barely modifies the incoming microphone signal. The *QuickAttenuation* primitive also leaves the feedback signal largely unmodified but it very quickly and strongly suppresses it.

The *WeakAttenuation* primitive represents a variation of the *QuickAttenuation* primitive in that it employs an intermediate interpolation time and only weak feedback attenuation. The *NarrowLocalAmplification* primitive is used to amplify local sounds within a very narrow and low spectral band. The *FeedbackEcho* primitive represents a variation of the *PureFeedback* primitive from which if differs by the use of a very long delay time which gives rise to an echo effect in the feedback signal. The *AmpModAttenuation* primitive represents a variation of the *AmpModResonance* primitive. It employs feedback attenuation rather than amplification.

	1	2	3	4	5	6	7	8	9	10
Pendulum 1										
Lowpass Freq in Hz	20	685	53	53	200	20	51	53	20	53
Highpass Freq in Hz	4000	6000	16000	500	4000	3000	1119	500	3000	16000
Interpol. Time Max in ms	1500	500	800	800	1500	70	200	40	1500	500
Interpol. Time Min in ms	500	200	100	100	30	50	100	20	500	100
Filter Gain in dB	-12	-11	2	2	-26	-23	-9	-3	-12	-8
Filter Q	1.83	2.5	1.6	1.6	1.93	1.8	2.5	1.6	1.93	1.6
Frequency Shift in Hz	0.	0.	0.	-1.	0.	0.	-171.	-9.	0.	0.
Delay Time in ms	13.	200.	59.	16.	13.	13.	2000.	20.	8000.	59.
Delay Feedback 0.0–1.0	0.89	0.2	0.77	0.81	0.89	0.89	0.	0.72	0.2	0.77
Delay Gain Out in db	-6.	-6.	0.	-3.	-6.	-6.	-6.	-4.	-6.	0.
Master Gain in dB	-2	0.	0.	0.	-1.4	-1.	-1.	015748	-2	0.
Pendulum 2										
Lowpass Freq in Hz	20	500	53	53	200	20	40	53	20	53
Highpass Freq in Hz	4000	6000	2000	1600	4000	3000	1200	500	3000	2000
Interpol. Time Max in ms	1500	500	800	800	1500	70	200	40	1500	500
Interpol. Time Min in ms	500	200	100	100	30	50	100	20	500	100
Filter Gain in dB	-13	-12	2	-5	-28	-23	-11	-3	-13	-6
Filter Q	1.88	2.5	1.6	1.6	1.88	1.7	2.5	1.6	1.88	1.6
Frequency Shift in Hz	0.	0.	-2.	6.	0.	0.	-206.	6.	0.	-2.
Delay Time in ms	20.	200.	59.	20.	20.	20.	2000.	30.	8000.	59.
Delay Feedback 0.0–1.0	0.355	0.2	0.736	0.66	0.355	0.355	0.	0.578	0.2	0.736
Delay Gain Out in db	-6.	-6.	0.	-7.	-6.	-6.	-6.	-8.	-6.	0.
Master Gain in dB	-2	0.	0.	0.	-0.9	0.9	0.9	0.	-2	0.
Matrix Preset	1	2	3	2	1	1	4	2	5	3

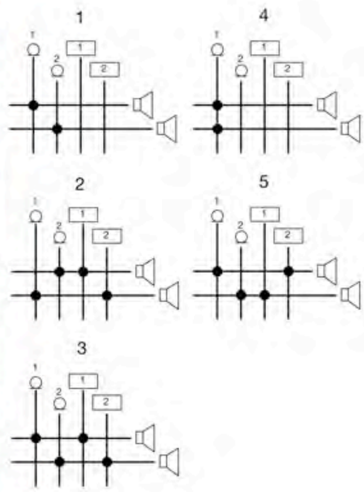

Figure 7: Musical Primitives. The table lists those parameter settings for audio signal processing that vary between musical primitives. For each primitive, the corresponding settings are listed in the column underneath the numerical index of the primitive. The routing configuration of the output matrix is also represented by numbers. The correspondence of these numbers with particular matrix configurations is shown on the right side of the table. In these graphical matrix depictions, outlined circles represent direct audio signals, outlined rectangles represent delayed signals, and filled black circles represent connected signal lines. The correspondence between the numerical index of a primitive and its name is as follows: 1) PureFeedback 2) LocalAmplification 3) AmpModResonance 4) Resonance 5) SlowAttenuation 6) QuickAttenuation 7) WeakAttenuation 8) NarrowLocalAmplification 9) FeedbackEcho 10) AmpModAttenuation

6. Installation Scenes

During the exhibition, the installation progressed repeatedly through a total of thirteen different scenes. Once a scene has finished, the pendulums return for a duration of ten seconds to a default setting before the next scene is initiated. In the default setting, the pendulums are at rest, all motors and led's are turned off, and audio output gain is set to zero. The progression of scenes is partially deterministic and partially randomized. The first and last scenes play the role of opening and closing a full play through all the scenes. These scenes are always chosen at this particular location in the play through. The intermediate scenes are chosen at random through a ballot type system that ensures that each scene is picked only once during a single play through. The duration of each scene is randomised within lower and upper time limits. The exact values of these limits are specific for each scene.

Each scene combines a particular set of movement, light and music primitives. The combination of primitives is always identical or at least very similar for all pendulums. This is based on the aesthetic decision that all pendulums should behave similarly within a scene. This endows each scene with a clear internal consistency and recognisable characteristics. Figure 8 provides an overview over all scenes, their minimum and maximum duration and the different primitives that they are comprised of. For some scenes, a link to a video excerpt on Vimeo is provided. Another visual impression of the exhibition situation and some of the scenes is given by Figure 9. Each of the scenes is described in some detail throughout the following paragraphs.

Scene	**1**	**2**	**3**	**4**	**5**
Min Duration in secs	40	30	60	40	40
Max Duration in secs	90	90	100	60	60
movement primitive	Oscillation	Rocking	Stepping	Rotation	Rotation
light primitive	GyroBrightness	Constant & OrientationBr.	ServoBrightness	OrientationBrightness	OrientationBrightness
music primitive	PureFeedback	PureFeedback	LocalAmplification	AmpModResonance	FeedbackEcho
Scene	**6**	**7**	**8**	**9**	**10**
Min Duration in secs	40	40	30	20	30
Max Duration in secs	70	80	90	60	50
movement primitive	Circling	Looping	Oscillation & Stepping	Rotation	Looping
light primitive	OrientationColor	OrientationColor	Constant	OrientationBrightness	Constant
music primitive	SlowAttenuation	SlowAttenuation	AmpModAttenuation	Resonance	SlowAttenuation
Scene	**11**	**12**	**13**		
Min Duration in secs	30	30	40		
Max Duration in secs	80	70	50		
movement primitive	Rotation & Stepping	Rotation & Stepping	Rotation		
light primitive	Constant	Constant	Constant		
music primitive	QuickAttenuation	WeakAttenuation	NarrowLocalAmplification		

Figure 8: Installation Scenes. The table lists for each of the installation scenes their minimum and maximum duration and the different primitives they make use of.

Scene 1 [13] is the opening scene. Here, the pendulums' movements gradually build up as each propeller turns on and off in alternation. Initially, the pendulums are constantly illuminated by white light from the center LED. But as the pendulums gain momentum, the illumination becomes repeatedly interrupted whenever a pendulum’s gyroscope sensor value exceeds a certain threshold. Acoustic feedback is initially very strong. But after a brief moment, the side-wise movements and orientation changes of the pendulums cause them to only occasionally come sufficiently close to and aligned with each other for feedback to happen. As a result, feedback becomes more intermittent and sonically resembles the occasional chirps of birds.

Scene 2 is similar to scene 1 in that the pendulums’ deflections gradually gain in amplitude. But due to the stronger propulsion of pendulums that results from the simultaneous actuation of both propellers, the swinging motions exceed those of scene 1. As a result, the distance changes among microphones and loudspeakers are more pronounced and cause stronger and shorter feedback effects. The scene combines two light primitives. The center LEDs change their brightness depending on the orientation of the pendulums. The side LEDs are always emitting maximally bright blue light that casts shadows onto the inclined surrounding ceiling walls.

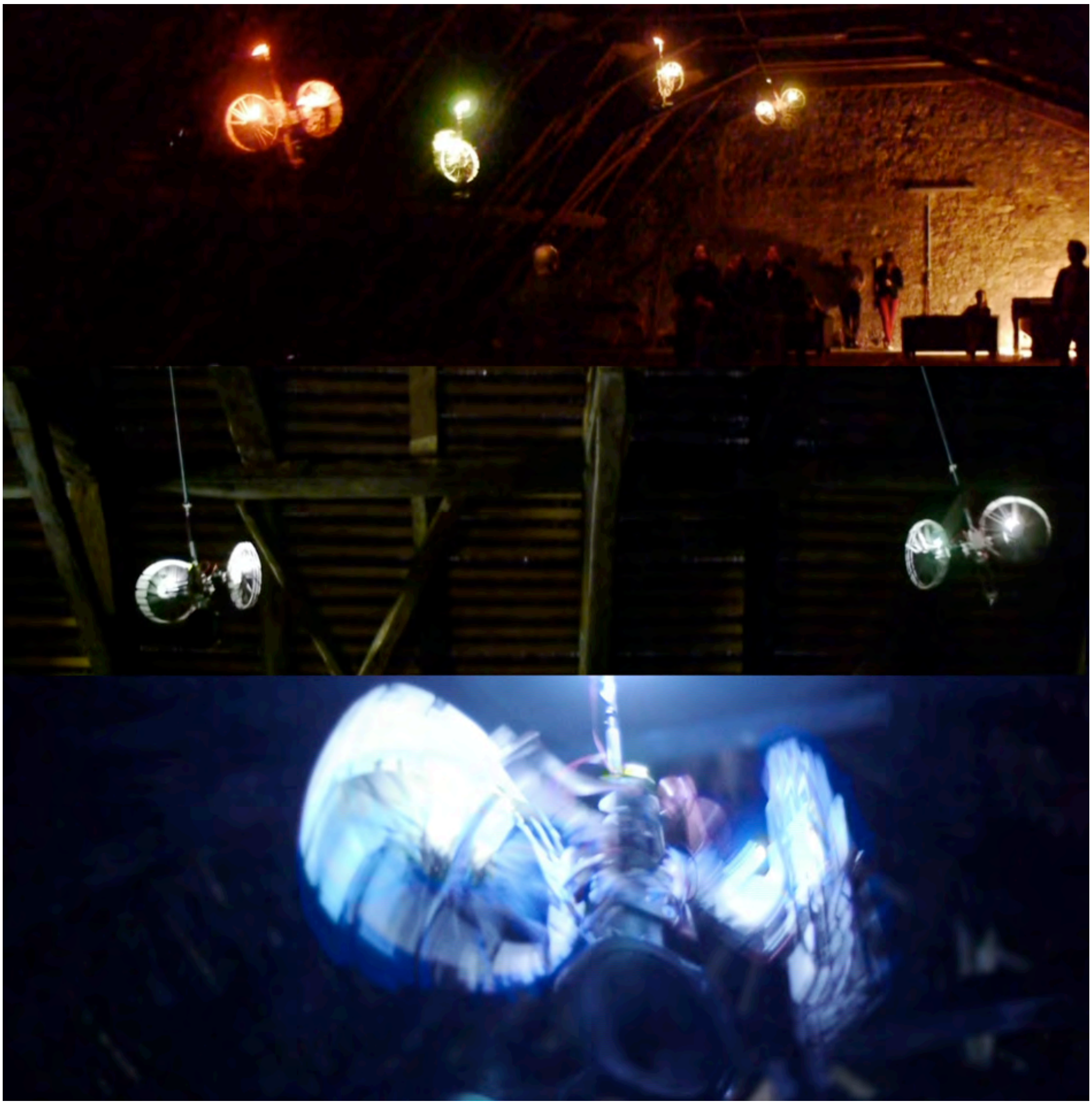

Figure 9: Exhibition Situations. The photographs provide a visual impression of the exhibition situation. The top image shows scene 6 being played during the opening of the exhibition, the middle image shows two pendulums performing scene 10 with the wooden roof construction of the venue as backdrop, and the bottom image shows a closeup of a pendulum that rotates very quickly during scene 5.

Scene 3 [14] is very calm and the pendulums barely move. There is no acoustic feedback and all audible sounds originate from the amplification of the electrical noises produced by the servo motors and the occasional collisions between propeller cages and the horizontal booms. This gives rise to a sound quality that is reminiscent of insect noises. Light emissions appear as short pulses that interrupt an otherwise very dark scenery. These pulses result from the servo motors briefly exceeding the upper and lower thresholds of their control values.

Scene 4 is very loud and aggressive. The pendulums rotate quickly around their own axes which leads to the occurrence of repeated bursts of acoustic feedback. The feedback sounds are additionally *chopped up* via amplitude modulation. This creates rhythmically changing textual patterns. On top of this, the pendulums' own noises are also amplified. The lights support the acoustic rhythm by alternating in synchronicity with the sound between darkness and white light at full brightness.

Scene 5 [15] employs the same fast pendulum rotation and the same light settings as scene 4. But this time, the pendulums that carry microphones rotate at a different speed than those carrying loudspeakers. This creates more complex rhythmical patterns. Also, in this scene, feedback is much weaker both because the matrix routes the audio signal in between the most distant microphone and loudspeaker pairs and because the feedback signal is attenuated rather than boosted.

Scene 6 [16] is a colourful spectacle with the pendulums performing circling movements. The orientations of the pendulums are mapped onto the hue values of the LEDs. As a result, the pendulums illuminate themselves and their surroundings with light that continuously changes colour. Feedback effects dominate the musical output. But these effects appear only sporadically since the pendulums rarely come sufficiently close to other. The feedback signal is slowly but strongly attenuated.

Scene 7 is similar to scene 6 but the pendulums follow more complicated trajectories. The trajectories combine a circling movement with rotations around the pendulums' axes. This creates different periodicities at which feedback can take place. As in scene 6, the LEDs change their colour in correlation with the pendulums' rotations, but these changes now happen at a much faster speed. Accordingly, this scene continues the musical and visual atmosphere established in scene 6 but at a higher and more complex pace.

Scene 8 [17] also employs rather complicated pendulum movements. These movements result from the combination of standard swinging movements with back of forth rotations of the pendulums' propeller cages. These cage movements create forces that repeatedly alter the direction of the swinging movements. With respect to light, the scene is very simple. All LEDs are constantly turned on and emit a purple colour. The repeatedly occurring acoustic feedback is transformed via pith shifting into glissandi that re-appear as echoes on the neighbouring pendulum's loudspeaker.

Scene 9 [18] creates a very melodic musical situation. The pendulums rotate around their own axis at low velocity. The LEDs emit white light that changes its brightness in synchronisation with this rotational movement. The musical output is dominated by resonances that are amplified within a very narrow and low frequency range. The remaining frequencies are barely audible since the feedback effect is faint. This is due to a matrix routing that only combines distant microphone and loudspeaker pairs.

Scene 10 [19] combines a looping pendulum movement with a strong but slow feedback attenuation. This causes occasional and briefly sustained feedback bursts. The LEDs emit constant white light.

Scene 11 [20] employs a combination of movement primitives that causes the pendulums to oscillate back and forth around their own axes. This gives rise to frequent and repeated feedback events. The feedback is very quickly attenuated which further strengthens the pointillistic characteristics of the sound emissions. In addition to this, the musical output also contain amplified noises that originate from the servos' movements. The LEDs emit constant blue light.

Scene 12 employs the same combination of movement primitives as scene 11. But contrary to scene 11, the spectral bandwidth of the acoustic signal is clamped to a narrower and lower range. Also, feedback attenuation is a bit slower in taking effect. In combination with a two seconds long delay time, the musical output is characterised by a slow and deep rhythm that is reminiscent of gurgling sounds. The LEDs emit constant red light.

Scene 13 closes the sequence of scene successions. This scene is very calm. The propellers are in a perpendicular orientation with respect to the boom and rotate very slowly. The pendulums barely move at all. The musical output consists only of noises produced by the pendulums themselves that are heavily filtered so that they only contain low frequencies. The LEDs emit constant and very dim red light.

7. Discussion

Composing for the *Pendulum* installation has turned out to be a fascinating but also challenging endeavour. This is largely owed to the fact that the combination of pendulum movements and motor actuations gives rise to a wide range of different kinetic behaviours most of which are difficult to control. Accordingly, the compositional activities focused for a considerable amount of time on the acquisition of an understanding concerning the different movement capabilities of the pendulums and the assessment of the reliability with which these movements could be achieved. The acoustic feedback on the other hand and the methods of its control was dealt with in a more straight forward manner. Many of the signal processing units that we chose to work with such as limiter, notch filters and frequency shifts are commonly used for controlling and attenuating acoustic feedback. But in our case, these elements have been implemented in such a way that their feedback subduing activities could either be turn off or delayed before taking effect. In the end, it was both the configuration of these signal processing elements and the control of the pendulum motors that formed the main compositional tools for exploring the creative potential of this installation.

The capability of this predominantly physical system to behave in unexpected ways became evident not only during the compositional process but also while the installation was exhibited. For instance, the transfer of the installation from the working situation at our university to the exhibition venue led to a change in the pendulums' movements. Part of the change was due to an alteration of the mechanical coupling between the pendulums. This alteration originated from material differences of the support structure to which the pendulums were attached to. In the exhibition venue, these support structures were made from wood rather than metal as was the case during the realisation of installation. Another change was due to significant differences in room temperature between exhibition venue and university workshop. Contrary to the normal office temperature at the university, the temperature in the venue was only barely above the freezing point. The low temperature altered the viscosity of the lubrication oil in the slip rings and resulted in a higher amount of friction. Finally, throughout the duration of the exhibition that lasted for a little bit less than two weeks, signs of wear in the mechanical joints and cabling started to increasingly affect the installation. The effects ranged from a further increase in friction up to the point of cables breaking. The pendulums affected in such a manner could no longer be actuated. This drastically altered the acoustic feedback situation. While these issues were of course less than favourable, they never led to a complete breakdown of the installation. Rather, they caused musical behaviour of the installation to increasingly diverge from the originally envisioned result.

The capability of the *Pendulum* installation to encourage interaction is largely owed to its physical instantiation. That the installation's musical content arises mostly from acoustic feedback was readily understandable by the audience. Based on this understanding, many visitors spontaneously decided to affect the musical output by standing close the a microphone equipped pendulum and producing sounds on their own. Depending on the particular scene that was active at that moment, these audience contributed sonic elements would remain audible for an extended period of time as part of the installation’s musical behaviour. More courageous visitors dared to intervene directly with the kinetic behaviour of the pendulums by manually stopping them and subsequently pushing them into a different trajectories. These altered trajectories affected the acoustic feedback and the IMUs’ sensorial values and therefore led to an altered visual and musical outcome.

8. Conclusion

To conclude, we would like to generalise our approach of combining physical and computational processes for creating a generative artwork. Based on our experience with the *Pendulum* installation, it seems evident that even simple mechanical and acoustic systems can exhibit a richness of behaviours that can readily be exploited for generative purposes. While the same holds true for many purely computational approaches, the physical systems outshine their computational competition with respect to their capability to integrate site specific environmental factors and audience participation into the core principles of their operation. This integration emerges naturally from the sensitivity of the acoustic and kinetic elements with respect to the material, geometrical and environmental properties of the exhibition environment. And since some of these properties such as temperature and humidity can change according to seasonal or circadian rhythms, an installation’s behaviour can even become correlated with these periodic patterns. Wether such effects take place and how the physical system will respond to them is hard to anticipate. Accordingly, it is not only the physical behaviours themselves but also their sensitivity to site-specific situations that operate with a large degree of autonomy and can therefore be considered to constitute processes to which an artist delegates part of his or her own creative authority. With respect to interactivity, artworks whose behaviours are based on physical principles that are familiar to visitors from everyday experience exhibit a rich potential for audience engagement. The physical principles themselves provide affordances that invite playful interaction and open-ended exploration. It is through this familiarity with physics, that even highly complex musical behaviours can be traced back by the audience to basic causalities and therefore become accessible for intuitive understanding and playful experimentation.

While researching historical and recent precedents to our approach, we were somewhat surprised by the apparent scarcity of documentation concerning physics-based works in the field of generative art and, on the other hand, by the abundance of information about such works within the field of sound art. We therefore conclude, that physics-based approaches possess a largely untapped potential for generative art. And we would like to encourage generative artists to gain inspiration from activities undertaken by practitioners in electroacoustic music and kinetic art.

Concerning our own plans for the future, we would like to further exploit the capability of the *Pendulum* installation to provide natural affordances for playful and open-ended interaction. We aim to integrate the pendulums into stage performances where they likely offer ample possibilities for improvisation. The improvisation between pendulums and human performers could take place on the level of physical movement (dancers) or acoustic interaction (musicians) or a combination of both. These plans are already taking concrete shape in the form of the context of a theatre performance which is planned to premiere at the end of 2018. Here, the pendulums will act both as scenographic elements and musical instruments that play alongside regular musical instruments.

9. References

[1] Bisig, Daniel, and Tatsuo Unemi. 2010. “Cycles – Blending Natural and Artificial Properties in a Generative Artwork.” Proceedings of the Generative Art Conference. Milan, Italy, 140–154.

[2] Bisig, Daniel, and Pablo Palacio. 2014. “Phantom Limb – Hybrid Embodiments for Dance.” Proceedings of the Generative Art Conference. Rome, Italy, 92–107.

[3] Bisig, Daniel, and Philippe Kocher. 2015. “DRIFT – Virtual Sand in augmented Space.” Proceedings of the Generative Art Conference. Venice, Italy, 51–64.

[4] Lucier, Alvin. 1980. Music on a long thin wire. Lovely Music/Vital Records.

[5] Tudor, David. 1968. “Rainforest description dated 1968.” David Tudor Papers, GRI (980039), Box, vol. 3.

[6] Wetzel, Roland, Annja Müller-Alsbach, Sandra Beate Reimann, and Heidy Zimmermann. 2016. “Méta-Harmonie: Musikmaschinen und Maschinenmusik im Werk von Jean Tinguely = Music Machines and Machine Music in Jean Tinguely’s Oeuvre.” Critique d’art, Catalogues monographiques.

[7] Murphy, Jim, Ajay Kapur, and Dale Carnegie. 2012. “Musical robotics in a loudspeaker world: Developments in alternative approaches to localization and spatialization.” Leonardo Music Journal 22:41–48.

[8] van Eck, Cathy. 2017. Between Air and Electricity: Microphones and Loudspeakers as Musical Instruments. Bloomsbury Publishing USA.

[9] Reich, Steve. 1980. Pendulum music. Universal Edition.

[10] Toop, David. 2002. “Humans, are They Really Necessary? Sound Art, Automata, and Musical Sculpture.” dalam Rob Young, Undercurrents: The Hidden Wiring of Modern Music, halaman, vol. 128.

[11] Eco, Umberto. 1962. Opera Aperta. Edited by Bompiani. Milano.

[12] Bisig, Daniel, and Philippe Kocher. 2013. “Early Investigations into Musical Applications of Time-Delayed Recurrent Networks.” Proceedings of the Generative Art Conference. Milano, Italy, 77–88.

[13] Pendulum Scene 1 Video, https://vimeo.com/243519605/9a6c86f77b

[14] Pendulum Scene 3 Video, https://vimeo.com/243519632/67fd72a2e3

[15] Pendulum Scene 5 Video, https://vimeo.com/243519658/0863a44fe9

[16] Pendulum Scene 6 Video, https://vimeo.com/243519728/a019013810

[17] Pendulum Scene 8 Video, https://vimeo.com/243519762/06846d4c8f

[18] Pendulum Scene 9 Video, https://vimeo.com/243519775/d825fc9429

[19] Pendulum Scene 10 Video, https://vimeo.com/243519835/3efa14c68a

[20] Pendulum Scene 11 Video, https://vimeo.com/243519877/fc50ae025a