CYMATIC: A TACTILE CONTROLLED PHYSICAL MODELLING INSTRUMENT

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ABSTRACT

The recent trend towards the virtual in music synthesis has lead to the inevitable decline of the physical, inserting what might be described as a 'veil of tactile paralysis' between the musician and the sound source. The addition of tactile and gestural interfaces to electronic musical instruments offers the possibility of moving some way towards reversing this trend. This paper describes a new computer based musical instrument, known as Cymatic, which offers gestural control as well as tactile and proprioceptive feedback via a force feedback joystick and a tactile feedback mouse. Cymatic makes use of a mass/spring physical modelling paradigm to model multi-dimensional, interconnectable resonating structures that can be played in real-time with various excitation methods. It therefore restores to a degree the musician's sense of working with a true physical instrument in the natural world. Cymatic has been used in a public performance of a specially composed work, which is described.

1. INTRODUCTION

The computer has enabled musicians to push back creative boundaries, in aprt by removing some of the physical constraints involved in playing acoustic instruments. Despite this, musicians are still searching for virtual instruments that are in many ways more like their physical counterparts. Electronic musical instruments are often described as 'cold' or 'lifeless' where real instruments might be described as 'warm', 'intimate' or 'organic sounding.'

Such criticisms can be met by: (a) using physical modelling to create organic sounds that more closely resemble those of physical causality, and (b) creating new user interfaces that enable musicians to interact with the computer in more intuitive and intimate musical ways.

The instrument, known as Cymatic, described in this paper takes advantage of both of these approaches to provide the player with an immersive, organic and tactile musical experience that is more commonly associated with acoustic instruments. Its origins are in TAO, a non-real time physical modelling system [1] that was designed to enable organic sounds to be synthesised from modular structures, and it also shares commonalities with sound synthesis environments such as Mosaic [2] and CORDIS-ANIMA [3]. TAO made use of a high level language in a paradigm similar to that employed by Csound [4], which although adequate for non-real-time operation, is not suitable for synthesis under real-time control. Cymatic extends TAO's functionality in a number of novel ways and it is implemented as a real time musical environment for constructing and playing physically modelled instruments using gestural, haptic controllers.

Haptic output is one of the most important means by which a player interacts with a traditional musical instrument [5], but it is rarely available in computer based instruments. A complex and realistic musical impression can only be fully created when tactile (vibrational and textural) as well as proprioceptive (awareness of one's body state and the forces upon it) cues are available combination with aural feedback [6]. Figure 1 from [7] shows a simplified diagrammatical representation of the contrasting input and feedback paths of typical acoustic and computer instruments.

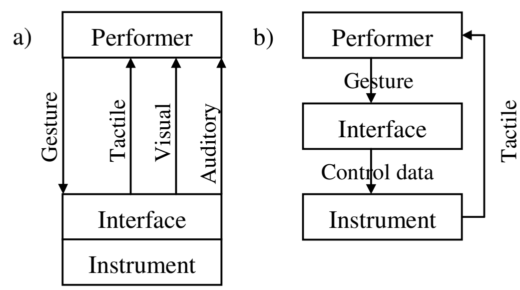

Figure 1: *input and output paths of acoustic (a) and computer (b) instruments contrasted*. (From [7])

Attempts have been made to provide some haptic feedback in electronic instruments [e.g. 8-10] using specially modifid interfaces. The approach adopted in the design of Cymatic involves the exploitation of cheap readily-available commercially devices in the form of a force feedback joystick and a tactile feedback mouse interfaced via MIDI.

2. CYMATIC

Cymatic user interaction is a two stage process. First, a graphical user interface is provided with which instuments are designed and shaped, including the selection of the excitation source to be used as well as the placement of the output microphone. The control properties of the joystick and mouse are also selected at this stage. The second phase is the live playing phase where the joystick and mouse are used to create sound.

These phases are described in this section with reference to screen plots of the user interface following a description of the basic principles of the physical modelling implementation.

Cymatic is currently implemented on a PC machine, and at a sampling frequency of 44.1kHz, it is capable of running up to 120 cells in real-time on a Pentium II 550Mhz PC; and up to 500 cells in real-time on a 2Ghz Pentium IV processor.

2.1. Physical modelling organisation

Cymatic is a mass-spring interaction physical model written in C++, where point masses are arranged in a regularly spaced, n-dimensional lattice. Each mass is connected to its immediate neighbours by springs and it is constrained to move within a single degree of freedom in the direction of the *z*-axis. Each mass cell is represented by a C++ object containing the following parameters which specify its state at a particular instant in time:

- mass
- tension
- damping
- position
- velocity
- location of its Neighbours.

The mass, position and velocity parameters describe the internal characteristics of individual cells, while tension, damping and location of neighbours describe the links with the external environment around the cell. A Cymatic instrument is stored as an array of cells, and each cell maintains a doubly linked list of springs as pointers to adjacent cells. Whenever two cells point at each other, the presence of a spring of user defined tension is implied. The use of linked lists to maintain springs allows for the dynamic allocation of new springs, thus permitting individual cells to be connected to any other cell in the system. Irregular and complex instruments can thus be constructed. Each cell maintains its own independent mass, tension and damping characteristics. At least one cell must have infinite damping characteristics (locked at z=0), in order to anchor the instrument itself, thereby preventing the whole instrument structure itself from drifting.

2.2. Physical modelling implementation

Physical modelling synthesis in Cymatic is carried out by calculating the mechanical interaction between the masses that make up the virtual instrument. Feynman's numerical discrete time approximation to the solution of the differential equation for a harmonic oscillator is employed. This method calculates the mass velocity half a time step ahead of its position, resulting in a more stable model than an implementation of the Euler approximation

Acceleration of cell at time t is described by:

$$a = F/m \tag{1}$$

where: a = acceleration, F = total force acting on the cell, m = mass of the cell.

The total force on the cell is the sum of three forces:

$$F_{total} = F_{spring} + F_{damping} + F_{external} \tag{2}$$

where: F_{spring} *= the force from springs connected to neighbouring cells,* $F_{damping}$ *= the frictional damping force on the cell due to the viscosity of the medium,* $F_{external}$ *= the force on the cell from any external excitations (pluck, bow etc.).*

F_{spring} is calculated by summing the force on the cell from the springs connecting it to its neighbours. This force can be calculated for each neighbour by Hooke's law:

$$F_{spring} = k(p_n - p_0) \tag{3}$$

where: p_n *= the position of the nth neighbour,* p_0 *= the position of the current cell.*

$F_{damping}$ is the frictional force on the cell caused by the viscosity of the medium in which the cell is contained. It is proportional to the velocity of the moving cell, where the constant of proportionality is the damping parameter of the cell. The damping force is therefore given by:

$$F_{damping} = -\rho v(t) \tag{4}$$

where ρ = the viscosity as given by the damping parameter of the cell, v(t) = the velocity of the cell at time t.

Combining these forces with equation 3, we can find the acceleration, and hence the velocity and position, of a particular cell at any instant:

$$a(t) = (1/m)(k\sum(p_n - p_0) - \rho v(t) + F_{external}) \tag{4}$$

where: m is the mass of the cell; k is the spring constant; p_n *and* p_o *are the positions of the* n^{th} *neighbour and the current cell respectively, ρ is the viscosity as given by the damping parameter of the cell, and v(t) is the velocity of the cell at time t, and* $F_{external}$ *is the force on the cell from any external excitations e.g. plucking or bowing.*

2.3. Excitation models

The following excitation models are available in Cymatic. These can be applied to any cell in the system; indeed, multiple excitations may be applied to individual cells. Cymatic models a number of musically relevant excitation functions which can be broadly separated as being time-dependent or velocity-dependent as follows.

Time dependent excitation functions

- **Plucking** and **striking** are modeled by a force which increases over an arbitrary period of time before immediately returning to zero. A large force applied over a short period of time would simulate a striking action, whereas a smaller force applied over a longer time period would exhibit more pluck like characteristics.
- **Wavetable** excitation applies a force whose variation with time is defined as a waveform function (currently: sine, square, triangular, and sawtooth).
- **Random** excitation is based on random number generation allowing noise to be applied to the instrument, causing each of the resonant modes of the system to be excited at random and providing a basis for interesting sonic textures.

- **Live-audio** excitation takes as input an external source such as a microphone, line-in or stored waveform file and applies each sample, after suitable scaling, as a force on a cell of the instrument. Live-audio mode therefore enables Cymatic to be utilised as a physical modelling effects post-processor.

Velocity dependent excitation functions

- **Reed** excitation is achieved through a look-up table.
- **Bowing**, which is a velocity dependent excitation, involves the application of an external force to the string that depends on the relative velocity between the bow and the string. This force-velocity relation has been determined experimentally [11], and it is implemented in Cymatic as a lookup table. This model requires just one calculation to find the relative velocity of the bow and the cell to which it is being applied, followed by one reference to the lookup table and a second calculation to apply the indicated force to the cell. Cymatic's new bowing algorithm accurately models a true bow-string relationship as indicated in the plots in figure 2, where a Cymatic bowed output can be compared with the motion of a bowed violin string measured using an optical tuning fork.

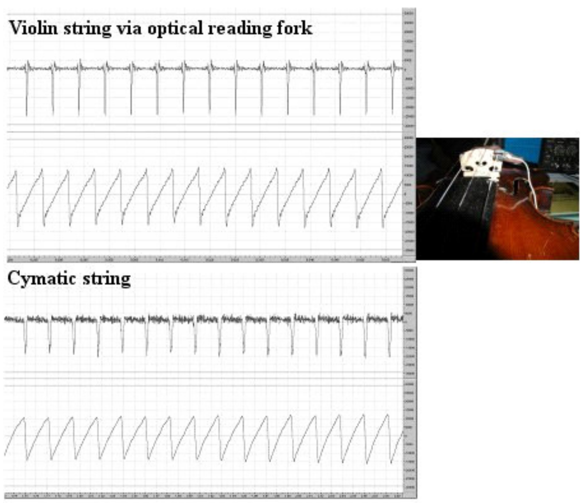

Figure 2: *Waveform output of a real bowed string alone by means of an 'optical reading fork' (photographed), courtesy of Jansson and Galembo from KTH in Sweden, (upper) and a Cymatic bowed String (lower).*
NB In each plot, the upper channel represents the velocity of the string under the bow; lower represents the displacement of the string underneath the bow.

2.4. Sound output

Cymatic's sound output is provided using 'Virtual Microphones,' which can be placed arbitrarily at any of the cells of the instrument. A virtual microphone outputs the time varying displacement of the cell to which they are attached on a sampl-by-sampl basis. This data record thereby provides a time waveform depicting the vibrations of the instrument at this point. Sterophonic outputs can be created by setting up two or more virtual microphones, and the output from each can be panned between the left and right output channels.

The outputs from the virtual microphones also provide the function that is used to scale the vibrotactile response of any connected haptic controller as a function of the amplitude of the microphone's output.

2.5. Designing Cymatic instruments

Instruments are designed via an intuitive graphical user interface (GUI). Instrument primitives, which are the basic building components of the virtual Cymatic instrument, are displayed in a 3D representation in an OpenGL 'Virtual Luthiery' where they can be cut into interesting shapes with the virtual scissors or joined to other components using the join tool. These components are available in the form of 1 dimensional (string), 2 dimenional (sheet), 3 dimensional (block), or indeed, any number of dimensional instrument primitives. (It should be noted that very little experience has been gained with instruments with a dimensionality higher than 3 due to the processing requirements and the inability to visualise the virtual instrument using a 3-D representation.)

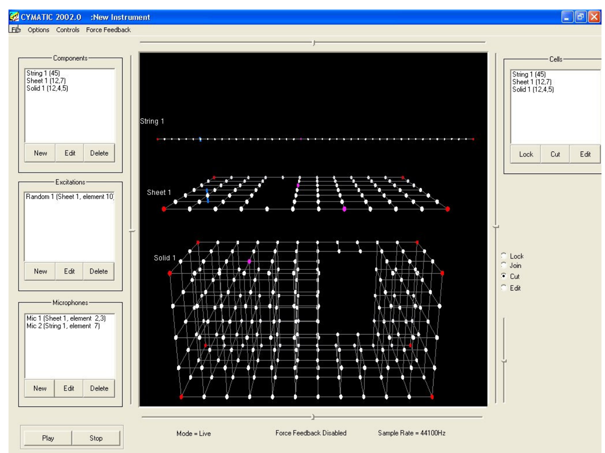

Figure 3: *Example Cymatic graphical user interface which is used to design virtual instruments. An instrument consisting of a string, sheet and block is illustrated with some cells removed. The placement of the xcitation and microphones can be seen in the relevant dialog entry.*

Figure 3 shows an example Cymatic GUI screen for a virtual instrument consisting of a string, sheet and block. Some cells have been deleted and these are clearly shown. The placement of the excitation and microphones can be seen, and their positions are described in the relevant dialog by co-ordinates on the relevant instrument component. It is worth noting that it is perfectly acceptable to place xcitations and microphone within block and components of dimensionality higher than 3. For example, the notion of bowing or listening from within a block is quite acceptable with Cymatic.

Individual cells of components are selected by the mouse to change their characteristics (this can also be done in in real-time during synthesis). For example, cells can be locked by mouse clicking them, preventing any movement, or a cell in one component can be joined to that of another component, or individual or groups of cells can be edited by using the 'edit' tool. Excitations are represented visually by green rings around the cell to which they are attached and virtual microphones are represented as vertical blue lines through the associated cell. Use of the OpenGL GUI allows the user to rotate and zoom the instrument in 3D space, which increases the illusion of working with a physical instrument and allows for easy customisation of individual cells.

Cymatic makes use of Microsoft's Direct Input interfaces to allow real time control with HCI devices. Tactile interfaces that have been used with Cymatic include two Microsoft Sidewinder Force Feedback joysticks, Logitech pedals and a Logitech force feedback mouse. There is a limitat of 16 simultaneous input devices that can be accommodated by Direct Input, which is many more that the degrees of freedom necessary for expressive real-time control in a musical instrument.

A Cymatic instrument can be saved to disk at any point in its construction enabling a library of instruments with differing physical properties to be build. The ability to load previously saved instruments enables the musician to build a familiarity with instruments that they have created, enabling skills on one particular instrument to be developed with practice, just as with acoustic instruments.

2.6. Playing Cymatic instruments

Cymatic can be controlled using any Windows compatible HCI device and it gives precedence to force feedback devices. With such devices it is possible to 'feel' the vibrations of a Cymatic instrument in much the same way as musicians feel the vibrations from an acoustic instrument, making the playing of a Cymatic instrument a much more immersive experience.

Physical gesture that provides the energy to excite an acoustic instrument (e.g. blowing, bowing, plucking or striking) is a vital aspect of the playing of such instruments. Advantage of his property can be taken using Cymatic, since the velocity of user movement along a gestural axis can be mapped to any synthesis parameter. Thus excitation functions such as plucking or bowing can be controlled via the velocity of continuous gestures. For example, the x-axis velocity of the mouse can be mapped to the velocity parameter of the bow excitation, giving the impression of actually bowing a string by left and right mouse movements.

Any gestural interface axis can be mapped to any parameter in the physical model. Cymatic provides an intuitive standard Windows-style dialog box to make this possible. An example is shown in figure 4 for the instrument illustrated in figure 3. Here, the joystick X- and Y-axes are mapped to the mass of the cells of the sheet and the tension of the cells in the solid respectively. The Z-axis (stick rotation) is mapped to the damping of the cells in the string, and the slider (throttle control) controls the pluck force. The use of buttons to supress gestural changes (see entries for buttons 1-4) enables jumps to new values to be utilised. In this way, transient change in mass, tension or damping can be imposed by ressing the button, making the movement (no change is heard), and then releasing the button (the value is immediately changed to the new value).

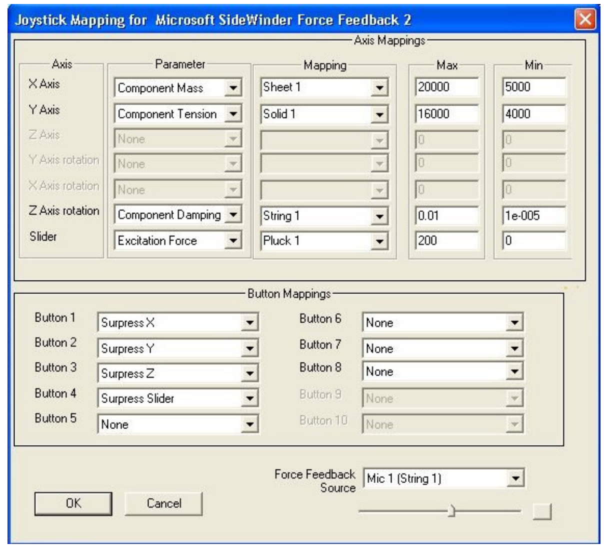

Figure 4: *Example Cymatic dialog for setting up the force feedback joystick for the virtual instrument shown in figure 3.*

Tactile sensations can be extracted from any part of a Cymatic instrument by attaching a virtual microphone and assigning it as a 'Force Feedback Source'. In this example, 'mic1' on the string provides this source. The amplitude of the Force Feedback Source is used to recreate a similar vibration on the force feedback device, and the slider on the dialog allows the amplitude of the force to be varied. Force sensations are realistic and responsive since they are updated at the sampling rate.

These tactile cues have been found to be particularly useful when bowing, due to the extreme sensitivity to fine variations in force or velocity. Instrument control is thereby more intuitive as the tactile dimension provides a valuable cue in support of audio and visual cues. Different force feedback controllers can be assigned different controlling virtual microphones, enabling different parts of the instrument to be felt with different controllers. This adds the possibility of modelling yet another important aspect of the interaction between a musician and her/his instrument, by providing the opportunity to simulate the effect of having each hand in contact with a different part of the instrument. Force feedback effects are programmed using DirectInput and the Immersion Foundation Classes.

3. CYMATIC OUTPUT

The output from Cymatic exhibits a number of differences when compared with that from more conventional synthesisers. It can be described as 'organic', by virtue of the fact that it includes aspects associated with acoustic instruments, such as bow noise, metallic string sounds, cymbal-like shimmering.

3.1. Example Cymatic outputs

One particular and distinct advantage of a physical modelling approach to synthesis when used in conjunction with gestural intputs is that each rendering of any given note remains unique, no matter how much one tries to repeat the motion. This is illustrated in figure 5 which shows three spectrograms of a bowed Cymatic instrument consisting of just a string. It should be born in mind that the bowing position in Cymatic is fixed and therefore not a variable; something that will very rarely be found even during a single bowed note on an acoustic instrument.

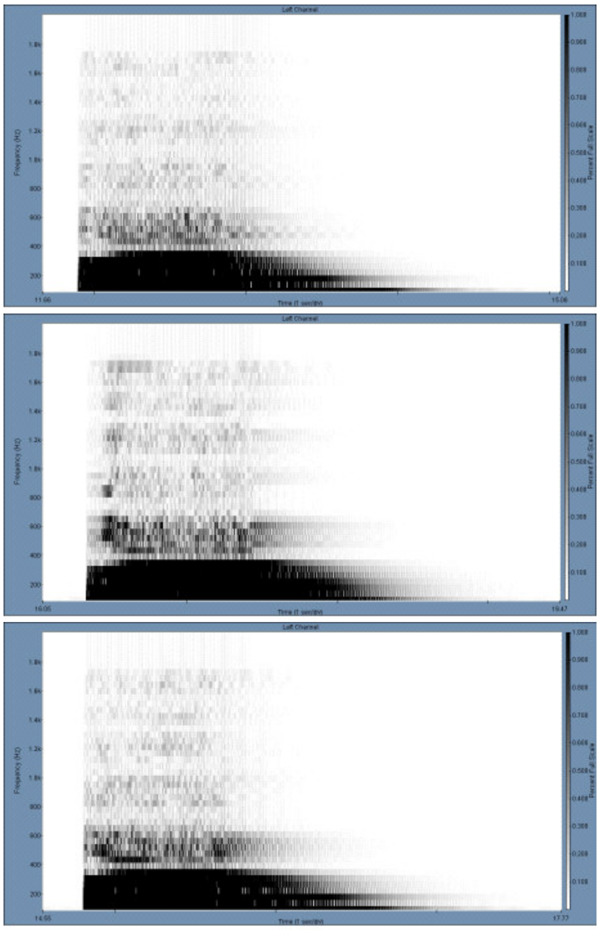

Figure 5: *Three consequetive renderings of a bowed Cymatic output to demonstrate the uniqueness in the detail of different Cymatic outputs and their organic nature.*

It is clear from the figure that there are acoustic differences in the three outputs illustrated in the fine detail of the spectrograms. This is most noticeable during the offset and in the region immediately above the main black band, and in the upper frequency regions. Such differences are bound to be subtle, since the only variable is the bowing velocity as determined by the movement of the mouse by the player. It is differences such as these that give rise to the perception of naturalness in the sound and a sense of its organic characteristic. It also means that the sound will be one that lasts in the sense that the ear will accept it as being more interesting when compared with sounds that remain exactly the same with each repetition.

3.2. Cymatic in public performance

The first work to be composed for Cymatic was "The Babe is Sleeping"; a work for SATB choir and Cymatic composed by Stuart Rimell. It juxtaposes traditional tonal writing for the choir alongside Cymatic's rich spectral content.

The Cymatic instrument used is depicted in figure 6. It consists of two cymbal-like plates and a string. The plates were shaped and cut so that each had a clearly perceivable dominant low frequency component while still containing many enharmonic high frequency components. The random excitation was used to create 'cymbal-swell' type textures, controlled in real-time using logitech pedals. This was achieved by mapping the excitation force to the pedals. The dominant frequencies of the cymbals were 'tuned' in real-time using a force feedback joystick, by mapping the mass of the cymbals to the independent joystick axes. This therefore took advantage of one of the main advantages offered by Cymatic; the ability to change parameters in real-time that would be impossible to change in real life i.e the mass of a complete instrument.

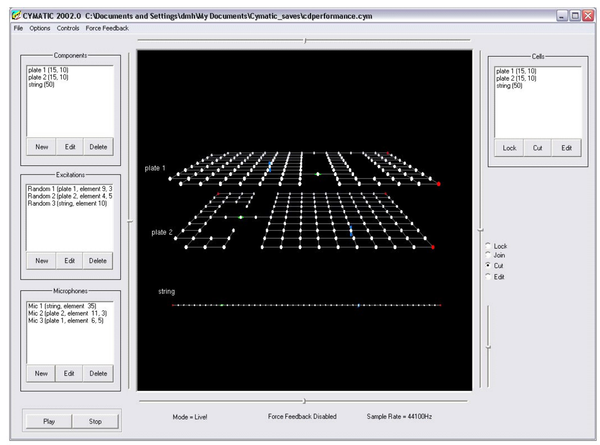

Figure 6: *The Cymatic instrument used or "The Babe is Sleeping".*

"The Babe is Sleeping" was first performed in a public carol concert in December 2002 by the Beningbrough Singers in Heslington Parish Church, York, conducted by David Howard. Cymatic was played live by the composer. An audience of over 200 attended this concert, where informal reaction was all positive, with many indicating that they had come to the concert uncertain of what to expect of this piece but were leaving having been satisfyingly surprised and eager to know more about and to hear more from Cymatic. The juxtaposition of the electronic (Cymatic) and the acoustic (choir) was highly successful, the organic nature of Cymatic's timbres sitting well in a traditional setting.

4. SUMMARY AND CONCLUSIONS

A new physical modelling musical instrument known as Cymatic has been described, which incorporates gestural control as well as haptic output. Cymatic runs on a standard PC, and haptic output is available when a force feedback device such as a joystick or a mouse is employed. The physical modelling mass-spring paradigm enables virtual instruments to be designed in an intuitive manner from basic components in 1, 2, or 3 or even more dimensions. The user can select an individual mass on each of two components for joining. Individual masses can also be deleted and their dampg properties can be changed at will. In this way, instruments with complex shapes can be realised.

Excitation can be selected from a number that are available, such as bowing, plucking or waveforms including random, sinusoidal and squarewave. The output is obtained from one or more virtual microphones placed on any desired individual mass elements.

Key novel features contained within Cymatic include the ability to edit the instrument while it is playing, real-time operation, intuitive design of virtual instruments, gestureal control, haptic feedback, and the capability to operate in more than three dimensions (although current processing deny this in real-time at present). Cymatic has been used in a public performance in a specially composed work, and informal audience response was very favourable.

Cymatic demonstrates that there is considerable potential for a physical modelling paradigm set up in the context of gestural control and haptic feedback alongside the acoustic output. It has further demonstrated that it is possible to run such a system on a standard PC machine with a soundcard incorporating ASIO drivers. The surface has hardly been scratched in terms of explorin the potential for the composer and performer, particularly in the areas of dimensionality greater than 3 which will have to await the availability faster computation. In terms of opening new horizons for electronic music, we believe that Cymatic brings one into closer focus.

5. ACKNOWLEDGEMENTS

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