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Musical Applications of Electromagnetic Field Sensing

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Abstract

This article describes a series of experiments and techniques for audiovisual performance composition using electromagnetic waves. These experiments represent the consecutive steps which led to the development of REBUS, a novel musical machine and interactive system that explores and expands contactless interaction techniques. Drawing on previous experience in designing simple synthesisers to transform light into sound, compositional systems that use invisible frequencies of the electromagnetic field were explored as both sonic material and interacting interface. A review and comparison of other sensing techniques is followed by a description of the potential of electromagnetic field sensing. Implementing state of the art technology and using previously unexplored frequencies, REBUS is a novel digital computational instrument that creates a space where any subtle interaction is detected independently of external light or sound and where invisible affordances can be touched and manipulated with the hands and the body — almost as invisible strings.

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«BEGIN ARTICLE»

When emitted and received, the electromagnetic field forms a three-dimensional interface that can be used as a sensor system. With the gentle guidance of Professor Clive Parini, who introduced me to the wondrous world of electromagnetism, I conducted a series of experiments to explore the potential of electromagnetic waves as an interactive interface. This led to the creation of two instruments, one analogue, featuring passive mode and single detection, and one active and digital: REBUS is a novel musical machine and interactive system for contactless interaction and gestural expression in electronic music, performance, and time-based media art. The expressive potential of interacting with the electromagnetic field was initially explored through my longstanding practice of making music with lights, which includes the creation of light controlled noise circuits (called Noise Bots) for live performance. This method was progressively expanded towards invisible frequencies of the electromagnetic field. Experiments, laboratory measurements and human centered tests verified the interactive potential of different electromagnetic frequencies and identified microwaves as the most suitable frequency for hand and body interaction. A variety of sonic instruments were created using a Total Power Detector, an integrated chip able to detect the amplitude of electromagnetic signals. Further research moved to more complex electromagnetic sensing techniques that involve active emission and realtime detection, a method which we have registered as REBUS technology, a system able to compare the received signal with values relative to the emitted waves, enabling the detection of movement with a precision that was previously unknown. The technique designed was first validated through a user study, and then miniaturised in the shape of a (musical) instrument responding to digital musicians' desire for expression and to media artists' need for compelling and poetic interaction. While for the first instrument the technical details are explained in greater detail, this paper will focus mainly on the basic input output paradigm, the look of the box and the interaction modes of the second instrument. Two main hypotheses inform our research path: the first is that the electromagnetic field can be interpreted as a multidimensional interface to mediate communication between humans and machines and that it may present an analogy between human perception and signification. The second is that the human senses can be trained to perceive invisible frequencies of the electromagnetic field if the cause-effect principle is reinstated.

Background

From the 18th-century the novelty of electricity inspired a few adventurous musicians and composers to modify their acoustic instruments, opening the way to the development of a completely new type of music. Early experiments combining music and electricity opened several paths, some of which have already seen widespread development, while others are still to be explored. Whereas most of those inventions were designed to augment or mimic traditional instruments, some, such as the Theremin, were more original and used electricity not only to control sound but also to generate it. This section reviews approaches in which the performer does not touch the instrument.

Russian avantgarde and the Theremin

One of the earliest electronic musical instrument, the first to be manufactured commercially and the first to be played without being touched is the Theremin, invented by Leon Theremin in 1919 (Smirnov 2014, p. 58). The inventor, formally trained as a physicist and musician, realised the possibility of producing pitched sound while fixing a radio station in Russia during the Civil War in 1919. The Theremin consists of two antennas protruding from a box, where the vertical antenna controls the pitch, while a horizontal loop controls the loudness. The antennas are not used to receive or broadcast, but they can allow the performer to control the sound through the principle of *capacitance*, which refers to the fact an electric field is generated between two plates having opposite charge. The field depends on the distance between the two plates and their area: there is a certain voltage difference V between two poles or plates if there is an electric charge $+q$ and $-q$ on them, and therefore there will be a certain electric field between them (Feynman, Leighton, and Sands 2010, p. 23-5). The influence that the interaction between static charges generates is commonly described as the *electric field*, whilst interactions between moving charges (for example, steady currents) produces an influence described as the *magnetic field*.

In the Theremin, the antennas and the hands of the performer form two plates of a virtual capacitor, the latter grounded through the body to earth; one antenna, controlled by the left hand, is used to control the amplitude of the output signal and hence the loudness of the sound. It uses a single variable oscillator whose amplitude is detected after it is passed to a Band-pass filter: when at the centre of the frequency band, the amplitude of the signal detected is highest, if the frequency goes at either side of the centre of the frequency band then the Band-pass filter attenuates the signal, and the attenuation increases as the frequency moves further away from the centre, therefore lowering the gain of the signal and subsequently the loudness. In fact this signal is used to control the gain of the amplifier as a voltage controlled amplifier. When playing the Theremin, both hands of the player act as plates of a capacitor, the right hand is the plate for the pitch, or frequency, and the left hand is the plate for the gain, or loudness. In other words, the Theremin measures the displacement current pulled from a transmitting electrode, as "*the performer's body increases the effective capacitance to ground of the antenna*" (Paradiso and Gershenfeld 1997).

Despite using antennas, which in the imaginary are automatically related to the transmission of electromagnetic waves, the Theremin is an instrument based on electric field sensing, a line of research that has been thoroughly explored by Professor Joe

Paradiso, who joined MIT Media Lab in 1994, just a year after the death of Léon Theremin.

Figure 1. Léon Theremin playing his own instrument, still from video, Public Domain (Theremin 1928). On the right, Russian artist Alexei Blinov playing with his room-wide Theremin, still from film by Zalewski (1991). Image copyright Szoda 1991, used with permission.

The Soviet Union played an important role in the birth of electronic music, sound synthesis and audio technology in the early twentieth century, especially in the period from 1910 to 1930 (Smirnov 2013). The influence of science in post-revolutionary times was based on the idea of cross-disciplinarity, and many musicians were learning mathematics or physics. Noise music was a diffused practice and it *"... was kind of a popular amateur activity to build instruments because of a lack of available instruments. On the other hand, it was something very secret and hidden from the public, behind the walls of the most radical theaters..."* says Smirnov in an interview with The Moscow Times in 2013, seeing many parallels between the historical avantgarde and contemporary noise music and DIY (do-it-yourself) culture, which is somewhat *"...similar to what was going on in Soviet Russia in the early 1920s. A kind of anarchical network of people, who come not to earn money, but to develop something for the future. It is also about self-development, about new technology..."*

Misir (2014).

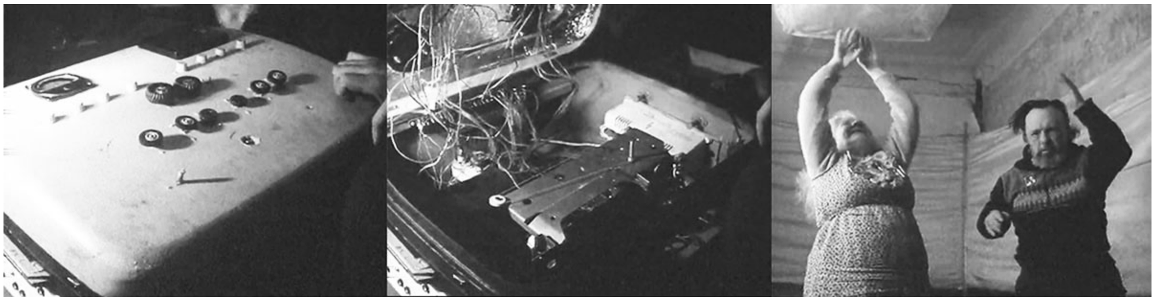

Figure 2. Room-wide Theremin by Alexei Blinov and enthusiast dancers controlling the sound with their body in a squat in Moskow at the end of the Gorbachev era. Stills from film by Zalewski (1991). Images copyright Szoda 1991, used with permission.

Contactless interaction

Research on systems for musical response to free gesture compares ultrasonic ranging, motion detectors, optical sensors, radar and microwave motion sensors to electric field sensing, analysing their peculiarity in interacting with technology without touching it. As Miranda and Wanderley (2006) remark, *"...in order to acquire information about body movements, forces, and so on, one usually needs to use devices that capture the phenomena of interest in terms of electrical signal..."*. Gestural systems based on ultrasonic distance or optical sensing technology present inherent limits: sonar systems have narrow bandwidth, limited resolution, no sensitivity past obstructions, delays and interferences from the environment. Similarly, optical systems are limited by obstructions blocking the line of sight, effects from background light, reflectance. Digital video systems can be confused in interpreting the image, especially in environments presenting varying conditions. Radar and microwaves can be sensed through non conductive obstructions, but the systems suffer from technological complications (Paradiso and Gershenfeld 1997).

The word '*radar*' was coined in 1940 by the United States Navy as an acronym for "*radio detection and ranging*": it is a system that uses radio waves to determine distance, direction and velocity of (distant) objects by measuring the direction and timing of short radio waves that are sent out and reflect back from the objects. The term microwave indicates a specific range of electromagnetic frequencies, between 300 MHz and 300 GHz, having a wavelength ranging between 1 millimeter and 1 metre. These very short and fast waves can cause heat in atoms of water (hence microwaves ovens). They are also used for Bluetooth and their wavelength is the same range as that of the sound perceived by human hearing, which commonly ranges between 20 Hz and 20 kHz: a 3 GHz microwave will have in fact a 10 cm wavelength, and a sound wave of the same wavelength has a frequency of 3.4 kHz.

An example of digital video system is Kinect, a line of motion sensing input devices developed by Microsoft for xBox. Based around a webcam-style add-on peripheral, it is a closed system that enables users to interact with their console through gesture and spoken commands, without the need for a game controller. Because it implements a vision-based approach, the field-of-view is limited and can be affected by occlusions and varying light (Pardue 2017). The Wii is a game console system that uses a combination of accelerometers and infrared detection to sense its position in 3D space when pointed to the LEDs in the sensor bar. A remote allows the user to control the game with physical gestures and button presses. The controller connects to the console using Bluetooth (with a range of approximately 9 m). Both Kinect and Wii require a direction towards a specific, non mobile point of entry, in one case the camera, in the other the receiver, although Wii seems to offer a higher degree of movement to the player. Razor Hydra uses instead a magnetic field to detect the position and the orientation of the controller in the range of one meter. This is done via a coil that can be easily separated from the controller's body, making it smaller and more portable (Basu, Saupe, Refour, Raij, and Johnsen 2012). It is therefore a more open and hackable instrument if compared to Kinect.

Paradiso and Gershenfeld identified in electric field sensing techniques, based on capacitance sensing, a means for tracking musical gesture that avoids some of the weaknesses of other contactless systems (Paradiso and Gershenfeld 1997). In 1997 they foresaw the future developments of a class of wearable user interfaces based around advances in RFID (radio frequency identification) sensing, which incorporates the use of electromagntic coupling in the radio frequency section of the electromagnetic spectrum to uniquely identify an object or entity. Seeking to transform flat surfaces and structures of everyday life in interactive surfaces capturing gesture, a variety of experiments were conducted by the Responsive Environment Group at MIT Media Lab. Among those, the chromakey technique is defined as the most common approach, although normally it is the body silhouette that is tracked (Paradiso, Hsiao, Strickon, Lifton, and Adler 2000). In 1997, Masaaki Fukimoto created a groundbreaking system that sensed fingertip typing by accelerometers then transmitted capacitively using the body as part of the circuit (Bainbridge and Paradiso 2011). In 2012, Humantenna proposed a different approach, offering an on-body sensing system that recognises whole-body gestures, transforming the human body in an antenna that receives existing electromagnetic noise from power lines and electric appliances in a building, therefore re-purposing already present electromagnetic waves for use in interaction (Cohn, Morris, Patel, and Tan 2012).

Another approach is proposed by Myo gesture control armband which allows muscles to trigger events in a computer. This gesture sensing device, wearable on the forearm, has muscle sensors detecting the electrical signal when the muscles are contracted; the device captures also data from orientation sensors (a gyroscope, accelerometer and a magnetometer) and sends it to a computer via Bluetooth (Fried 2016). The bracelet, divided in eight cells, reveals an intense manufacturing process, multiple batteries and DSP for sensors analysis. Before being discontinued, Myo has been explored in gaming and prosthetics, but also in expressive music performance, notably by musician Atau Tanaka (2014), who explored sensor-based interaction and the use of bioelectrical signals in musical performance since the early nineties (Tanaka 2000). More recently, Google Soli proposed a gesture recognition technique based on very short-range radar signal (60GHz, 4.99 millimeters wavelength circa), one emitter and multiple receivers embedded in an integrated chip, employing machine learning algorithms to recognise predefined gestures (currently limited to five) (Hayashi, Lien, Gillian, Giusti, Weber, Yamanaka, Bedal, and Poupyrev 2021). However, larger scale detection capability and interpretation scope for non-discrete gesture beyond the coded repertoire isn't currently possible and the product never gained much traction.

Collins (2022) explored the potential of electromagnetic field sensing in musical performance through the construction of sensors systems to "*sniff*" everyday electronic appliances with guitar pickups attached to a glove and amplifying it through the guitar strings, therefore engaging in a novel form of feedback. Numerous experiments in recent years have devised techniques exploring the potential of electromagnetism in the creation of live and novel interfaces for musical expression, mainly investigating the possibility of augmenting traditional acoustic instruments with notable contributions such as the Magnetic Resonator Piano (McPherson and Kim 2010) and the Self-resonating Feedback Cello (Eldridge and Kiefer 2017). Other projects intersect AI, robotics and experimental music: an example is Ghost Play, where a violin playing robot uses seven electromagnetic linear actuators for controlling the bow and the pitch on each string (Kamatani, Sato, and Fujino 2022). However, as outlined by Geiger, Reckter, Paschke, Schulz, Poepel, and Ansbach (2008), although the Theremin has had a long-lasting influence, the controllers and instruments it has inspired tend to be similar to the original. A hundred years after the Theremin was introduced, the REBUS was premiered (Figure 3), offering a radical redefinition of the Theremin's contactless interaction technique, one that is slowly being accepted into the realm of electronic music.

Figure 3. REBUS premiere streamed on 27 June 2020. The event was curated by Nebularosa and IKLECTIK with support from UKRI, Arts Council England and Queen Mary University of London.

Light

My inspiration for developing techniques to make music with the electromagnetic field comes from Phantasmata, a performance that uses self built oscillators modulated by lights captured through solar panels and light dependent resistors (Oreggia 2010). Under the moniker *xname* I created a series of devices to transform light into sound called Noise Bots, small entities at the intersection of do-it-yourself music and sculpture. These minimal synths use mainly the CMOS family of chips, in particular the 74HC14, an Hex inverting Schmitt trigger composed of six *not gates*, the simplest gate of the truth table, consisting of a single input and output (Figure 4).

These instruments, which turn logic gates into simple oscillators, detect light in two different ways: through light sensors, therefore in the form of resistance (R); or through solar panels, therefore in the form of electric power, or direct current (DC). These units are

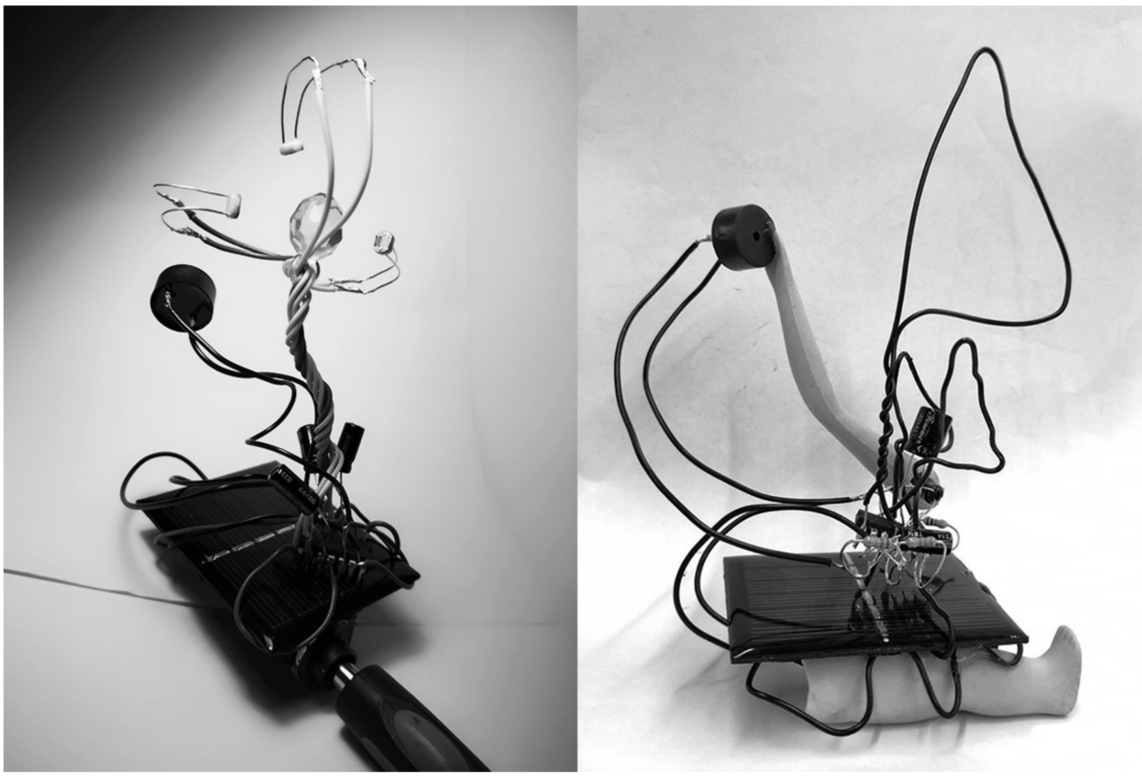

Figure 4. Hanakotoba and Mar Migrante, examples of Noise Bots, xname 2019.

in a proportional relation given by Ohm's law $(V = IR)$ and therefore as current increases, resistance decreases, and vice versa. Most light instruments use either solar panels, or LDRs, or both. The interaction of the two creates the most interesting results. Light bots usually don't have a power supply or a battery and are activated by solar panels (in this sense, they have some form of autonomy, hence bots). Other chips that have been used in a variety of combinations include the 4093 astable oscillator, a Quad 2-Input NAND Schmitt Trigger which oscillates spontaneously between unstable states and presents four NAND logic gates, and the 555 timer.

Some bots didn't even have a chip: the simplest instrument to transform light into sound consists of a solar panel connected to a female audio jack, which turns the voltage detected directly into a sound signal: there is no oscillator or music making circuitry, the detected amplitude is directly fed into a mixer as an audio signal. The light emitted and received, with its colour and intensity stable or flickering, steady or moving, obfuscated by the hands or without interference, becomes the absolute source of the sound.

Electromagnetism

James Clerk Maxwell (1831 - 1879), the Scottish scientist who formulated the classical theory of electromagnetic radiation, bringing together electricity, magnetism and light as different manifestations of the same phenomenon, was, in his theory published in 1865, the first to propose that electromagnetic waves move at the speed of light, and that light was just such a wave (Maxwell 1865).

Maxwell noted that the equations and laws that had been discovered up to his time were inconsistent when seen as a whole, and for the system to be consistent he had to add another term to his equations. With the new term of *displacement current* (a time-varying electric field generating a magnetic field) came the realisation that a time varying electric field can produce a time varying magnetic field and viceversa, leading to the discovery of the existence of electromagnetic waves and radio propagation at long distances and uniting the theory of electricity, magnetism and optics into one single unified theory.

Maxwell realised that electric current in one place can affect charges far away, predicting the basic effect of radio transmission, radar, etcetera. This is because fields, as the scientist was the first to understand, do not vary as the inverse square law, but only inversely as the first power of the distance (Feynman et al. 2010, 28-1). The scientist showed, theoretically, that a magnetic field should be produced by a time-changing electric flux just as an electric field is produced by a time-changing magnetic flux. A flux is defined as the rate of flow of a property per unit area, it represents the number of field lines going through a virtual surface. Whereas fields are real and can be measured, fluxes are theoretical constructs that enable us to remove the effect of space or the material the field is in.

Maxwell's Equations are the fundamental relations of the whole of Electrical Science. From them Maxwell predicted the possibility of electromagnetic waves; these were later detected experimentally by Hertz. According to Maxwell's equations, the electric and magnetic field are at the right angle to one another and to the direction of propagation (linearly-polarised), as illustrated in Figure 5.

In certain circumstances, a combined, time-varying electric and magnetic field can detach itself from the sources and propagate through space as an energy package, known as electromagnetic wave; antennas are responsible for this detachment process.

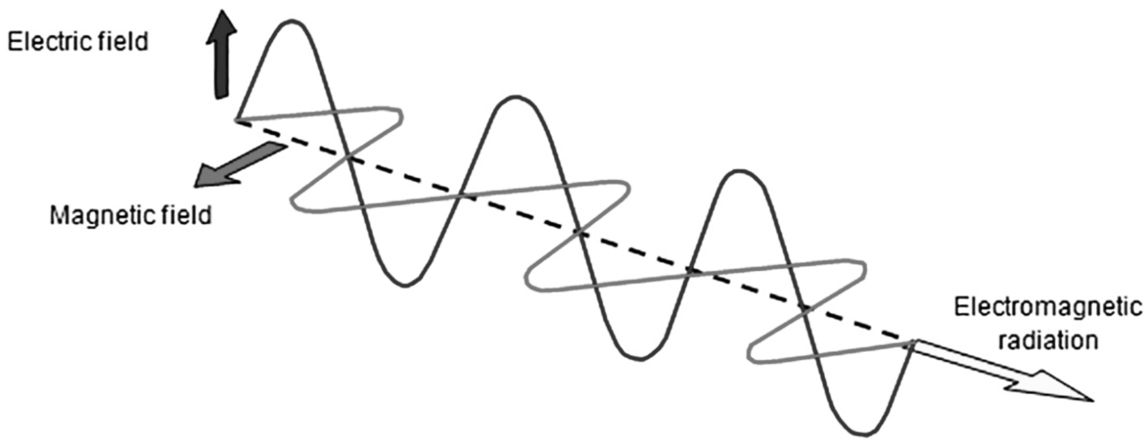

Figure 5. Classic illustration of the electromagnetic wave.

Waves detection

The most minimal electromagnetic network consists of two antennas, one emitting and the other receiving, and the simplest experiment we carried out analyses a set of measurements of the received signal while the transmission is obstructed by physical events that act as interference between transmitting and receiving antenna (Figure 6).

We encountered variations in the detected signal's power across a range of frequencies while observing the network's behavior when different types of events occur, for example when a hand, placed between emitter and receiver, interferes with the signal. The power of the signal, detected in the form of squared Voltage, is used as input to another device. Actions taking place in the space between an emitter and a receiver can be detected, measured and mapped for musical applications. This mode constitutes the basic technique that this paper proposes, which is applied in a variety of settings and electromagnetic frequencies, from light to microwaves, from the Noise Bots to the TPD and finally the REBUS.

Preliminary experiments started from the use of a Total Power Detector (TPD), a small circuit to detect the power of microwave signals which uses the AD8313 logarithmic

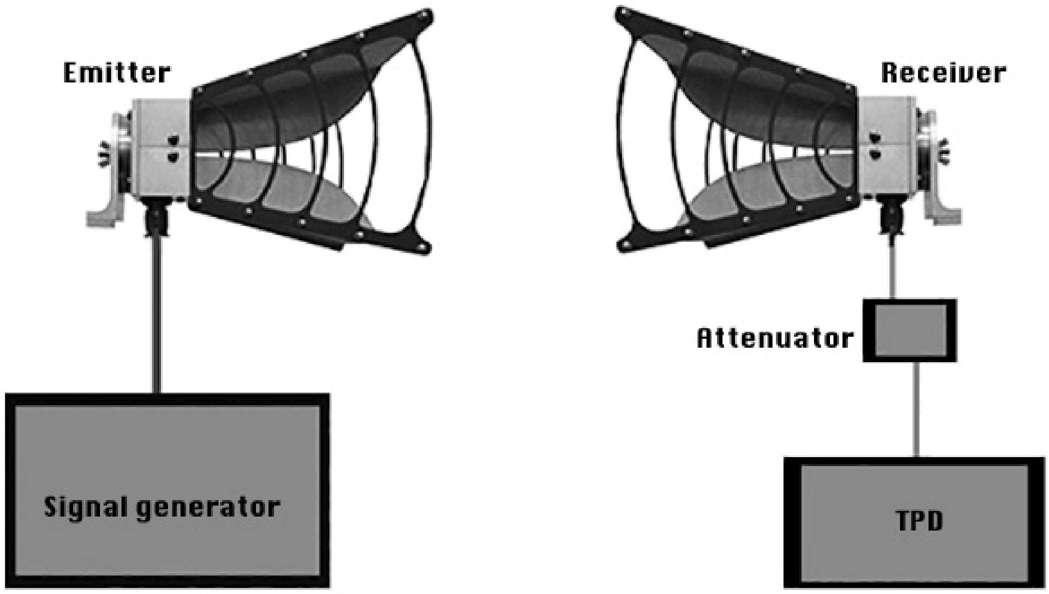

Figure 6. Signal flow, via an emitter and receiver in free space, from an electromagnetic signal generator to a total power detector (TPD).

amplifier, a surface mount chip that can accurately convert an RF signal at its differential input to an equivalent decibel-scaled value at its DC output. The AD8313 detects the range between 10 MHz and 3 GHz, and requires a single supply of 2.7 to 5.5 V. The detector was tested at five different frequencies: 0.857 GHz, 1.250 GHz, 1.5 GHz, 1.75 GHz and 2.15 GHz, measuring the signal received at the TPD output voltage.

The Voltage output of the TPD was then measured for every given input (Figure 7). The results showed a linear region between input powers of 0 dBm to -50 dBm for all the frequencies except 2.15 GHz where the linear range is limited to the range +10 dBm to -30 dBm. In all cases, the TPD gives around 0.1 V per 10 dB change in signal input. we selected the middle frequency of 1.45 GHz and used it to measure detection variations when the signal is received with no barriers between the horns (antennas), with a hand blocking the signal and finally with the whole body interfering with the detection, varying the distance between the two horns at 40, 60, 90, 120 cm (Figure 8).

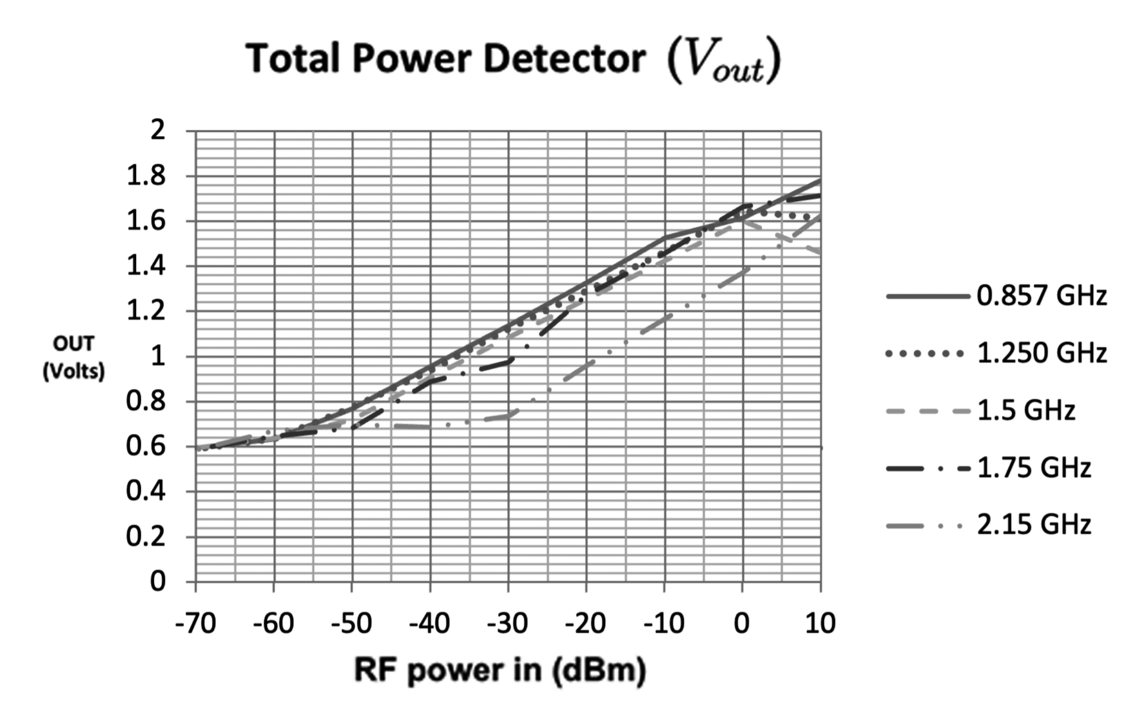

Figure 7. Conversion from dBm to Volts using the AD8313 TPD.

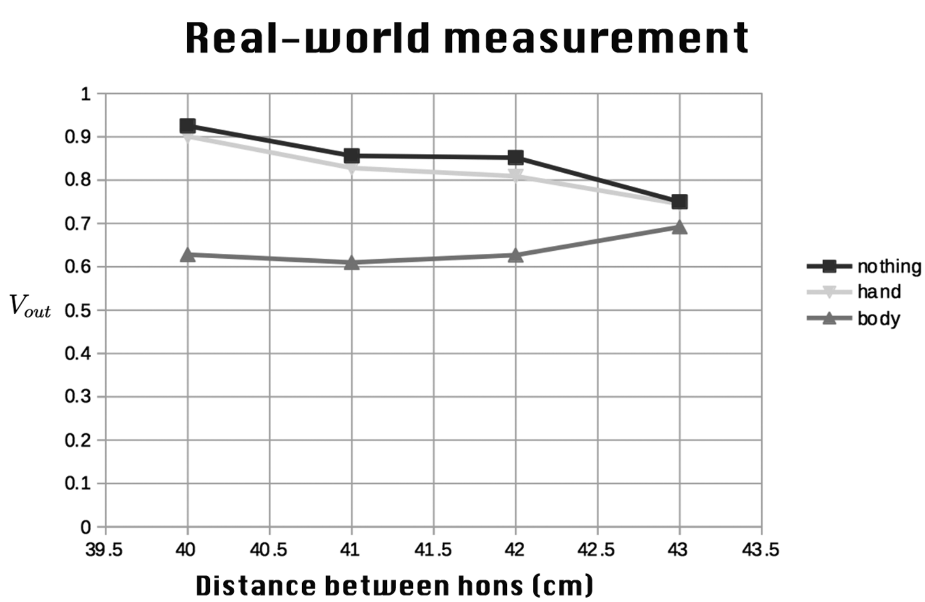

Figure 8. Power detected by the TPD varying the distance with hand, body or no interference.

As the power of an electromagnetic signal drops with a $\frac{1}{R^2}$ dependence responding to the inverse square law, the experiments confirmed that if the body obstructs from a large distance the signal is highly attenuated, whereas at a close proximity the body almost completely covers the emission. These important preliminary experiments confirmed that the body is a good absorber of microwaves and the hand is capable of obstructing the signal, thus microwave power can be detected measuring the DC voltage from the TPD because, when the hands or the body interfere with the signal, a changing output voltage is observable. The objective of this experiment was to verify whether the hand could produce a Voltage variation significant enough to be used, if properly implemented and mapped, to (gesturally) modulate sound. A simple voltage controlled oscillator was therefore connected to the TPD, transforming a light-controlled oscillator into an instrument that could be played moving the hands between the horns (Figure 9).

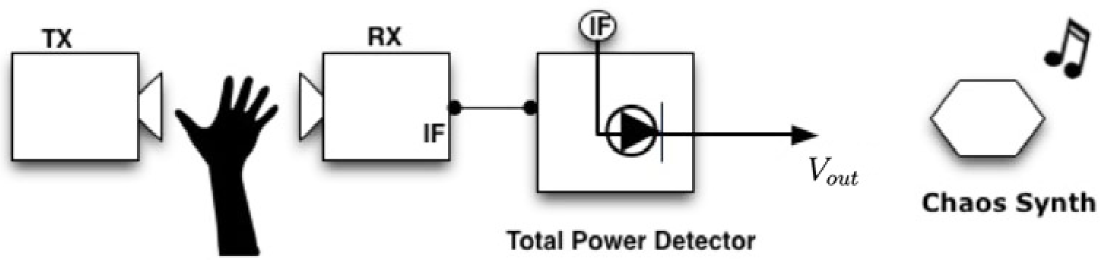

Figure 9. Signal flow of the first performance using a Total Power Detector.

An optical isolator was made by connecting a LDR (Light Dependent Resistor) to an LED (Light Emitting Diode) with black tape and a straw, shrunk with a heat gun to isolate the two components and avoid the dispersion of the light. This homemade vactrol is an optoelectronic device made of a source and a detector of light, optically coupled and electrically isolated from one another (Collins 2006). Vactrols were used by Buchla as voltage controlled potentiometers in virtue of their sensitivity and response; they are said to contribute to the very natural peculiarity of Buchla sound. In this case the Voltage variation of the TPD output (V_{out}) controls the LED, which is sending light to the LDR. An operational amplifier (OPAMP) amplifies the Voltage input (V_{in}) from the TPD, in the range between 0 and 2 Volts.

The instrument was tested in a live performance: the variables to modulate the sound were the signal generator's frequency, a potentiometer of 10K added in series with the 220 ohm resistor, and the movements of the hands. The effect had something emergent and organic, as if the whole electromagnetic "magma" of the mixing desk was creating an unstable signal that had intrinsic variations in time in the domain of continuous non-linearity, even without human intervention (Figure 10). The limit of this approach is that the electromagnetic field simply acts as a controller, ultimately performing the function of a knob, whereas the purpose of the experiment was expanding the light controlled technique to invisible microwaves, therefore focusing on the expressive power of gestural interfaces.

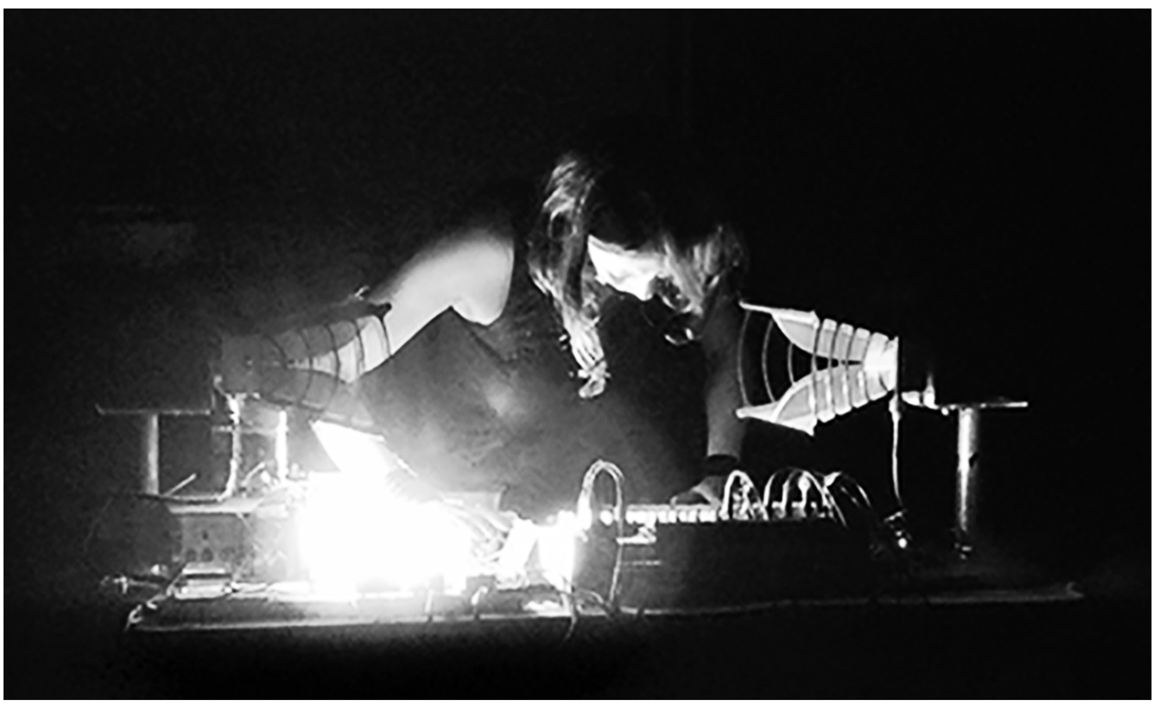

Figure 10. Performing with Horns at Electro Anthro Visceral Intensity (EAVI) in London, 13 November 2013. Photo by Atau Tanaka, used with permission.

In line with the minimalist approach described in the previous section, I made a second microwave instrument connecting the amplified voltage signal from the TPD to a female jack. The resulting sound featured patterns, melodies and noise because Total Power Detectors selectively amplify the prevalent signal, and the urban environment is filled with competing signals from electronic devices and communication infrastructures which often recur at regular intervals creating evolving sound structures. This seemed like an interesting instrument for noise musicians, although also techno musicians may appreciate it. Whereas techno music tends to be geometric, formal and mathematical, where predictability and minimum variation constitute the essence of the often desired loss of the self into the music, noise musicians prefer unpredictability, error, harsh sounds, broken beats, polyrhythmic and unstable patterns as the manifesto of their sonic aesthetics.

This device, named Spectropticon, was designed as a small board that can be connected to Standard Gain Horns or patch antennas, which can also be printed in the same circuit board, making the instrument more compact but less open. It is a microtonal site specific noise synth operating in the frequency domain (Figure 11). A track featuring recording from the 19th floor of the Balfron Tower in London using the Spectropticon with Standard Gain Horns and the Noise Bots was published by the label Alien Jams (xname 2018).

Ghost detectors and EM amplifiers have long been explored in sonic research and pseudo science. Soma Ether by Soma Laboratory is a wide band receiver described as a device that "*makes it possible to perceive the electromagnetic field around you*" (Kreimer 2019). It reached the market in March 2019 and was presented as '*anti-radio*' because, instead of having only a coil and a low frequency modulator like usual inductive sniffers, it has a demodulator, making it a radio wave receiver rather than just an amplifier of low frequency fields (Kirn 2019), somehow echoing Kristina Kubisch's Electric Walks (Kubisch 2004-ongoing). A similar product is Elektrosluch 3+, created by Lom (a Bratislava-based record label and instrument manufacturer), an open source device for electromagnetic

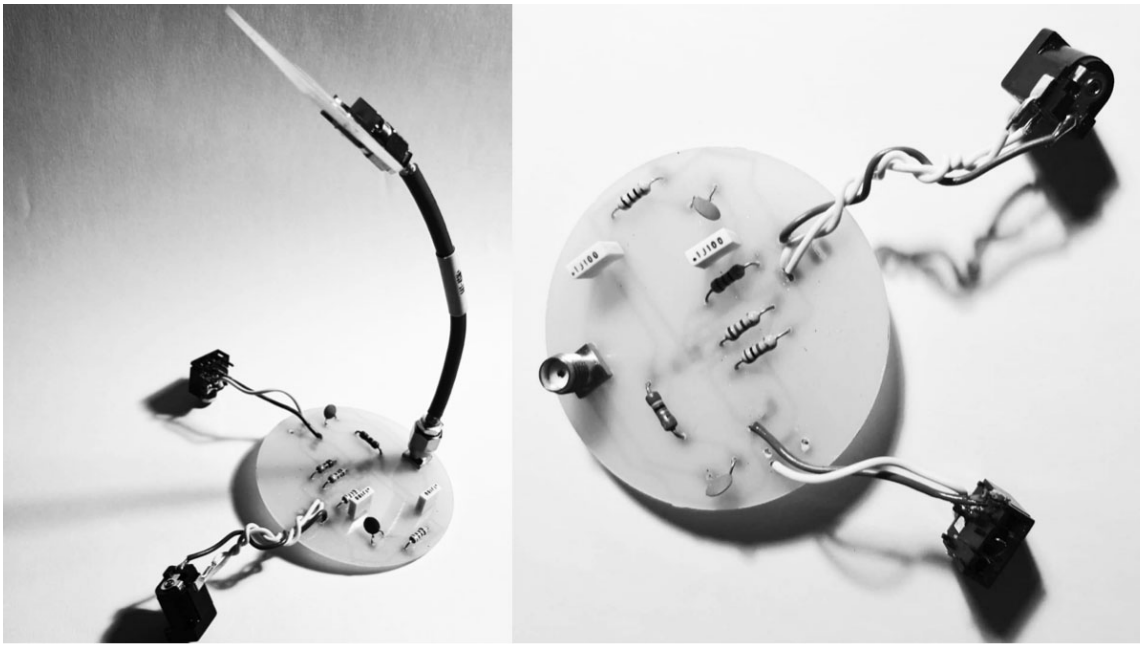

Figure 11. Spectropticon, xname 2018.

listening particularly effective in the short range and used by artists such a Richard Devine (Gruska 2016).

Vivaldi antennas

A series of experiments were designed and conducted using two Vivaldi antennas operating in the frequency range of 2 GHZ to 3.5 GHz, modifying the design of the antenna described by Sharma, Parini, and Alomainy (2014) to a 27 mm by 48 mm size (Figure 12). Vivaldi antennas are a particular type of patch antenna which is made from a dielectric plate metallised on both sides. The advantage of this type of antenna is that it emits electromagnetic waves over a conical area because they are metallised on both sides and can operate over a wide frequency range (ultra-wideband). Patch antennas are often used nowadays because of their frequency range and because their manufacture is relatively cheap using common methods for PCB production. The aim of this experiment was to define the optimal frequency range that the Vivaldi antennas constructed could be

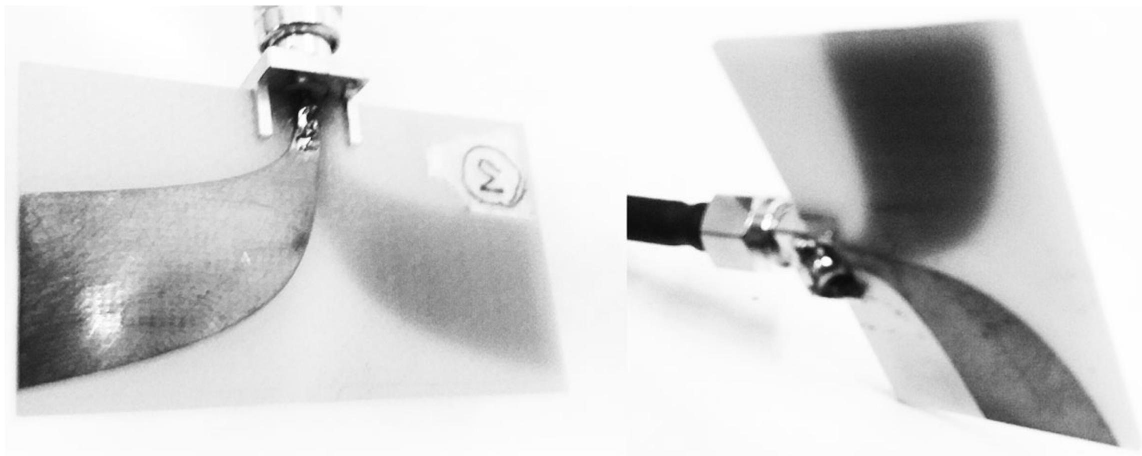

Figure 12. Vivaldi Antenna, range 2 GHz to 3.5 GHz.

able to emit and detect. The decision to use microwaves was determined by their wavelength in relation to the human hand.

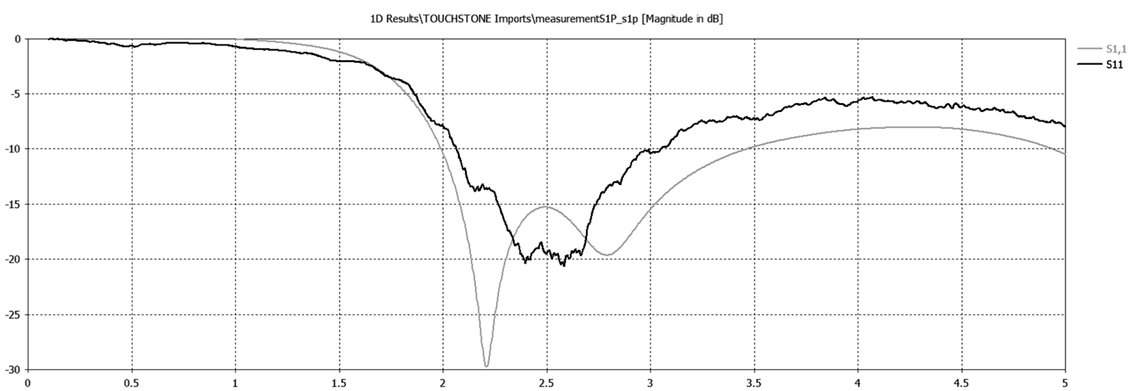

Figure 13. Measured S11 of Vivaldi Antennas (2 GHz to 3.5 GHz) versus its simulation (in grey).

The simulation of scattering parameters in Figure 13 shows two resonance bands around 2.2 GHz and 2.8 GHz. The two curves indicate the frequencies at which the antennas constructed offer the best emission and detection capability. Scattering parameters (S-parameters) are complex numbers which represent the behaviour of EM waves, describing the reflection (S11, S22) and the transmission (S12, S21) occurring when a wave propagates through a two-port (or multi-port) network (Figure 14), for example when an electromagnetic wave is incident on a material interface. It is common practice in antennas and electromagnetics to confront a software simulation of scattering parameters with real world measurements, to verify whether the antenna is behaving as expected. The invisibility of the electromagnetic field makes the methodologies of its experimental study very specific.

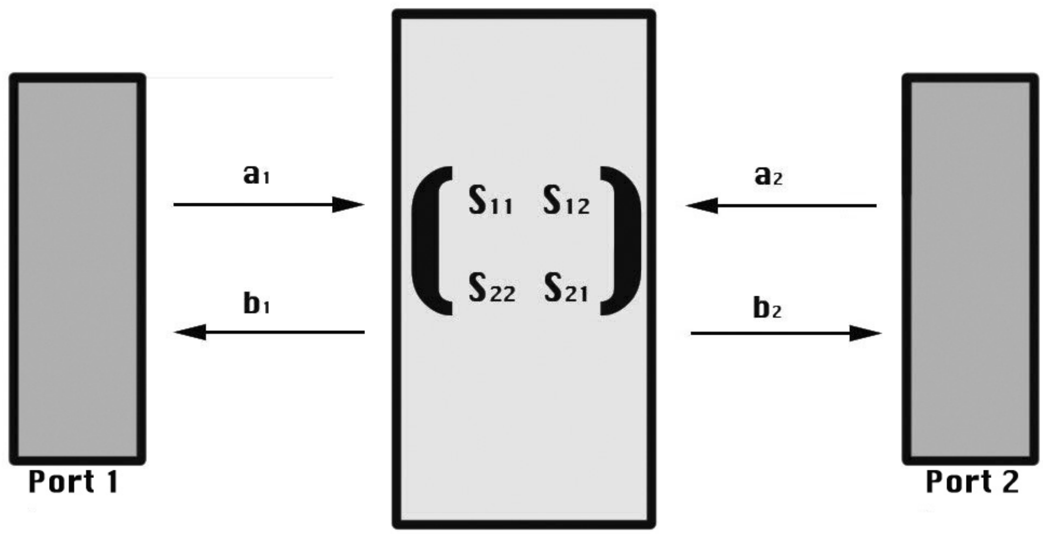

Figure 14. S-parameter matrix in a two port network.

A novel system

After these experiments, with the introduction of a new and more advanced sensing technique (later named REBUS technology and registered at QMUL with MyIP No. 2018088), measurements were taken while obstructing the signal with objects of different material, using overlapped layers (up to three). The results confirmed that combined barriers produce a greater variation than single material barriers. Triple material barriers generate very significant variation and the order of the materials has an influence on the results. In a sense, complex settings increase the precision of the system. This early result regarding the correlation of precision and complexity in electromagnetic field sensing is characteristic of this particular method, also in comparison to other sensing techniques:

the detection of electromagnetic waves is not affected by noise, light conditions, or a particular line of sight, enabling the construction of systems which can perform consistently in the laboratory and in the real world.

In this novel system, which is active and integrated in that it synthesises, emits and receives an electromagnetic signal, the sensor data from the receiving antenna is passed as analog signal to an embedded computer specialised in digital signal processing: Bela, the Beaglebone black with audio cape initially developed by Andrew McPherson at Queen Mary University of London, and specialised in audio digital signal processing (DSP) and real-time analogue sensing (McPherson 2017). Bela acts as the sound engine in virtue of its particular real-time operating system, a modified version of the Linux kernel which gives priority to sound processes over any other thread or system task. The curious reader who would like to explore the technical details of this sensing technique, including diagram, circuit, and all necessary instructions to reproduce the instrument, will be able to refer to to Oreggia (2020b), where the results of all preliminary experiments are thoroughly discussed and the engineering decisions explained step by step. The initial results were obtained using very large equipment and expensive components, and the miniaturisation phase, for the instrument to be portable and potentially affordable for artists or musicians, was a non trivial phase of research and development spanning across a few years. The field of antennas and electromagnetics is undergoing an intense and exciting development which resembles that of early computers described by Moore's law, from the huge and expensive machines which could only be accessed in scientific laboratories, to the personal computer slowly entering the house, and finally the laptop followed by the smartphone, which attaches a computing device to almost every individual.

The culmination of all this work, currently under development to explore serial production, will be narrated focusing more on interaction modes than technical specifics. The study described in the the next session preceded the miniaturisation of the system but informed its becoming an instrument.

Perception

Shifting the focus from engineering to interaction design, and from spectator to user, a first study was designed to investigate human behaviour in a controlled interaction with the system, with the objective of turning it into a musical machine. The software was designed to create a scaled symmetry between pressure and electromagnetic waves, drawing on the fact that the wavelength of sound at 3.4 kHz is the same as the wavelength of a 3 GHz electromagnetic signal. The users were informed that the study presented the skeleton of a new technological system for touchless interaction in the attempt to investigate different possibilities to develop intuitive forms of interaction, using invisible affordances and sensing the electromagnetic field. Eleven participants from a variety of backgrounds, demographic, age and gender were recruited and asked to perform four tasks in a space where three antennas formed a triangulation; no further explanation was given. The study was designed to investigate whether people could become familiar with a certain degree of unpredictability and indeterminacy, and how *zones of non-control* could be explored simply relying on invisible affordances. In the context of novel musical instruments and handmade synthesisers, we refer to a "*zone of non-control*" as an area in which the user lacks control but has developed a certain knowledge of how to approach the zone with "*a controlled loss of control*" (Oreggia and White 2018)[pp. 60].

An electromagnetic experiment

The study, entitled "REBUS. An electromagnetic experiment", was presented as an observation of phenomena related to perception, leaving undeclared the connection to musical interfaces so as to prevent aesthetic notions of music from biasing the results and to accommodate participants who lack a musical background. At the beginning each subject was asked to complete a brief questionnaire which asked two questions, an open one: '*What is the electromagnetic field*'; and one with three possible responses (yes, no, maybe): '*Can you touch the electric magnetic field?*' (Figure 15), and they were given approximately twenty minutes to interact with the sound in the space. The system featured two receiving antennas at a distance of 10 m, forming a triangle with the emitter. This 3-antenna setup was tested in this experiment for the first time to increase the precision of the system in the large performance space. In order to cover it, we used Standard Gain Horns, which are very powerful but also large, heavy and expensive. Differently from the Vivaldi antennas discussed earlier, these horns emit a focussed beam. The triangulation had the function of rendering the interactive area three dimensional other than limiting it to a line connecting emitter and receiver, therefore enabling study participants to move more freely in the space circumscribed by the three antennas, the two speakers and the subwoofer (Figure 16).

The first task asked the participant to *gain any form of control* over the system; the second task asked the participant to *turn down the volume*. The third task requested the production of *a minimal, simple sound*, as opposed to the fourth task, which asked for a *complex, layered sound*. At the end of the study participants had three minutes to respond to an additional set of questions.

The software, named Spectrifier, was purposefully deceiving: the electromagnetic data in the form of voltages was not only used to control the interaction but also sonified, using the gain and phase of the waves detected to modulate the frequency and amplitude of the voltage signal received and turned into audio. This aimed at increasing the illusion of homology between electromagnetic and sound waves.

This open and underdescribed system was perceived and interpreted in a very

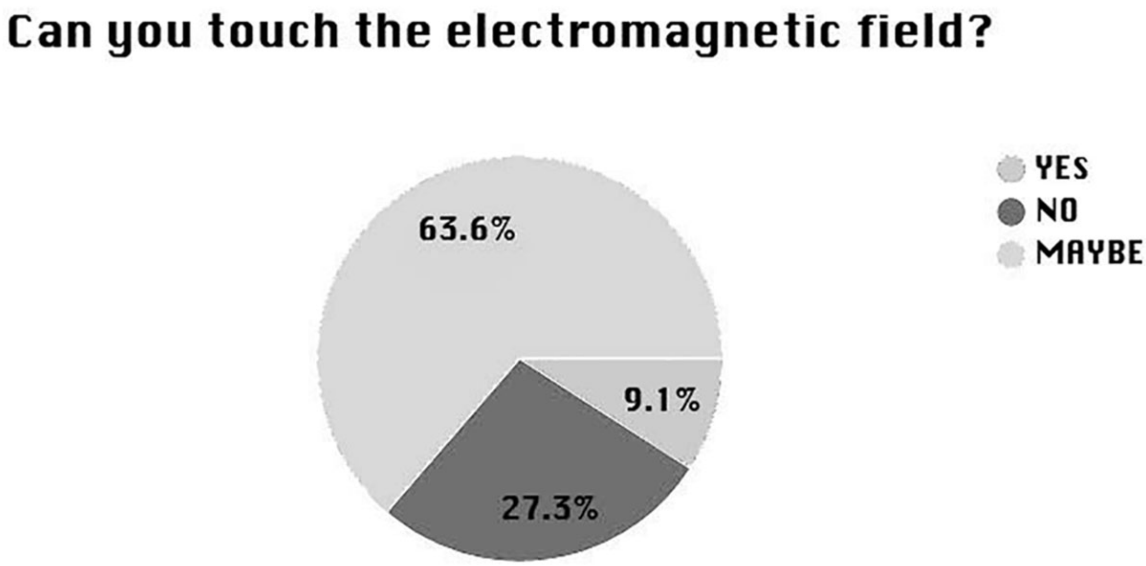

Figure 15. A pie-chart visualising the answers to one of the questions of the introductory questionnaire.

different way according to the background of the participant: for example, a user who develops realtime audio processing software lamented the presence of a delay. An orchestra director imagined two sounds being played along two imaginary lines connecting the two receive antennas and the emitter. Where some participants naturally engaged with the space, others focussed on the antennas, which, being horn shaped, were often interpreted as sound sources. The idea of invisible lines connecting the antennas, corresponding to the trajectory of the field, was recurrent. While the speakers 'S1' and 'S2' were located in the vicinity of the receiving antennas, the sub was lateral and most of the pressure waves were traversing the room from West to East of the map, whereas the transversal electromagnetic waves crossed the room from North (centre) to South-East and South-West (Figure 16).

A few patterns immediately emerged: most subjects made large movements at the beginning, becoming almost still after a careful exploration of the system, when it became obvious that minimal movements could produce significant changes in the sound, also thanks to the use of two receive antennas. A participant started to control the sound with

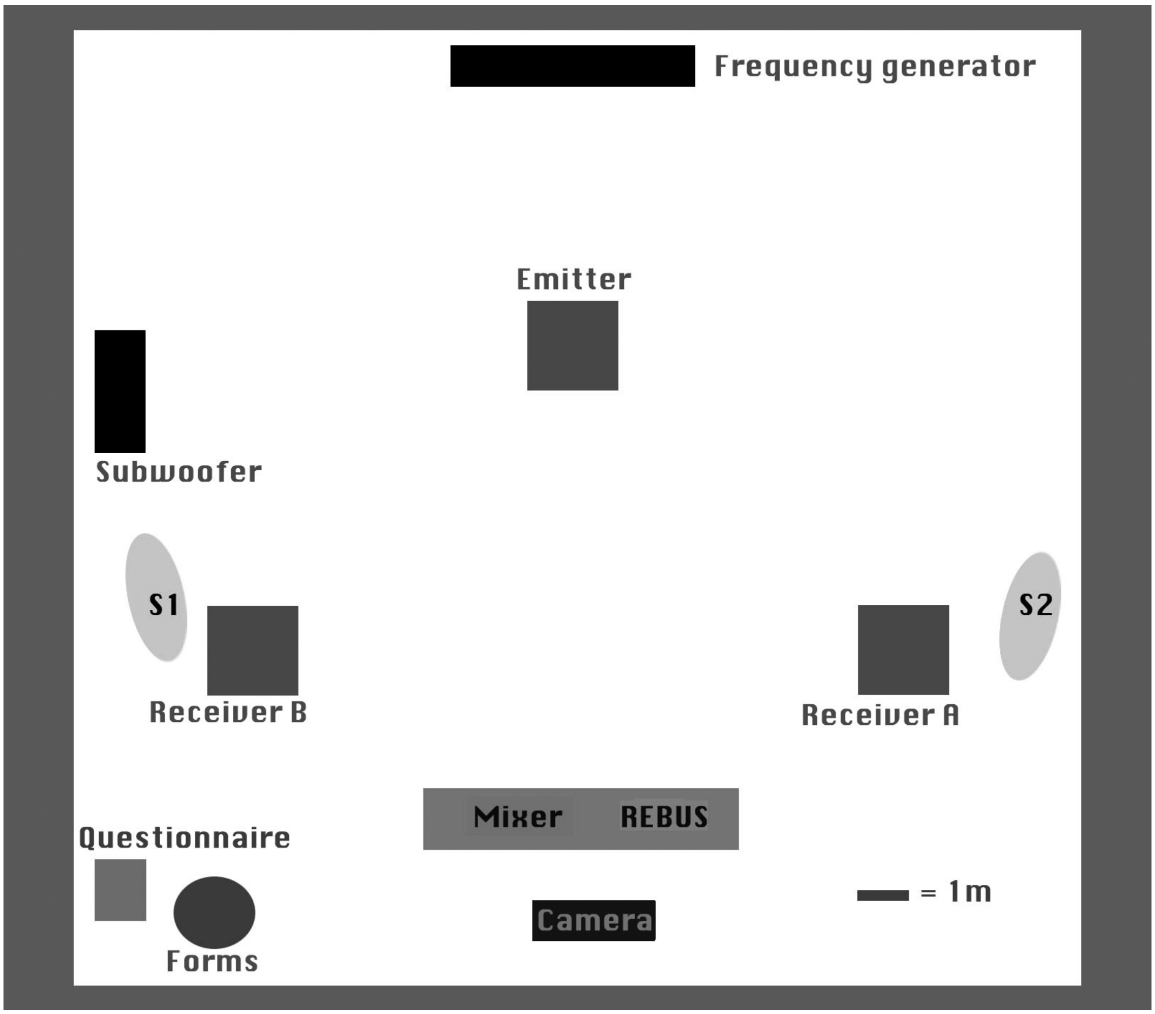

Figure 16. Map of the study space illustrating the placement of the speakers (S1 and S2), that of the two receiving antennas (A and B) and the questionnaire's table and ethical forms at the bottom left.

his breath. Those who had a defined idea of what a synthesiser should be like, displayed a certain resistance in exploring the system; others who had a strong background in classical music were frustrated by the lack of linear control and repeatability (the same action in a different part of the space could produce a different result). Users expecting a coherent and predictable action-response relation started imagining defects in the system, and a few interpreted each sound as the product of a particular antenna: in fact many behaved as if the antennas were speakers.

The final questionnaire enquired about the perception of the electromagnetic field with a Likert scale, a psychometric scale widely used in survey research that employs questionnaires; the question "*Can you perceive the electromagnetic field?*" was asked four times. In the first case, the choice was between '*bodily sensation*' or '*movement*'. The majority of the answers opted decisively for movement, however for two participants the perception was equally a bodily sensation and a result of movement (Figure 17). In the second case, the choice oscillated between the electromagnetic field being a property of the space or a property of the body, with four users opting for a choice in the middle, which might mean that they perceived it as equally belonging to space or the body, or that they didn't know what to answer and chose the middle way (Figure 18). Figure 19 shows a varied result, with only one participant perceiving it as absolutely tangible, two users in the middle point, and four tending for tangibility, against four opting for the absolutely immaterial. Figure 20 shows another example in which the experience of the subjects involved varies, with a large majority in the centre, and a distribution that favoured presence over movement in a non categorical way.

Finally, four open questions regarding each different task, and one about movement ('*Define your movement in space*'), completed the data to be analysed. The results of the experiment suggest that it is possible to manipulate invisible inferences if a response is received by the person interacting and that subjective factors contribute in compensating

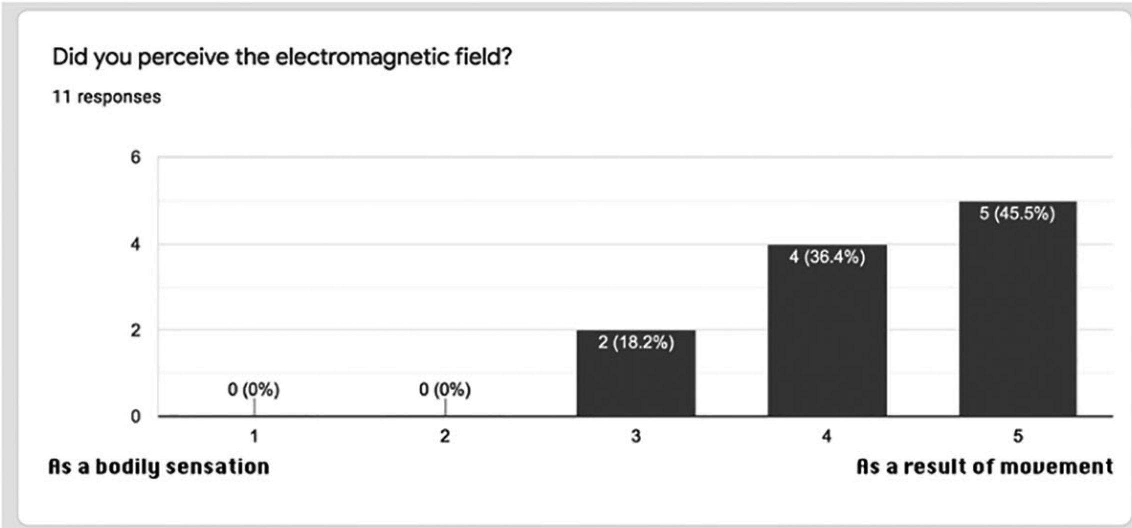

Figure 17. Likert scale from 'As a bodily sensation' *to* 'As a result of movement' *in the perception of the electromagnetic field.*

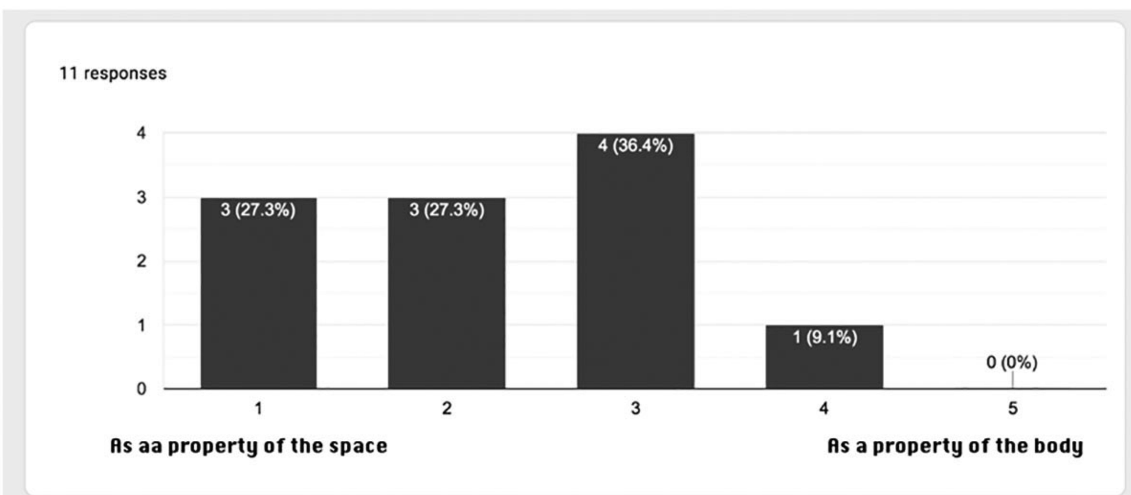

Figure 18. Likert scale from 'As a property of the space' *to* 'As a property of the body' *in the perception of the electromagnetic field.*

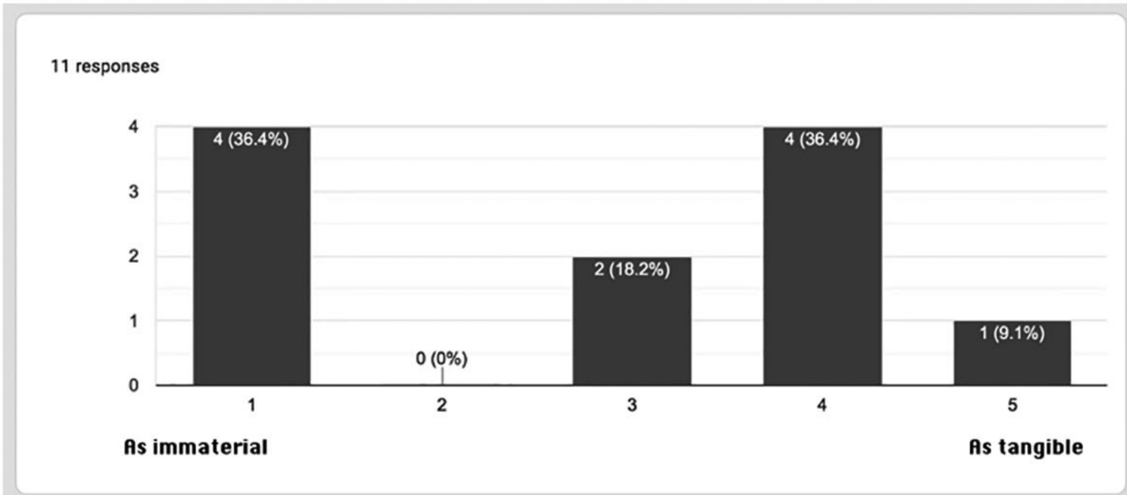

*Figure 19. Likert scale from '*As immaterial*' to '*As tangible*' in the perception of the electromagnetic field.*

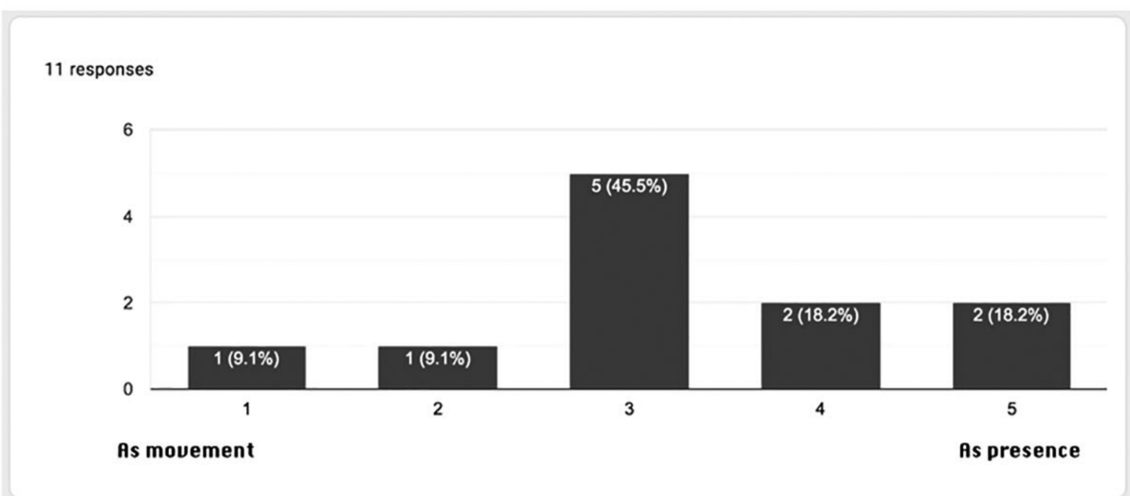

*Figure 20. Likert scale from '*As movement*' to '*As presence*' in the perception of the electromagnetic field.*

for the invisibility of the interface.

Thematic analysis

The composed video material was annotated and coded using a software for qualitative and mixed research methods (MaxQDA), following the thematic analysis methodology outlined in Braun and Clarke (2006). The main themes emerging were movement and touch, so the evaluation of the video material observed the frequency of the codes 'Move' and 'Touch' as they recurred through the different tasks. Touch was divided in two main subcodes: 'Touch Real' and 'Touch Imaginary'. 'Touch Real' included 'Touch Antenna', with the three antennas as subcodes. 'Touch Imaginary', identifying occurrences where the participants where touching imaginary objects, had the 'Touch diagonal' subcode, where the initial division in touch diagonal to right and touch diagonal to left was absorbed because the two subcodes had an identical frequency.

The movement code had more branches: 'MoveBody' looked at the particular body part that is engaging in the movement, as for example 'head', 'arms', 'hands', 'fingers', 'belly', 'torso', 'right hand and arm' or 'left hand and arm'. 'MoveHow' looked at the quality of movement, with subcodes such as 'move up and down', 'move lateral', 'oscillate', 'squat', 'rotate', 'rapid', 'slow', 'back and forth', 'large', 'small', 'symmetrical' and 'repetitive'.

Touch had a total score of 112 for TouchImaginary and 101 for TouchReal (Figure 1). This confirmed that human instinct doesn't find strong oppositions in relating to invisible and immaterial affordances if they receive some form of feedback. The total for Touch was 213, as opposed to the total for Move scoring 1,010: test subjects realised that, to trigger reactions, movement in space was more effective than touch. TouchImaginary identified the act of touching an invisible object (Figure 21), an act different from a simple movement

Table 1. Frequency of the 'Touch' code.

Name	Frequency	Percentage	Percentage (valid)
TouchImaginary	112	56.6%	56.6%
TouchReal	101	47.4%	47.4%
TOTAL (valid)	213	100.0%	100.0%
Missing	0	0.0%	-
TOTAL	213	100.0%	-

in space or the waving of the hands.

Apart from the initial and final questionnaires, participants were not asked or encouraged to speak during the experiment. However, over 11 participants and 4 tasks, Task2, Task3 and Task4 were commented respectively by 3 users, 2 users and 1 user.

Figure 21. Study participant patting an invisible line. Still from video, used with permission.

The theme of 'Uncertainty' emerged through the analysis of the transcriptions of unrequired spoken words during the experiment. Other themes appeared from the answers of the participants in response to the questionnaires, adding the theme of 'Level', where 'Easy' and 'Difficult' were branches. A series of words were related to 'Musicality', including 'constant', 'dynamic', 'granularity', 'balance', 'frequency', 'rhythm'. The themes of 'Perception' grouped words such as 'felt' and 'sense', while 'EM' represented all words related to electromagnetism: 'invisible electronic vibrations', 'interconnecting signals', 'magnetic object', 'charged object', 'lines'. The last two themes collected all the words related to 'Interactivity', and those that refer to the 'Body' (Figure 22).

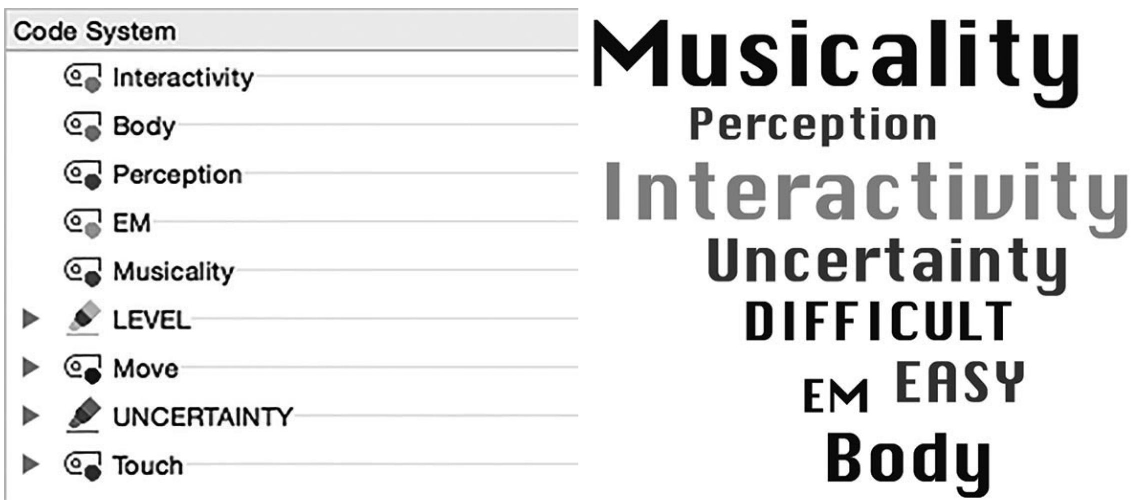

Figure 22. Code system for thematic analysis and codes cloud (second questionnaire).

The most significant result was that the words used to described perceptual phenomena were denoting a degree of uncertainty, and the codes 'Perception' and 'Uncertainty' displayed overlaps, suggesting participants were starting to doubt their perception. 'Level' presented the strongest discrepancy: whereas some users defined a task 'easy', others described the same as difficult. The words 'easy' and 'difficult' were used extensively in written comments, even if the question only asked to comment on the task and did not request to specify whether the task was easy or difficult. The word 'intuitive', included in the 'Easy' subcode, was repeated two times by different users commenting on Task1, two times in the comments to Task4, and once in the description of the movement in space, totalling five times. Most participants found the second task more difficult, however opinions differed, showing that the experience was subjective. Whereas one participant reported: "*Difficult to reduce the overall level*", another said "*It was not clear* *to me*", and where two other users wrote the word '*difficult*' and said '*I had difficulties*', another said that the same task was not too hard.

Two users during the tasks used the word 'feel': ''*I feel like I could go to Tai Chi*'', and "*it sounds like ... it feels like a certain activity...*", whereas another user reported using "*ear as feedback*", and another admitted "*everything was an interaction between body and space - I don't understand the separation*". One participant said they "*felt it more towards the end*", showing that practice increases mastery and validating the second hypothesis outlined in the introduction, that if the cause-effect principle is reinstated, and an action upon an invisible frequency generates a response, humans may begin to develop the capability of consciously perceiving the electromagnetic field (beyond the small section corresponding to visible light). A user declared "*I imagined two lines between the two frontal antennas and the back antenna*', suggesting imagination was used to compensate the invisibility of the affordances. Another user displayed a more conservative approach: "*I was not sure how to use more than one antenna at the same time*" and the illusion must have been so strong that a subject commented on Task3, which requested the production of a simple sound: "*found it easy to find the core sound of each antenna*".

REBUS

As Wanderley (2001) explains, although one-to-one or direct mapping is the most common, other strategies can be used that allow for more idiosyncratic approaches than that of the engineer. De Campo (2014) proposes complex mapping as a methodology that can provide a form of Metacontrol, seen as an artistic strategy that allows the performer to be surprised by the system she interacts with. Zappi and McPherson (2014) observe the emergence of personal playing styles when investigating the process of appropriation in digital musical instrument performance in relation to a deliberately constrained musical instrument. The results show that a very simple musical instrument stimulates a wide variety of musical styles, and that adding a control dimension reduces the exploration of hidden affordances. McPherson and Zappi (2015) also reflect on the fact that the implementation of a musical instrument tends to remain somewhat opaque to the performer, even when the relationship between action and sound is readily understandable, as the internal hardware or software operations remain inaccessible.

There is a fundamental difference between (1) devising a system, its function, components, connections, code, electronics, connecting the parts together to achieve a function, and (2) encasing a technological system into an instrument or device that can be plugged and played. A *proto* technology is an open end, its uses can still be reimagined and different parts substituted to respond to the *particular*. A specific approach is required for the process of finalising and enclosing in a box a technological system in order to transform it into a device that possesses an identity and forms a singularity, turning a multiplicity of parts into a functional *entity*. The study outlined in the previous section, which presented an open system which turned a room into an interactive musical instrument (whose costs, size and weight would have made its diffusion impossible), along with focussing on perception, informed the successive phase of development to scale the system into a compact machine which could be portable and intuitive to use. The result was named REBUS, initially the title of the study, to reflect the emerged code of uncertainty, implying something that has to be guessed, or where a part of the signifying mechanism is hidden, like in a riddle (Figures 23 and 24).

REBUS compacted the electromagnetic sensing device, the antennas and the embedded computer in a metal box (22x25x8 cm) that can be carried around in a small case. The machine has stereo input and stereo output; CV output which enables it to control with hands gesture any other synth having CV input, and, apart from two antennas, it offers the user a single button on one side, used to cycle through different

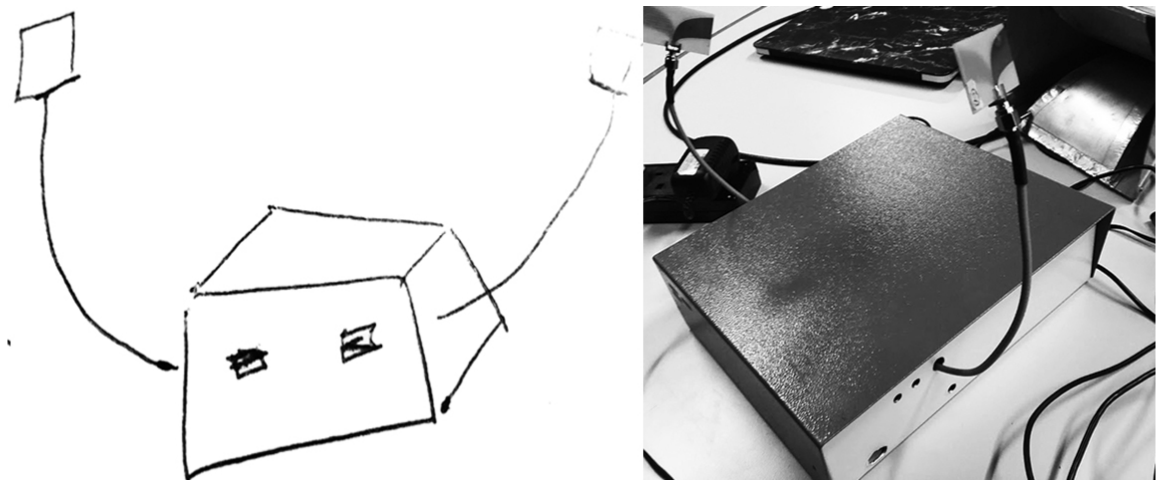

Figure 23. A sketch of the idea (left) vis-à-vis the real instrument as presented for the first time to Professor John Chowning at Queen Mary, University of London in 2019 (right).

Figure 24. REBUS in the surround sound studio at Elektro Musik Studio in Stockholm.

compositions. The term composition in this context indicates a software that, uploaded onto REBUS, defines the link between movement and sound. As the instrument developed, a series of video documents tracked its progress, starting from 'REBUS: the Mother of All Demos' (Oreggia 2019b), the first clip ever filmed featuring the instrument as standalone, followed by a short documentary narrating the research to a non academic public (Oreggia 2019a). Soon after, a demo was requested by NIME (Oreggia 2020a). More recently, a music video was produced by Goldsmiths University of London in collaboration with Mind the Film (MindtheFilm 2024).

The instrument creates an electromagnetic field and detects it; it can be played by interfering with the field (Figure 27). The electromagnetic data is analysed and used in the form of voltage, as analogue sensor data, in a variety of mappings suiting different aesthetics. Two Vivaldi antennas, sensitive in the range 2 GHz - 3.5 GHz, are suggested as the default, but other types of antennas can be attached to the connectors at the side of the box (Figure 25). Vivaldi antennas offer a range of sensitivity having an umbrella shape, much more spread than a beam. The box containing the instrument is metallic, which helps reflecting the signal all around the instrument, enhancing its sensitivity. For larger installations high gain antennas can be used to cover whole body movement in a 10 m square region.

Different approaches were initially taken in designing sound and composing for REBUS, from the initial code using electromagnetic data as both musical material and modulating data (Spectrifier), to the idea of emulating a Theremin, mapping the electromagnetic data to amplitude and frequency of the emitted sound. A slightly different approach was taken in the composition 'Rhythm0', where the frequency is constrained between 50.0 and 55.0 Hz, producing an almost inaudible tone. The second frequency is calculated adding 1 to the first frequency, which depends on the received electromagnetic signal, implementing the formula: $f_2 = 1 + f_1$.

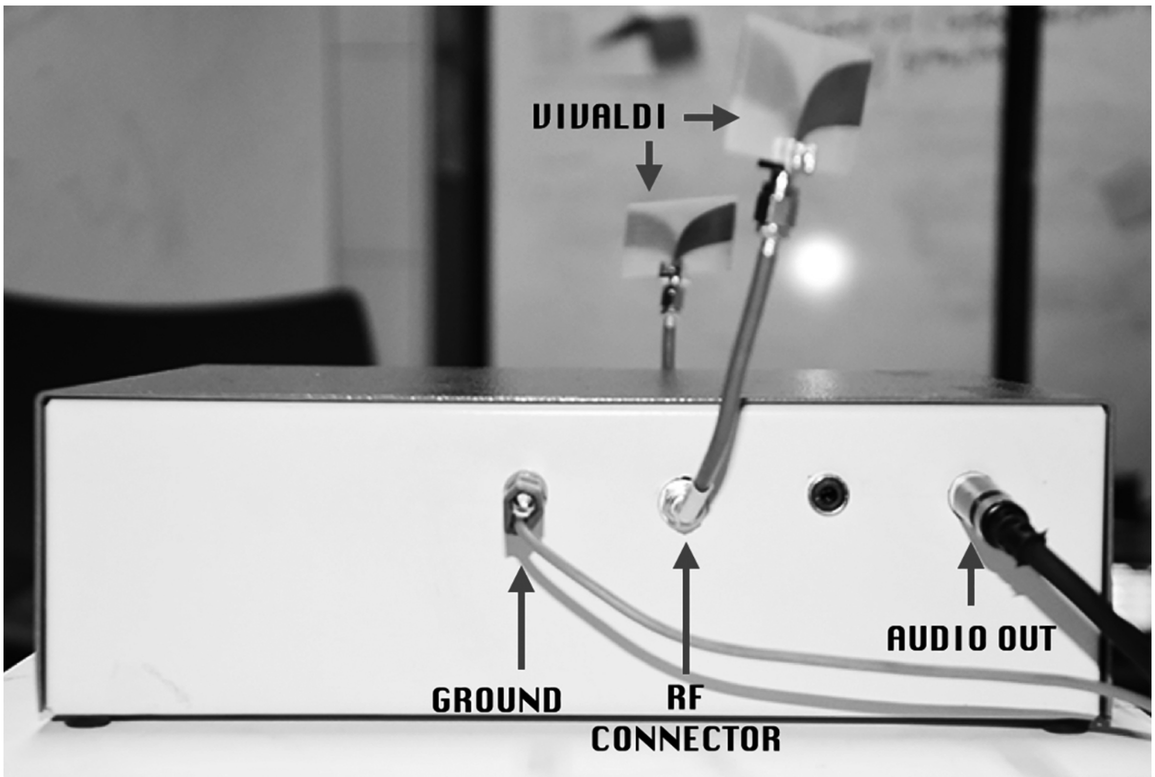

Figure 25. Connectors on the side of the instrument allow the use of different antennas that can be attached via coaxial cables.

Two different outputs are calculated, one per stereo channel, using two different phases, both starting at value 0. Therefore the two audio signals, directed to the right and left audio channels, have a very small variation in frequency and also a small variation in phase (Figure 26).

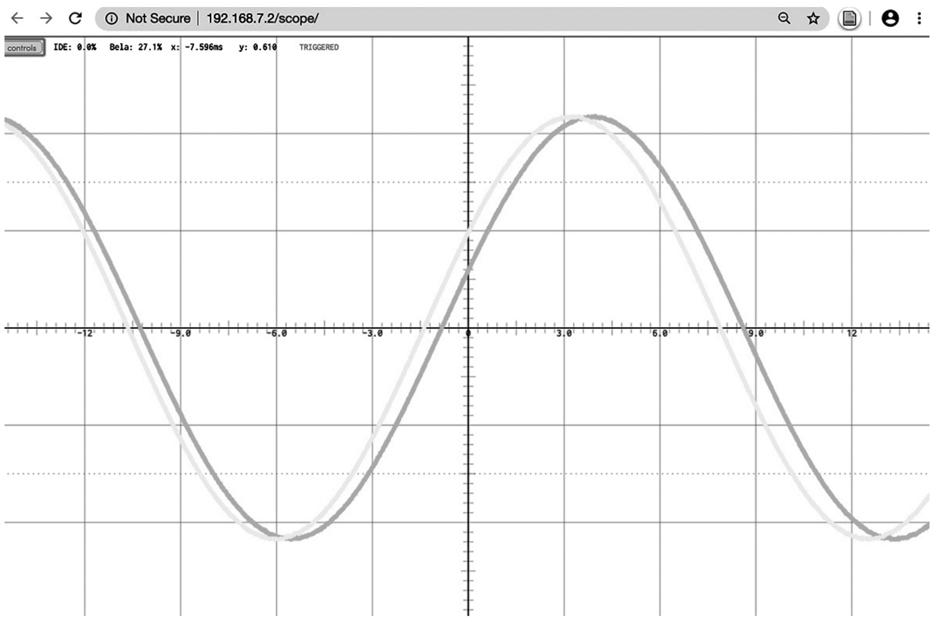

Figure 26. Bela Scope showing the two audio signals in 'Rhythm0'.

The result is an oscillation at a slowly pulsating intensity. When amplified, a very subtle, tactile beat emerges from the sum of the two sine waves. The idea of sending two different frequencies towards right and left channel has also another objective, as beats would emerge even if the two sine waves were summed before the output, with right and left channel emitting identical waves. Yet this is a conceptual piece exploring a metaphor: the transformation of electromagnetic waves in sound waves. If a sine wave is emitted in a square room from only one speaker, either the right or the left, the pressure wave will propagate diagonally. Because electromagnetic waves travel diagonally whereas pressure waves travel horizontally, in the case of an identical wavelength (REBUS uses a microwave frequency whose wavelength is very similar to that of sound, as shown in

Figure 27), and in a setup where a pressure wave is traversing the room diagonally, the electromagnetic field can be *somehow* perceived in the form of pressure.

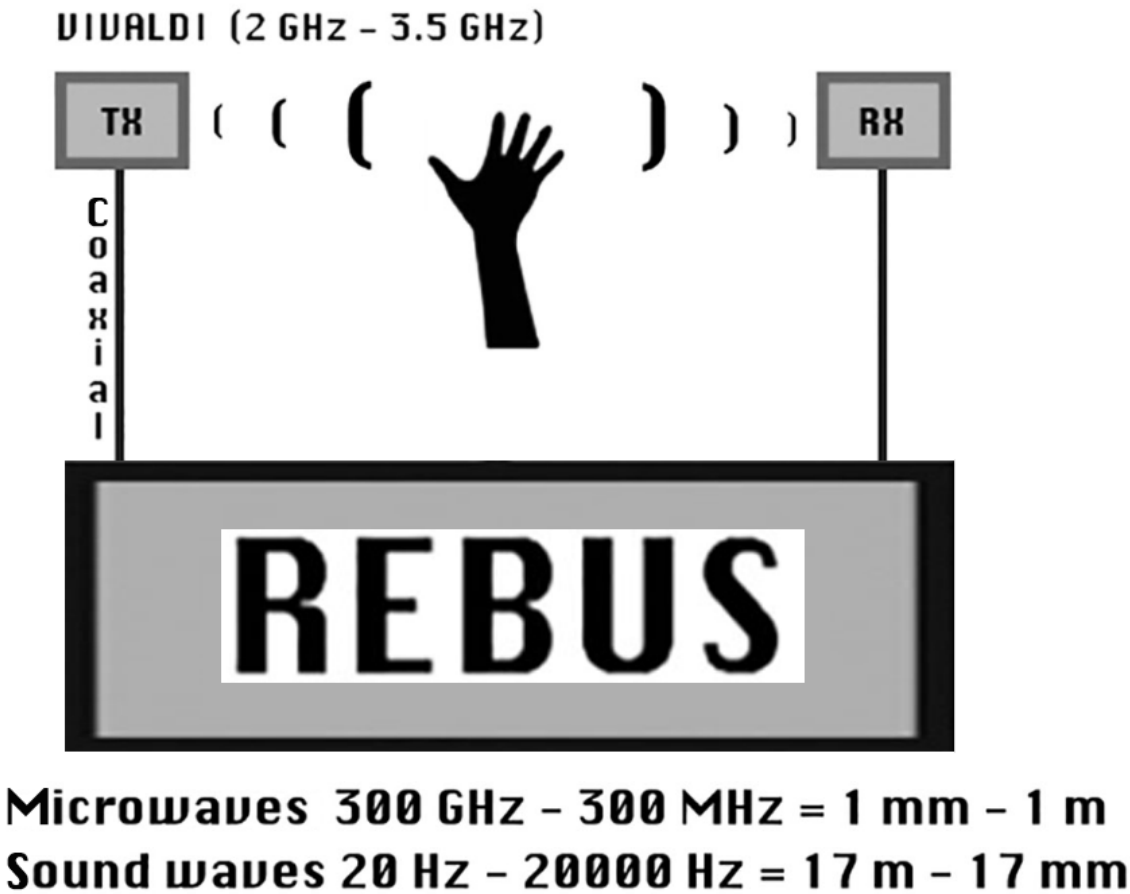

Figure 27. REBUS diagram with comparison between audible sound frequencies and microwaves.

This particular composition is site specific as the result changes greatly according to the sound system used to amplify it and the acoustic properties and size of the room where it is played. One interesting effect discovered by chance while experimenting in the living room of my family house in Milan, containing glassware in front of a very high quality sound system, was that, while the beats were bordering the inaudible, subtle movements of the hands could modulate the sound, hitting the resonant frequency of different types of glasses and plates which were then amplified by the cupboard containing them, to the point that, with a slight movement of a finger or the hand between the antennas, it was actually possible to play with the vibration of different objects placed in the room. In this case the amplified sound, being almost inaudible, becomes mainly a form of vibration that produces movement: the perceived sound is not what comes directly from the speakers, but indirectly from physical vibration caused by the pressure waves that the speakers emit. In this sense, the result proved the *action-at-a-distance* principle: touching an electromagnetic field a mechanical force can be triggered on a distance object. This transformation of signals or phenomena from one form to the other, in this case the electromagnetic field translated into air pressure, can be poetically imagined, echoing classical mythology, as a metamorphosis which gives humans divine powers, where the change in form or substance becomes the manifestation of something magic or infinite.

Conclusions

Electromagnetic field sensing presents a large potential in musical instruments making, and where simple detection (offered by a chip such as the TPD) is mainly suitable to detect presence, the REBUS technology, calculating the wave as a relative value, opens the way for a peculiar form of interaction where very subtle movements can be captured and the waves plucked and manipulated as invisible strings. REBUS can be reminiscent of a Theremin and can be programmed to emulate one, but the compositional possibilities and potential applications of this digital instrument are far greater. Whereas the Theremin is an analogue musical instrument, REBUS is a digital one. Although both instruments can be played without contact and use two antennas, their technique differs substantially: the Theremin uses electric field sensing and the interaction is given by capacitance, whereas REBUS senses the electromagnetic field and the interaction is given by interference. In the Theremin, the circuitry of the two antennas are completely separated, and only connect before the audio output, where the amplitude detected from the left hand loop antenna is used as a voltage control to determine the loudness of the tone produced by the other antenna. Whereas the Theremin is extremely difficult to play and requires many hours of rehearsal, REBUS can be personalised and customised, presenting a dual nature: on the one hand it can be programmed to be easy, intuitive, playful and simple. On the other, it can also be configured as a complex and expressive instrument, rewarding because always offering new challenges. While each musician, player or performer can have a completely different instrument than that of another and no previous knowledge of electronics or music theory is necessary, and a performer does not need to be a software developer or a trained musician to be able to play it, successive studies have shown that practice increases mastery and the true nature of the instrument requires an almost meditative form of concentration and very subtle movements for its expressive potential and character to emerge. Not only it has satisfied the definition of musical instrument from a variety of perspectives, it may represent the prototype of a new family of instruments that can be played by plucking electromagnetic waves (Oreggia 2024). Over the years, a variety of well known electronic music composition techniques have been reproduced and adapted for REBUS, including tremolo and various effects, sample players, arpeggiators, drum machines, step sequencers, but also complex algorithms, Stochastic methods, boids (bird-oid objects) synthesis, strings simulation, simple machine learning, decomposing a sample as a function of gesture, and other unconventional approaches. REBUS seems to induce in the player a meditative state with mood altering effects, perhaps because of the concentration it requires in stretching the limits of perception.

While the exploration of different mapping strategies and compositional approaches is ongoing, the design offers the user a minimal amount of controls, which equals to a single button to cycle through the different patches or software compositions. The sensor data can be mapped and processed to suit a huge variety of compositions and interactive applications but the only way to interact or modulate the sound is through the interaction with the field, using the hands and the body. Independently from the sound design or score selected, the electromagnetic interface dictates how the instrument can be played, and the only way to learn it is through practice. The peculiarity of REBUS as an instrument does not lay in its timbre but in the original way in which it is possible to manipulate its oscillation, in the musical potential of the vibratory motion of the pressure waves modulated through manipulating electromagnetic waves.

The future of the instrument in academia is currently travelling on parallel tracks both informed by music and art, one oriented toward technology and science, and the other more speculative and philosophical. On the one hand, the research, currently conducted at Goldsmiths, is envisioning the use of invisible interfaces with a focus on three main use cases: music, which is the main application; performance (art, theater and dance); installation (including immersive interactive art, games and VR). As a seed, a tiny laboratory, the Waves Lab, is slowly evolving in South London, with the aim of exploring the potential of electromagnetic waves in interacting with sound waves and more in general with electronic machines. The collaboration with the mothership (the Antennas Measurement Laboratory and the Antennas & Electromagnetic Research Group at QMUL) is still active and the instrument and technique is undergoing successive phases of improvement. On the other hand, a cultural perspective is also developing. Along with researching the effects on perception of using the electromagnetic field as an interface, and imagining the possible development of new senses through what we call *perceptual domain shift*, indicating when a sensory feedback is received in response to an interaction with the field, an ontological reflection upon the philosophical and aesthetic implications of the use of the electromagnetic field in the arts, sort of empirical ontology of electromagnetism, is emerging. This upcoming contribution to aesthetics and epistemology reflects upon our experience after years composing with waves and making music and art with electromagnetic fields. Beyond academia, the question whether the REBUS instrument can be of interest to a wider public, and transform itself again, will soon be answered. The author envisions a future where EM based musical instruments and invisible interfaces become ubiquitous, providing novel expressive ways to play with the immaterial and manifest the power of imagination.

Acknowledgments

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