Fab Synthesis: Performing sound, from Musique Concrète to Mechatronics

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1. Introduction

Since the beginning of Pierre Schaffer's research at Radio France studios in the 50s', recording sounds outside or in the studio was an essential part for a lot of tape music at that time. This tradition has continued to attract the composers' interest until today where composers in search of new sounds and ways to control them have incorporated new technologies such as digital fabrication, cybernetics, and mechatronics[1]. It is the synergy of human dexterity and expressivity with the precision of electrical, computer and mechanical technologies where instruments make sound themselves or extend human agility. The aim of the present study is two-fold. Firstly, to explore and identify the implications of sound performance and expression as a building block in electroacoustic sound composition. Secondly, it attempts to introduce and describe Fab Synthesis as a sound synthesis, design and performance practice that facilitates uncompromised sound expressivity and encourages the combination of human and electromechanical agents to interact seemingly.

The binding element of this interaction is the sound as the sole bearer of musical experience; a sound virtuosity and musicianship that is embodied in the sound alone, within the context of music for fixed audio projected on loudspeakers with no live intervention of instrumentalist(s). However, the luck of instrumentalists on stage has opened ongoing discussion weather removes something from the music experience or not. This question continues today even if we enjoy listening to our favorite compositions via our home audio system without complaining that our favorite band or orchestra is not sitting right in front of our living room. So why the electroacoustic music community is still battling with this issue? Is there something that possible missing, and if yes is this the luck of the performers on stage or something else? McNabb writes

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[1] Mechatronics is best defined as the synergistic use of the latest technologies in precision mechanical engineering, controls theory, computer science and electronics in designing improved products and processes (Ashley, 1997). Principal elements of mechatronics systems are as follows: Mechanical, Electromechanical, Electrical/ Electronic, Control Interface/ Computing Hardware, Computer (Kapila, 2010).

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"The reason that a lot of tape music sounds unsatisfactory is not because there is no performer on stage, but simply because there is no performer at all (McNabb, 1986)." When a composer goes around, and record sounds for the next piece the moment the rec button is on to record the sound the composer becomes the performer of it. Performing sound is essential to get expressive sounds with depth, detail and full musical potential without sounding generic. The stage is everywhere, in the kitchen, in the studio, in the forest or the construction site, all it needs is a performer to capture the moment with expression, musicality, and virtuosity. Further audio editing and processing effects may follow as the composer crafts the piece, but this article will focus on the way the sound is made.

In electroacoustic sound-based composition, the relationship among composer, instrument[2], performer, concert hall and listener often collapse into one holistic aggregate. The composer is often the performer and the listener; the one who makes or founds the instrument, the one who discovers a tiny machine sound or a serene deep soundscape, and the one who defines the properties of the imaginary space in the piece and the physical arrangement of the speakers in the concert hall. The composer is responsible for the conception of the sound, the design and implementation of the instrument, the performance and finally the recording of each sound.

1.1 States of communication

Anders Friberg proposed a model of four distinctive stages of musical experience and three corresponding transformations all in one direction from composer to listener in which the output of one stage feeds the next (Friberg, 1997). This approach makes it possible for four stages to take place at different points in time and places. Kendall and Carterette based their approach to similar information-processing theories of communication added more connections between stages allowing bidirectional interaction across the stages as well as omnidirectional from stage to stage (Kendall & Carterette, 1990). Both theories above, assume the three main stages correspond to three independent groups of people. In Fab Synthesis practice all stages are states of one system, one person and they dynamically inform each other in parallel and serial mode. They all happen at the same time, in the same place, by the same person. The composer writes instructions/score on how to perform the sound, builds/ modifies the instrument if necessary, makes the sound and records/ listens to it; the composer operates all steps.

Fab synthesis is closer to Caroline Palmer's theory where she proposed a distributed theory of musical communication of information which considers the changes within a single composer/performer/listener's mind. Palmer writes (Palmer, 2015): "A completely distributed model of the same three states (in contrast to stages), allows the

[2] For simplicity reasons any kind of musical instrument, instrumental device, physical object, found object or mechanical device that produces sound in a broad sense will be called instrument. However, the purpose here is not to play music but to generate sound.

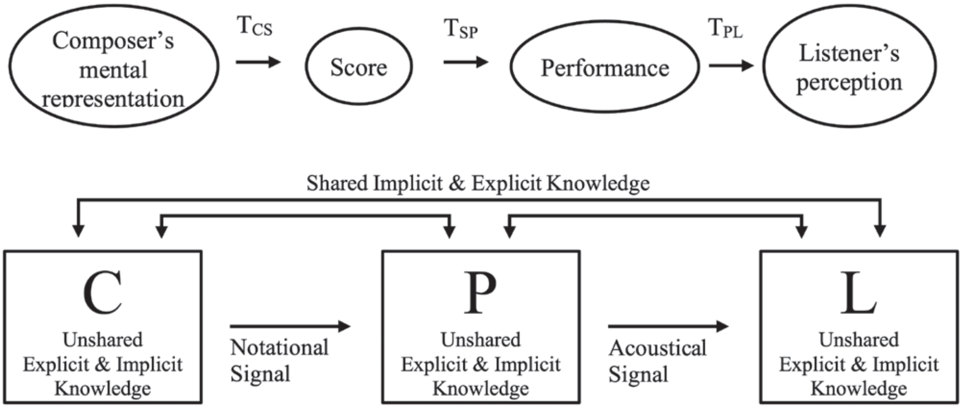


Diagram 1. Schematic representation of musical communication models Composer, Performer, Listener. Top Anders Friberg 1997; bottom: Kendal and Carrerette (1990).

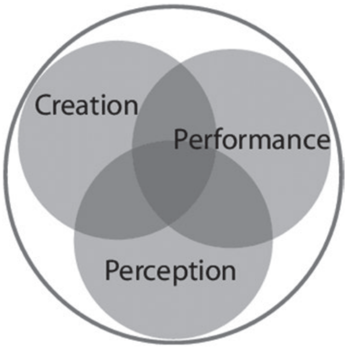


Diagram 2.

melodic context in which a performer encounters a melody to influence his/her subsequent perception of that melody; this shared representation holds similar predictions across other composition, perception, and performance interactions." Similarly, in Fab synthesis, the composer agent operates in four states – composer, maker, performer, listener. All of them are in a feedback loop system which continuously converts the signal from notational to data to acoustical in any combination and at any time.

To this extent, the composer must address several questions. The answers to them may not be universal or standardized, but suitable to each composition; suitable to the sounds imagined, such as: How to play a new or an existing instrument? Where to touch, hit, strum, hummer, press, strike, blow, tap, bow or scratch a resonant body or a string? What is the sound this instrument is supposed to produce? How many different sounds can one instrument produce? What is the 'right' position, posture or way to play it? How much tension should be applied to a string, a membrane or, to the bow hairs? Where the human virtuosity ends and how mechatronics can add to it? How much practice time is needed to reach a high level of virtuosity for a sound? How to produce an expressive, musical sound? Is mechatronics necessary to produce the desired sound?

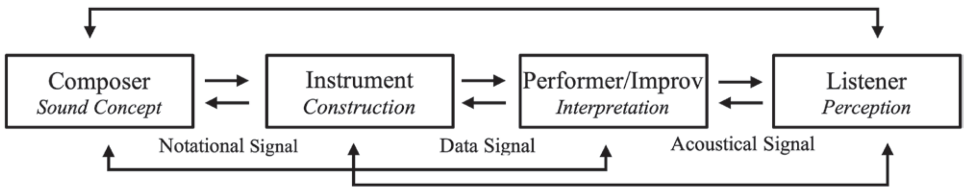


Diagram 3. Fab synthesis model from conception to realization.

When performing sound to be used in a composition, there is no single answer to the above questions, and all the possibilities are equally open. There are as many answers or solutions as each composition demands. In one sound, a single string custom instrument may be played using a bow, hammer or plectrum. In another sound, the string could be coupled with the use of 'unconventional' objects, such as brass or glass slides, metal sticks or brushes or could be detuned, all in favor of obtaining better control, expression, and transformation of the sound in search. Performing sound emphasizes the production of a sound ecology, where acoustic systems, performer, electromechanical parts, coding and perception all interact in real time. It challenges every aspect of music making, performing and listening and the consequences are vast and unpredictable. Performing sound requires a different type of virtuosity, a sound virtuosity, a concentration not only on the accurate rhythmic motives at the exact tempo and intonation but rather on the minutiae details of each and every moment in the sound. It demands the precise production of variable sound possibilities and the clear distinction between one timbre and another to convey the musical ideas and eventually the structure of the piece. The composer can quickly move back and forth, fine tune and adjust the system until the right sound is made; creation, design, performance, perception are all part of the same process, the making of the sound.

Interactions and influences in a man-machine performance environment, improvised or composed have been discussed in various scenarios and paradigms (Overholt, Berdahl, & Hamilton, 2011), (Traube, Depalle, & Wanderley, 2003), (Wessel & Wright, 2002), (Eldridge, 2005). The schematic framework in Diagram 4 allows us to view the roles of human motor learning, controller mapping, and generative software as an overall adaptive system that aims for better sound control and more intuitive interaction between human and mechatronics performer agents. The intentions include the composer's idea to perform a sound for a piece. Besides the planning of, pitch, volume, articulation, gesture control level, etc. the composer plans the design of the instrument. The instrument could be an existing one, e.g. a western classical musical instrument or a fabricated instrument. The Motor program is the translation of intentions to the body's sensorimotor system or the programming environment. Since this is not a music performance model where a piece of music is interpreted in front of an audience, the audience cannot modify the whole process and is out of the schematic.

Four feedback loops are running while the sound is generated that happen almost concurrently. The first feedback loop is the evaluation of the motor program. In the second feedback loop, the composer evaluates haptic force feedback returning from the interaction with the instrument, in response the performer adjusts position and

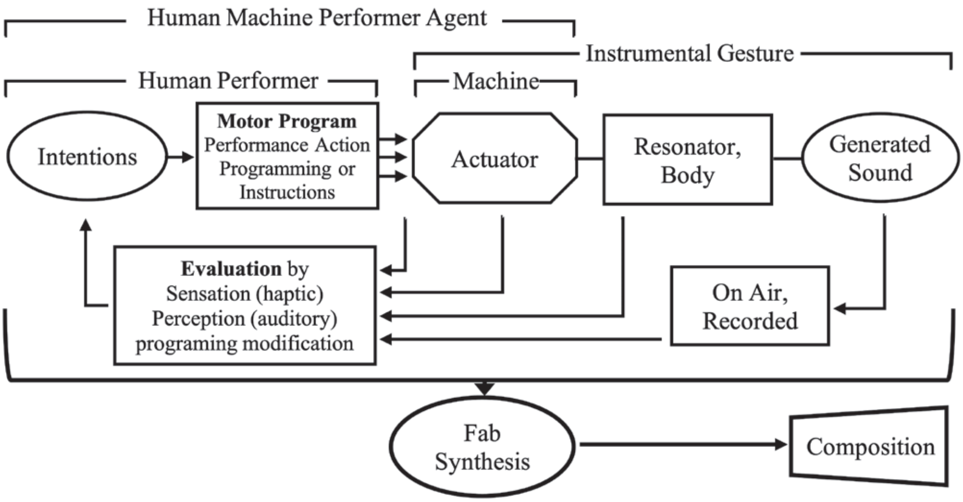


Diagram 4. A flowchart of Interaction among the performer, the machine, and the instrument and how the information is processed and the role of agents.

velocity. In the third feedback loop the composer analyses the sound's structural information such as gestural information, timbre, pitch, volume, associations even mood triggers and reacts by adjusting the system; finally, the sound should be recorded and stored for further use in the composition.

Michael McNabb continues on the role of the composer/performer paradigm in tape music: "…but composers of electronic music must realize that they are the performers, and are therefore responsible for adding all the nuance of performance to the music if there is not going to be someone at the concert to do it for them. The composition process must extend down to subtler levels (McNabb, 1986)."

2. Defining Fab Synthesis

In order to describe al the nuances of performing sound in electroacoustic sound composition, this article proposes Fabrication Sound Synthesis as a way to organize, systematize a practice that has been used since the 50s and continues developing till today. Hopefully, this will help composers, performers or theorists to break down and analyze the process of making sound in electroacoustic music. A practice rarely documented yet critical to the composition process.

Fab Synthesis refers to a sound synthesis practice in which a sound performer agent effectively applies energy to physical resonator(s) while the resulting acoustic signal is recorded by conventional audio recording means.

The control of the sound properties of the acoustic signal (frequency, timbre, amplitude, gesture, texture, articulation, etc.) is carried out by one or more agents - the performer, the mechatronic system or the synergy of the two. Various scenarios of interaction between human performer and robots have already been explored (Eigenfeldt

& Kapur, 2008) with agents defined as autonomous in a predefined frame, social if more the agent is performing, reactive, and proactive (Wooldridge & Jennings, 1995). Similar attributes are required for a human performer agent. The mechatronic agent is usually a mechanical or electromechanical instrument that is controlled by a human performer and/ or an automated system in real-time. The instrument has physical properties, the interface remains tangible at all states and generates acoustic waves transmitted either through the air, liquid, or solid. The physical sound generators could involve traditional or new instruments, found objects, natural sounds and could be used both as driver/exciter or body resonator.

The human performer agent doesn't need to be a classically trained musician regardless if the instrument is a classical orchestral instrument, a modified instrument or a completely new one. However, one should practice and develop a sound performance practice that allows to play intuitively, expressively and control the character of each sound with precision. Although there is no score to be read, a set of notes in the form of sketches, words, or notation is expected. The composer has a clear idea of the sound to be recorded. The recorded sounds are usually a few seconds long, and they do not constitute musical phrases or motives, although it could happen occasionally. There is a clear distinction between play music and make sound.

The mechatronic performer agent is mechanical or electromechanical and remains tangible throughout the sound generation process. The control of the mechanism is operated through digital or analog controllers that communicate different messages to electromechanical components or automaton mechanisms in mechanically based systems. The excitation mechanism could consist of one or multiple actuators positioned carefully in various parts of the instrument. The actuators are stationary mounted on a mechanical beam or mobile using robotic arms or belts.

2.1 Background

Fab Synthesis could be considered as the first and most common method of generating sound materials used in the early pieces of Musique Concrète. France composer Pierre Henry composed his piece "Variation pour une porte et un soupir" in 1963 (Henry, 1963). The only sound type used in the movement Etirement was various creaking door sounds. Some of them fast or slow, others long or short. Pierre Henry treated the door as an instrument. He developed a performance practice for the door that included control over timbre, register, and tempo. The door used in the piece is the door to the attic of a house the composer stayed during the summer of 1962 in Vic, Aude/ France. As Michel Chion and Pierre Henry describe:

"Pierre Henry does not rush to record it, he practices the door as he would do at the Conservatoire, his two hours of door practice a day, then he installs in front of the door a Neumann U47 microphone, connected by a long cable to the tape recorder that controls from the ground floor Isabelle Chandon. Then he records the door systematically, exhaustively, almost like a piece of music, he makes it speak and scream in so many different ways: sometimes with very small gestures of the wrist, sometimes by shaking it like furious, straddling it, or making it sound like a scream" (Henry, Pierre HENRY, Variations pour une porte et un soupir, 1963), (translated by the author).

It is the performer who chose this door and not any other, the composer who discovered the door's sonic possibilities after hours of practice and experimentation. Without going through this process, there is potential but no sound or, there is sound but not a performer. In my electroacoustic sound composition *Magic* (Kokoras, Magic, 2010). I recorded more than seven hours of piano sounds after days of practice inside the piano using various objects and bitters. A great number of sounds explored with attention to timbre detail and expression. After a while, a kind of sound virtuosity emerges suitable for this instrument and this type of sounds. Like in the case of Pierre Henry's piece there is no sound manipulation other than basic editing techniques, the results of Fab synthesis are not like raw sound material but almost finished musical phrases ready to be added in the mix. The same applies to environmental sound; only the composer should be able to spot the right variance of cicadas' texture before deciding to add it in the piece. In this case, it is the nature that takes the role of the performer and the composer its ear.

2.2 Criteria

The Signal Acoustics and Processing Laboratory of the University of Helsinki proposed three families of criteria as part of an assessment of different synthesis methods they contacted in 1998 (Tolonen, Välimäki, & Karjalainen, 1998). Even if Fab synthesis loosely fits into the other sound synthesis methods mentioned in the report, this article will attempt to relate the three families of criteria to it.

According to Tolonen et al. the first family of criteria concerns the use of the following parameters: intuitiveness, perceptibility, physical sense, and behavior. Fab synthesis remains tangible throughout the process using physical objects and acoustic signal. It enables intuitive sound performance in a closed feedback loop interaction between composer/ performer and machine, allowing for precise control of the sound from conception to perception.

The second family of criteria is the quality and diversity of the sounds that are produced with the following parameters: robustness of the sound identity, extent of the sound pallet, and with a preliminary analysis phase, where appropriate. Fab synthesis encourages the discovery of unique sounds and the same time embraces virtually any known sound. It generates rich, organic, and high-resolution sounds with an endless variety of minute changes to dramatic transformations. This precise sound expression allows for spectromorphological approach to sound generation.

The third family of criteria deals with implementation solutions, with parameters such as computation cost, the memory needed, control, latency, and multi-tasking processes. Fab synthesis combines composer, performer, engineer, and blends sound performance, instrument design and programming all in one process. It is modular, adaptable and expandable to one or more mechatronic performer agents. The mechatronic agent could follow step by step moves written by the composer or be allowed to perform within certain limitations. Machine listening and learning algorithms could be implemented allowing for better and more intuitive automated sound performance or the co-manipulation between human and mechatronics.

Also, the versatility of Fab synthesis facilitates classic digital sound synthesis techniques in an acoustic and tangible context. For instance, combining various resonant bodies and/ or exciters such as blowing on different pipes using a mechanical bellow system or an air compressor, an additive notion to sound generation could be achieved. Similarly throwing grains on a steelpan produces a granulated sound or damping certain areas of the exciter or the body a subtractive sound synthesis approach could be utilized.

3. Instrument Design

There are numerous examples of mechatronic musical instruments, and it is beyond the article's scope to provide an extensive list of them (Berdahl, Niemeyer, & Smith, 2008), (Britt, Snyder, & McPherson, 2012), (McPherson, 2010), (Rector & Topel, 2014), (Chang & Topel, 2016), (Kapur, 2006-2015), (Synthhead, 2015), (Chinen, 2010). In Fab synthesis, the composer must either find or build the instrument(s), before performing and recording the sounds for the piece. In any case, one will have to either define or design the physical components and the excitation parts of the instrument. Following Pierre Schaeffer's writings about the three criteria of the instrument: timbre is the first one which doesn't change and gives to the instrument its signature sound. Register and playing potential are the other two which are varied by the performer to give to the sound the right shape and character (Schaeffer, North, & Dack, 2017). In Fab synthesis, any tangible sound-producing physical object can be built from a set of vibrating substructures which are defined by the composer. Sub-structures are connected, and they can respond to external excitations such as blow, bow, strike or pick. The excitations could transfer energy into the instrument in a continuous mode, or the energy could be transferred to the instrument in short impulses, the impulsive mode. A usual substructure could consist of a hollow or solid body, neck, bridge, bow, tube, membrane, plate or bell. The composer considers the acoustic characteristics and functionality of each substructure and their reactions. The process is open and can be applied to structures of arbitrary complexity. The following three stages describe the design state of Fab synthesis from conception to generation to perception.

Stage I: Intentions
Stage II: Design a. Design Driver
b. Design Waveguide
c. Design Resonator
Stage III: Output recording

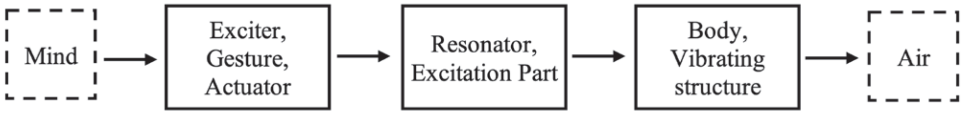


Diagram 5. design block diagram implementation with the three main design components of the instrument.

The following main criteria make a mechatronic instrument suitable for Fab Synthesis:

- Sonic signature: A set of unique sound characteristics that differentiate one instrument from another. However, the composer could change the sound signature of an instrument by modifying one or more parts of it. Thus, it is not the physical instrument and its mechanics that define its identity but the sound each instrument generates.
- Sound virtuosity: it is defined by the temporal control of the sound, the ability to shape the sound character instantly or over time, accurate control over numerous variations of one sound type including pitch, volume, timbre, or other sound elements.

3.1 Stage I – Intentions

Before even begin working on the instrument the composer should have as clear as possible idea of the sound to be performed and recorded within the musical context of the piece. Although sometimes it is inspiring to start improvising with an instrument looking for an inspiring sound it could also provide little to no results. Having a sound imagined; a type of gesture or articulation is an essential part of the process. Depending on the sound the composer should decide about the materials, the excitation model, the shape and many other features.

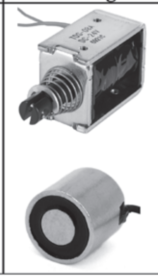
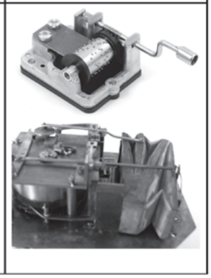
3.2 Stage II – Instrument design

This stage consists of three substages – energy input mechanism, acoustic waveguide resonator, and acoustic body, each one with its own weight depending on the sound needed. For instance, if the composer uses no other excitation device but the hands, then the next substage might be the one to research and develop, the resonator and the body of the instrument.

3.2.1 Energy input mechanism

Physical objects or acoustic instruments require an energy input mechanism to apply energy to the instrument in different forms. An excitation source or a sound generation device, that gives the system energy to operate. The exciter could be the performer's bare hand; a mallet tapping on clay pottery; a mechanical wind up spring motor and gearbox or a crank mechanism; or an electromechanical actuator exciting a metal plate; the nail or a pick plucking a balloon; the arm moving the rasping stick on a tile or a stepper motor rotating a friction wheel on a string; a player's breath; or a regulated air compressor blowing a bamboo pipe. It could also be an electromechanical device using actuator(s); a resonant structure itself or a more complex system. It could be performed by a single or multi-agent human and machine performer combined; for example, a plucked string maintains vibration using an electromagnetic actuator in which its frequency gradually turns into a random impulse.

Table 1. Various types of electromechanical and mechanical actuators.

Vibration, Stepper, DC, Servo, motor	**Air compressor with airbrush**	**Solenoid and electromagnet**	**Voice coil motor linear Actuator**	**Gear, spring, bellow, crank**
				

The above table is not exhaustive but describes the main ways of using a driver to excite a resonant body; the possibilities and variations are endless. The composer has the task to decide which actuator would be the most appropriate for each sound or group of sounds. Among the different types of motors, a vibration motor could vibrate a surface with pebbles producing a granulated texture. A stepper or servo motor could function as a plectrum, hammer, stick, mallet or as a kind of wheel bow like the hurdy-gurdy or other zither type strings in China and Korea like Vazheng or Ajaeng respectively. Moreover, stepper motors can operate with extreme precision and reliability. Other, examples could include air compressor to drive the air jet of a resonant duct or Helmholtz resonator to generate high-frequency fundamentals, very fast attacks or long sustained tones. Solenoids or motors in the right configuration could pluck, hammer or tap almost anything. Voice coil motors are excellent to perform continuous and dynamic movements with high capacity torque and speed which can be used to produce tremolo sounds, sensitive strokes, even bends or stretches. Mechanical only exciters could have similar functions using parts such as gears, springs, bellows, and cranks.

One of the challenges using electromechanical parts is to control the noise levels of the mechanical parts. For instance, a linear actuator is significantly noisier than a voice coil motor; or the motor noise of the air compressor itself could mask all the sound nuances of a delicate wind sound. Often, high-end parts make less noise but also it

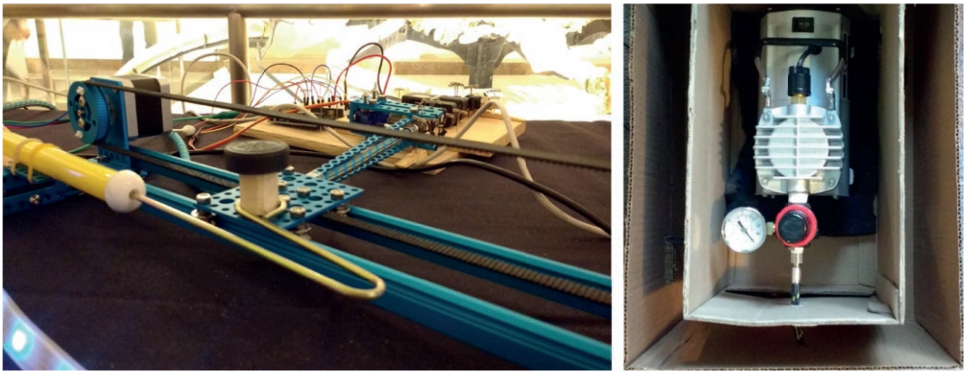


Figure 1. instrument used to generate sound material for the electronic part of Jet for recorder and electronics.

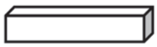
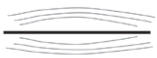
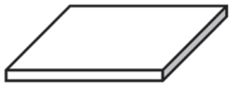
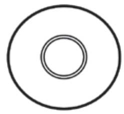
is harder to find, and they are costly. In my piece *Jet* (Kokoras, 2010) I built a slide whistle controller in which the air jet driver was a regulated air compressor. During the recording, I placed the air compressor in another room and the compressor inside a custom-made box in a box container. This way I was able to eliminate the noise of the air compressor leaking into the delicate, fast staccato sounds I was recording.

3.2.2 Acoustic waveguide resonator

The acoustic waveguide resonator is the main part of the instrument that oscillates; it refers to the playing surface. For instance, a string tightly stretched across a hollow wooden box or the air column in a pipe or a reed. The oscillating system produces a waveform that varies depending on the combination of materials, sizes, and shapes. The most common resonators are beams, strings, plates, tubes open or closed and membranes. Some of them could generate the sound directly, and others modify the sound by enhancing or damping specific frequencies, such as the bodies of the classical instruments. A resonator could also be varied in length, stiffness, air viscosity, internal damping which affects the timbre, the time it takes for the sound to decay after the excitation pulse and might affect the pitch. The combination of exciters and resonators or resonators alone can provide endless sound possibilities.

Two or more resonators could be used in parallel or series. In parallel, the resonators are excited simultaneously by the same or different exciters providing a thicker or layered sound texture. For instance, hammering two metal sheets or plucking two strings of varying size at the same time. In series, the coupled resonators will modulate each other, unlike digital synthesis techniques where often one resonator linearly modulates the other. Because Fab synthesis is based only on acoustic resonators, it creates a complex bidirectional interaction among the resonators resulting in rich, unique and sometimes unpredictable sounds. Resonators in series could even replace the presence of an acoustic body which is the substage to be examined next. The composer adjusts the amount of coupling between the resonators. Coupling two acoustic waveguide resonators in series will sound more predictable if the first resonator has a fast decay time and let the second resonator to sustain the sound. It is even possible the acoustic waveguide resonators to offset the need of an acoustic body.

Table 2. Acoustic waveguide resonator types.

Beam	String	Plate	Tube	Membrane
				

Depending on the excitation method and the type of waveguide-resonator the composer decides other parameters particular to that method such as stiffness, tension, pressure applied on a string or force of hammer, rate or changes on the rate start speed and end speed. The vibration pattern is determined by the way the system is driven or excited as well as the shapes and the materials used in the instrument.

In the piece *Construct Synthesis* (Kokoras, 2009) I used a twisting latex balloon minimally inflated, which acted as the resonance body of the instrument. The balloon was fixed from the one side while holding the other side I could control how much to stretch the balloon; the more I stretch the higher the pitch and vice versa. Also, moving my hand up and down at a specific frequency rate I could control the pulse speed of the ring bouncing on the balloon. Finally, two metal rings hold together placed through the balloon which acted as exciter, resonator, damper and pitch controller:

- exciter, to onset the vibration of the stretched balloon as it bounces up and down the string;
- resonator, the two rings made a ringing sound when colliding to each other;
- damper, the rings locally applied a soft and instant dampening to the balloon and;
- pitch controller, the bouncing rings would affect the pitch depending on the position they hit along the balloon.

Figure 2. Construct Synthesis (2010) sounds of this built extensively used from 6:04”- 6:26”.

The excitation part stimulates the acoustic waveguide resonator such as a guitar or violin string, a bass drum membrane, a marimba bar, or the air jet on a wind instrument; the waveguide resonator transfers the vibration to the piano harp, the wooden cello body, or an air column in a flute which further extends, amplifies and shapes the tone of the subsequent vibration. It is possible in a single instrument to implement one or more resonators that are coupled together, such as a reed on a wind instrument, its wooden body, and the air inside the body.

3.2.3 Acoustic Body

This component serves to reproduce the acoustic behavior of a resonant cavity; it is the resonating body behind the resonator like the hollow body of an acoustic guitar or the soundboard of a grand piano. It is typically the sound box, bell or body of the instrument. Practically speaking, it's useful to think of the body elements as tiny reverb spaces with heavy EQ, which is ultimately how they behave, sonically. This component primarily takes energy away from the resonator to reproduce the acoustic behavior of a resonant cavity. The body will oscillate in sympathy with the resonator so changing the oscillation of the resonator and modifying the resulting timbre.

The piece *Anechoic Pulse* (Kokoras, 2004) starts with the sound of a Korean wooden traditional spinning top spinning on top of a 10mm textured glass that sits on three PVC pipes coupled on a 19 inches timpani head. Several contact and condenser microphones are mixed-down and recorded. In this case, the spinning top is the exciter controlled by two hands, excitation gesture. There are two acoustic resonators

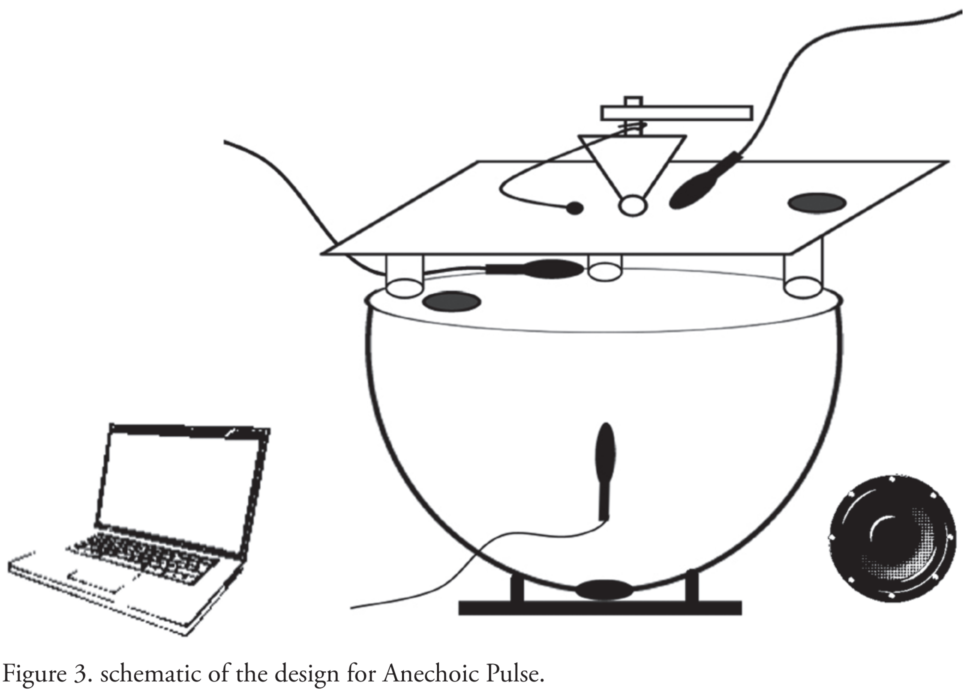


Figure 3. schematic of the design for Anechoic Pulse.

coupled in series, the glass and the tympani membrane connected through the PVC pipes. Finally, the bowl of the tympani acts as the main body of the resonators. The timpani pedal could work as a modulation gesture, but in this case, there was no use of the pedaling at all.

3.3 Stage III: Output

Stage three is the capturing of the performed sound, the output of the signal observed at a point defined by the composer. This may include different pickup/microphones positioned in various places, a/d converters, preamplifiers, headphones, and software. As well as different spaces: studio, home, anechoic chamber, concert hall and open field among others. The room where the sound is recorded could be considered as a second acoustic body depending on the acoustics of the space. The composer could further manipulate the sound in real-time or step time using audio processing techniques; however, this step is not part of the Fab synthesis practice. As soon as the sound device is ready and a few ideas have already been sketched out, it is time to practice, before the rec button is on. Each sound should be practiced, and certain confidence in control and manipulation of the instrument should be acquired. Controlling an instrument that combines acoustical and/ or electromechanical components is a challenge; these highly sophisticated systems demonstrate complex sonic behavior that makes it difficult to explain and control (Chang & Topel, 2016).

The three stages excitation, wave guide, and resonant body are grouped as an instrumental gesture that creates a loop between the performer and the instrument. Instrumental gestures generate a stimulus to the performer that influences the stimuli that occurred previously (Cadoz, Luciani, Florens, Roads, & Chadabe, 1984). This effect could be taken into consideration or ignored by the performer agent. Cadoz et al. emphasize the distinction between Excitation Gestures and Modulation Gestures. This distinction is useful in Fab Synthesis as well. Here the performer agent – human and/ or mechatronic - is the source of energy which is applied to the instrument.

In a string-based instrument is the hand that moves the bow or the motorized wheel fiddle rubbing against the string. In a percussion instrument is the hand that holds and strikes with the mallet or the electromechanical actuator that hits the surface. The excitation gesture transfers energy from the performer agent to the

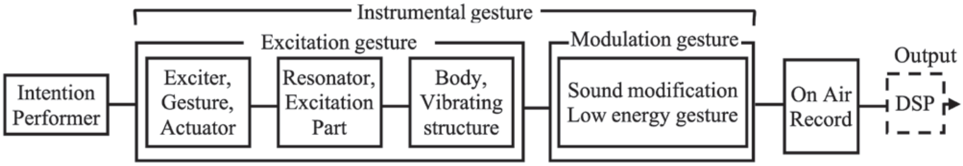


Diagram 6. Block diagram from conception to output of the instrumental gesture, the interaction between the performer agent the instrumental gesture and the output is a closed feedback loop system as it is not affected by a third person, performer or listener.

instrument. The second part of the instrumental gesture in Fab Synthesis is the Modulation gesture which is responsible for modifing various qualities in the sound by applying for example pressure on a stretched membrane or change the length of a pipe. The Modulation gesture requires less energy and usually doesn't contribute to the excitation of the instrument significantly (Cadoz, Luciani, Florens, Roads, & Chadabe, 1984).

4. The four modes of performing sound in Fab Synthesis

The advances in physical computing, cybernetics, and digital fabrication make it possible to adopt a sound performance practice continuum organized in four modes. The four modes place the performer agent from close proximity in mode one and to remote control in mode three and four. The first mode requires only the motor skills of our two hands and/ or mouth. In the second and third mode both the human and the mechatronic system excite and modulate together the sound. In the fourth mode, the system is totally decoupled from the human performer agent leaving the mechatronic agent only to perform a routine already programmed, in best possible detail, by the composer. The classification below perhaps could be applied to the traditional performance practice of instrumental play; however, in Fab Synthesis the focus is on sound practice and performance only. When performing sound, the main aim of the performer agent is to make sound not to play music. Slight timbre differences or similarities are delicately mixed, only the precise control, production and comprehension of each sound reveals its potential and eventually its structural role in the piece. In Fab synthesis a notion of sound practice and performance should be introduced, a sound virtuosity where the medium is not another instrument but the sound itself.

4.1 First performance mode

The first mode of Fab Synthesis requires gross and fine motor skills. The human performer agent should play the instrument only by hands and/ or mouth with or without another passive excitation source such as bow, pick, and mallet. The composer performs an excitation and/ or modulation gesture on the instrument. The instrument responses to the gesture and provides auditory, tactile and visual feedback to the composer. All the sounds generated using musical instruments fall under this mode such as pizzicato on the strings, woodwind multiphonics, sounds inside the piano harp or a triangle where the composer holds it with a string and strikes it with a wooden beater near the bottom corner, causing the triangle to rotate while ringing. The performance limitations of this mode are similar to the ones playing a musical instrument. Also, biophony or geophony soundscapes recorded carefully by the composer could be considered as part of this mode.

4.2 Second performance mode

The second mode facilitates the synergy of both human and electro-mechanical agents to co-manipulate the sound. The main characteristic of this mode is the use of mechanical or electromechanical devices and sensors (vibrators, solenoids, motors, cranks, etc.) controlled by hand and played on the instrument. The excitation and modulation gestures are triggered by either or both agents. Continuing with the triangle example above, in this case, the triangle is suspended from a dc motor that rotates the triangle. The composer strikes the triangle and switches on and off the motor at a given speed and direction. Electric guitar players often use the EBow to play long sustained notes. The EBow could be used to either excite or modulate a sound. However, the role of the human performer agent is to control how close to the string will be placed the EBow in what angle and which part across the string. Similarly, Paul Vo's Wond II string exciter is a handheld exciter, sustainer and controller for string instruments. It is a magnetic plectrum for strings, that lets you create infinite sustained sound and play the harmonics of a string in new ways. Also, Léo Maurel developed the Archet Motorisé, a handheld device like a bow that applies to any instrument working with continuous excitation. It uses two leather friction belts coated with rosin and driven by a motor whose speed is controlled via a pedal on the ground. The human performer excites the string by adjusting the position angle, and pressure of the rotating belts controlling with the foot pedal the speed of the motor (Maurel, 2018).

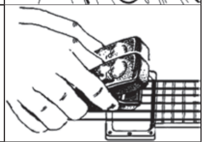
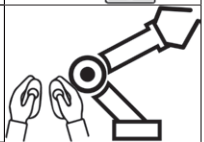
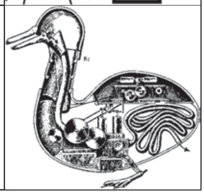
The performer needs to develop the gross and motor skills to precisely manipulate the electromechanical device which works as an extension of the performer's body. The first two modes are the most commonly used by the electroacoustic music community.

4.3 Third performance mode

The third mode of Fab synthesis facilitates mechatronic performer agents operated via controllers by a human performer agent. All the control maneuvers are taking place in real-time by the human performer using various controllers such as joysticks, push buttons, knobs, faders, etc. The performer is encouraged to focus on other as-

Figure 5. Paul Vo's Wond includes a haptic feedback system to provide a sense of touching the string. Léo Maurel's Archet Motorisé (right) a motorized wheel bow with variable speed via a foot pedal.

Table 3. The four modes of Fab synthesis performance practice.

First Mode Fab Synthesis – motor skills (gross, fine) – Use of sound/found objects (resonant chambers, instruments, DIY) played **only by hands and/or mouth** and/or another passive excitation source (bow, pick, mallet).	
Second Mode Fab Synthesis – prosthetic – Use of **mechatronics controlled by hand** and played on the instruments.	
Third Mode Fab Synthesis – cyborg – Use of **mechatronics operated via controllers by hand** in real-time played on the instrument.	
Fourth Mode *Fab* Synthesis – algorithmic – Use of **mechatronics** alone to autonomously (e.g. programmed, AI, automaton) play the instrument. There is **no human** intervention during the sound performance.	

pects of sound practice by controlling when, where and how the electro-mechanical energy should be applied. A simple example of third Fab synthesis performance mode is the use of an electromechanical actuator that hits a triangle; the human agent uses a pad controller to activate the actuator and hit the instrument. The faster the performer pushes the pads the faster the drum plays, or the softer one taps the pads the softer the hit on the drum. In my piece *Qualia* (Kokoras, 2017) I experimented and recorded sounds using the uArmSwift Pro[3] four degrees of freedom and 0.2 mm repeatability desktop robotic arm by combining it with a Leap Motion[4] sensor. As a result, I could control the robotic arm with hand gestures recognized by the Leap Motion sensor and translated into robotic gestures.

In this mode, the composer has the advantages of the previous modes in increasing order of complexity, precision, speed, and strength. The mechatronic and the human agent bond into a cybernetic symbiotic system which allows to explore and express the potential of each sound fully. Such advantages are:

- dexterity and versatility,
- perform complex and fast maneuvers that most humans couldn't,
- scaling hand movements by translating them into smaller more precise movements while playing the instrument,
- improves balance, coordination, fine and gross motor skills,

[3] https://www.ufactory.cc/

[4] https://www.leapmotion.com/

Figure 6. uArm desktop robotic controlled via Leap Motion performed several sounds for Qualia. Also, it has been used to perform timbre maps, as part of the Fab synthesis project, for woodblock at a 0.5mm distance per strike. The woodblock experiment gave 35500 sounds at 355 x 100 strikes across its surface.

- hyper-precise movement without human artifacts such as dyspraxia, shaking, slide, shift, or other faults,
- the performer could receive enhanced audiovisual and haptic feedback while performing sound.

On the other hand, each controller or electromechanical device has its own technical or artistic limitations and that could potentially limit the creative freedom and expressions of the performer. It is helpful to get adequate performance experience and understand the limitations of the instrument or to return to the lab and improve upon the instrument, and the limitations encountered previously.

4.4 Fourth performance mode

The fourth mode of Fab synthesis uses mechatronics only to play the instrument autonomously. Although it remains entirely acoustic and tangible the sound generation process, there is no human intervention during the performance. However, it doesn't mean there is no human agent in the performance at all. In this mode, the human agent contribution is on the programming of the instrument so that it performs precisely the way the composer intents. If the sound is not satisfactory, the algorithm should be adjusted until the desired sound is achieved. A simple example of the fourth mode is the programming of a robotic arm with an actuator attached to its end that precisely and quickly excites a wooden plate at specific nodes. In this mode, the mechatronic agent is interpreting the code already programmed by the composer. The robotic arm has been programmed to move fast and strike at specific points on the plate in speed, strength, and precision that no human could possibly do. The missing link of emotional expression should be addressed in the programming stage, although

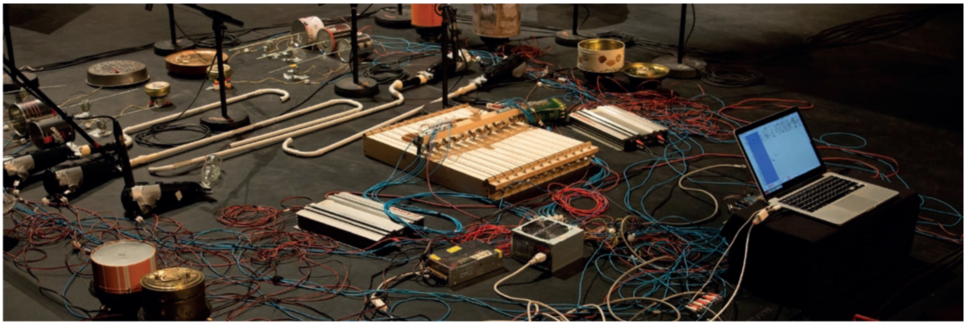


Figure 7. Regnum Lapideum at IRCAM/Pompidou by Andrea Valle and Mauro Lanza. Photo taken on February 19, 2019 Herve Provini, All rights reserved (Provini, 2019).

the intention is not a musical interpretation of a score, the interaction with other musicians and the audience, but rather the generation of normally short sounds that are properly designed to work in the piece. Nonetheless, this mode is the least developed, the implementation of image, sound and haptic feedback along with advanced AI algorithms could increase expressivity and autonomous performance aspects.

Andrea Valle has developed several automated sound instruments as part of his Rumentarium project, a computer-based sound generating system involving physical objects as sound sources. The Rumentarium is a set of handmade resonators, acoustically excited by DC motors, interfaced to a computer. While entirely computationally-controlled, the Rumentarium is an acoustic sound generator (Valle, 2010).

During a sound performance, more than one mode could be combined in succession or mixed together. Fully autumns mechatronic sound performance has characteristics such as:

- It allows the performer to leave all the performance to the machine agent and therefore to concentrate on sound details and optimize the sound performance.
- It opens new possibilities for performing sound that would otherwise be difficult or impossible.
- The two instrumental gesture parts, excitation gesture and modulation gesture, can work synergistically to optimize efficiency and allow for more sound control.
- The sound performance is augmented with qualities that are adjustable by the human in step time while remaining tangible throughout the process.
- Multiple mechatronic performer agents combined could offer better control over complex sound behaviors.

5. Performing sound and beyond

Fab synthesis aims to formulate a sound synthesis practice for the electroacoustic medium by means of human and mechatronic performer agents, acoustical signal and physical sound generators that remain tangible throughout the process. While composers incorporate recorded sound in their music, it is not often documented or analyzed the process of generating these sounds. This article will hopefully serve as a model on musical analysis and documentation for the complex work of performing sound in an electroacoustic sound composition. To facilitate the above aims the term Fab synthesis and a classification continuum of performing sound have been introduced. Fab synthesis describes a practice for generating sound material to be used in a composition.

In Fab Synthesis the composer, the instrument acoustics, the mechanics, the vibrating parts, space, the motion and the meaning inherited in the sound are not disconnected from the sound; not the reason for the sound, but in fact are the sound altogether. The instrument is not the one that defines the sound, but the sound suggests the design, the properties of the instrument and its performance practice. Mechatronics, sound source identification, cause guessing, sound energies, gesture decoding, and extra-musical connotations are not independent of the sound but are vital internal components of it. Performing sound is a transcendental experience where composer, performer, maker, listener, are all part of the system they are the sound.

The advances in actuators technology towards a safer, energy-efficient and highly dynamic motion (Vanderborght, et al., 2013) facilitate Fab synthesis practice with improved functionality. The integration of AI in sound performance practice will improve the interaction between human and machine and will open opportunities for new creative and expressive ways of making sound.

Listening to electroacoustic music, doesn't mean there is no performer involved. In electroacoustic sound composition, the composer has a unique opportunity to imagine and perform each sound in detail and precision so that it fits precisely in the composition's structure. Developing a sound virtuosity is an essential part of this process as well as developing or adopting the instruments and technologies to realize the imagined sound. Perhaps there is no performer on stage during the concert put there are hours of design and practice in the making of the sounds, only waiting to be heard and get alive every time they are played back.

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