Paradigms for the new string instrument: digital and materials technology

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The applications of technology in instrument design contribute to the resulting sound on many levels, particularly in the context of new evolutions representing the traditional instruments of our culture. Materials technology is seldom given consideration in the description of Western string instruments, but our choices of woods, metals and synthetics can dramatically alter the sound without altering the substance of instrumental performance. In the design of modified string instruments which mimic features of natural acoustic predecessors, new technology is applied on many levels. A taxonomy is proposed for the past, present and future of instrument design. Due consideration is given to the music which results from the new sound world, especially that involving interactive electronic processing. The advantages and disadvantages of directions in instrument design for the future are evaluated within the proposed schema. Some extended techniques on the cello are proposed to be further extended with electronics, and audio examples and descriptions are provided. A model for future collaborations between composer, performer and engineer is proposed.

1. A TAXONOMY OF INSTRUMENTS FOR THE PAST, PRESENT AND FUTURE

This paper examines the history of instrumental technology, considering how physical changes to acoustic instruments over time – and the resulting timbral differences – might inform the creation of an electronic instrument, and proposes future strategies for interaction between performer and machine, paying particular attention to the nature of the created music.

For simplicity in observational schema, we imagine most traditional instruments to be fairly static and homogeneous, even if we understand that the great Cremonese instruments of the mid-eighteenth century have a sonic pedigree outweighing that of a more recent factory export. For this reason, I want to draw attention to the alterations an individual player makes to an instrument under varying performance circumstances which contribute to a uniqueness and considerable flexibility of sound. Research often suggests how imitation of the traditional instrument sound might be reformulated, perhaps with a physical modelling algorithm driven by a specially designed controller. In fact, it is necessary to begin with consideration of where the sonic model is formulated for a 'Natural Instrument' (definition below), and how it can be altered. This examination will cover the applications of construction materials, organic and man-made, to the sound world, and also the applications of new playing techniques, which themselves provide a richer world for an interactive computer-based acoustic processing environment.

I propose the term Natural Instruments (figure 1) to designate those that represent a long-standing tradition within their culture, even as the modern concert era removes them from their intended arena. While this is a lengthy topic for consideration elsewhere, the postulation is that original instrumental design arises from a particular situation for the instrument. The gentle sound of the Chinese zither (*gu qin*), the instrument of poets and philosophers, is sufficient for its context, often played for an audience of one listener. In recent times, the desire to fit into a new context has resulted in displacement of the sound world through innovations like nylon instead of silk strings, adjustment of the curves of the sounding boards, and reshaping the sound holes. Even amplification is slowly becoming the norm for *gu qin* performances.

Many Asian instruments have undergone this type of evolution as technology of material and design crosses over from other traditions, and new playing styles emerge. The largest driver of alterations to instrumental design is the desire for more dynamic range, triggered by the emergence of a solo tradition, separate from a role of vocal accompaniment or ensemble context which had previously constrained instrumental development for centuries.

The implication of technology in design of Western and Eastern instruments is that modern electric and electronic technology can be applied to enhance expressive strengths of each instrument while eliminating technical weaknesses. While it is clear that a first-order weakness is that of limited resonance in the modern performing venue, others can easily be addressed. The new design must take into account the performer's existing abilities, the sound production that is required, and the intended musical result.

An interesting aspect of this instrumental technology

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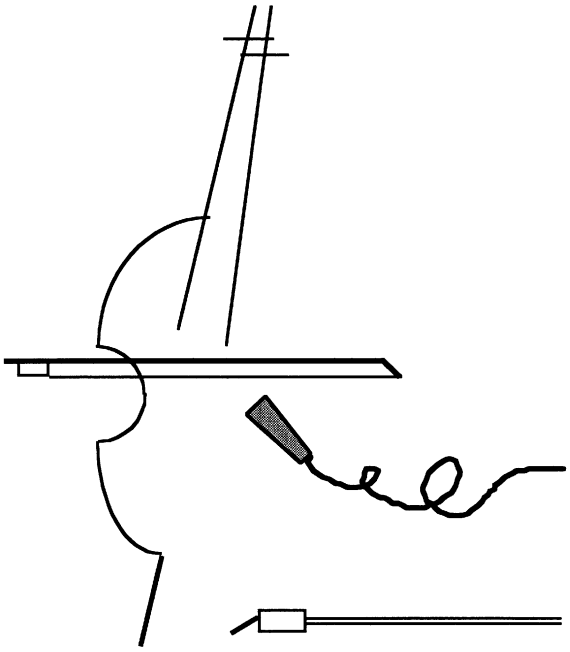


Figure 1. The Natural Instrument (supplemented for a new musical environment with microphone and footpedal).

evolutionary process is the environment developed around the electric guitar, an instrument in its own right, and in its own arena (the sports arena). Little backwards impact is now felt on its ancestral ancient lutes and acoustic guitars, except perhaps in the area of string materials. But the development process began with the need for a performance role in a new context, the solo voice amongst drums, keyboards and bass.

Perhaps we stand at a similar point in history with the natural Western bowed string instruments, where the definition of future directions – always driven by compositional needs – will determine the course for invention of a new instrumental technology. With this as a primary goal, a brief history is offered of the state of the art in violin family technology, with particular emphasis on the cello.

2. THE TECHNOLOGY OF NATURAL INSTRUMENTS

Acoustic instruments represent an evolution of materials and building technology which has been developed in the West for several centuries and in the East for considerably longer. In today's orchestra, players are experimenting with flutes made of wood, platinum, silver plated with gold, and gold plated with silver. Each of these attempts at innovation represents the search for a new instrumental sound, and perhaps more importantly, an enhanced level of control by the player. For string instruments, the selection of materials – pernambuco, horsehair, spruce, pine, ebony, maple, graphite, titanium, steel, copper, chrome-steel, synthetic gut – provides a similar extension of the original capabilities of the instrument.

The majority of changes in string instruments have been applied to the formulation of strings. From the original gut strings have evolved a wide assortment of metals, sometimes as many as three wrapped on a copper core. Synthetic substitutes for gut are available, attempting to provide the same warmth of sound with more reliability. Gut strings are notorious for stretching substantially under the rigours of performance, and then contracting overnight. Producing strings that are matched in tone is a particularly important problem. Cellists often employ pairs of strings from one manufacturer for the top and another for the bottom (more, it seems, than other string instrumentalists).

One of the most important requirements for strings is that they are 'true in fifths' (fourths for the bass). This means that stopping adjacent strings anywhere along their length will produce pure fifths. The pitch of a string varies as a function of its length, tension and density. The length can be considered equal from string to string. But, adjusting for slight tension differences, the mass per unit length ratios between strings should be 3:2, the ratio of the pure fifth. This can be accomplished in manufacture by wrapping more metal or by metals of different densities. It was common for cellists two generations ago to insert a small piece of a cardboard match under the string by the nut in order to shorten it slightly. This was intended to compensate for the gradual 'drift' of the fifths as the left hand travelled higher up the string. Both playing techniques and string materials make this an infrequent practice now.

The end pin is one of the more static elements in instrument design, but its importance in radiating the sound of cello and bass into the floor for additional resonance is not to be underestimated. A Japanese company makes a titanium end pin, available for a hefty sum, which is supposed to make a dramatic difference in the instrument's projection, when compared to steel. Tailpieces (the lengthened triangle connecting the end of the strings to the body of the instrument) are available in woods, metals, plastics; costing in the range of $75–100, even this is an investment in the instrument's sound.

Perhaps the most closely watched technological modification, as yet unembraced by performers while avidly pursued by designers, is the use of alternate bow materials. Pernambuco, from the eponymous East Coast Brazilian province, is the only natural material ever used for professional bows. Its characteristics of strength and resilience are prized by bow makers, but it is becoming rare and exports are controlled. Fibreglass is used for extremely inexpensive unbreakable student bows, but the future of the new bow is clearly cast in carbon fibre. Many such bows are available, and they present the attractive combination of strength, custom formulation to match a player's requirements, and low price point. A carbon bow can sell for one or two thousand dollars,

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partly reflecting high initial design cost. For comparison, an authenticated French bow from the turn of the century would be a bargain at $12,000, and earlier examples can fetch $50,000 at auction. Modern wooden bows are still very well made by craftsmen, but cannot always offer the beauty of sound that an older bow can.

3. THE TECHNOLOGY OF REPRESENTATIONAL INSTRUMENTS

A controller can be built which isolates only the instrumental performance elements which best serve the compositional vision. The controller is playable using the basic skills of an existing instrument, focusing on the refinement of technique, but dispenses with conventional form and acoustics to provide other degrees of adaptability. The desire for different degrees will be briefly mapped; most of these are familiar concepts in controller design.

The Representational Instrument (figure 2) attempts to capture a series of key aspects of the Natural instrument's playing techniques, while providing a substantially different level of control to be applied in interactive electronic environments. The instrument should be readily accessible to trained string players, but is designed to fill a particular role in computer or amplified music. Most particularly, it does not necessarily offer the acoustic sound associated with the Natural Instrument, but instead provides control data to be processed by electronics. This signal may be a filtered audio signal, separating the output of each string, or other types of controller information generated by sensors observing the player's motions.

I further divide this evolution of instrumental design into categories of musical/technical purpose. The Representational Instrument borrows as much as it can of the physical and acoustic elements of its inspiring instrument, for quantity of control information. I refer to this as the 'feature-rich' current of instrument design, where the features are borrowed from a traditional mode of playing a traditional instrument. But for certain research and control purposes, instruments that examine only one aspect of the player's interface can be developed. These I term Virtual Instruments (figure 3), as they remind one of the motions required for instrument playing, but are significantly reduced in control capacity. This trend in instrument design can be termed 'feature-isolated' as it explores the control aspects of a limited dimension of instrumental control. The specific purpose in the evolution of instrumental technology will be described later.

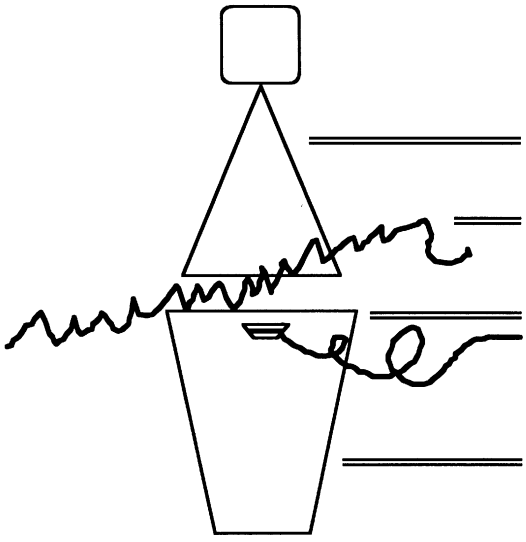


Figure 2. The Representational Instrument (feature-rich) with supplementary control channels and pre-processed audio signal.

4. UPSTREAM AND DOWNSTREAM TECHNOLOGY IN ELECTRONIC MUSIC

I have proposed separating interactive electronic music's future into the art of processing the acoustic sound of the Natural Instrument and the art of constructing a maximally imitative controller. The first can use two kinds of technological advances: the materials technology in building the instrument, even along traditional guidelines, and digital signal processing technology in processing the output sound. I propose the designations Upstream and Downstream for the two sides of this problem. Figure 4 iconically depicts the Upstream portion of the interaction equation: the previously defined instrumental directions. Each provides data streams, whether unprocessed audio or controller data, on/off switches, sensor systems, or pre-processed input to be incorporated by the 'listening' environment. All aspects of instrumental design are included in this segment, with sensor technology and microphone technology incorporated as well. The Upstream includes a high level of abstraction, circumscribes that which is termed 'performance', and is suitable for multiple performances of multiple compositions by any performer.

The Downstream technology (figure 5) encompasses all post-processing aspects which can be controlled by the performer in real time, although in a composer/engineer-designed system this is largely predefined to process input in known ways. The Downstream contains the abstraction of the actual composition and engineering solution, and is specific to a particular composition. It is flexible for ready adaptation, and responds well to input from the appropriate segment of instrumental

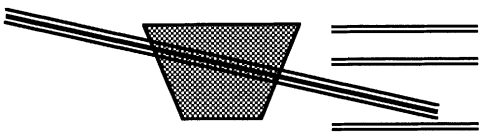


Figure 3. The Virtual Instrument (feature-isolated).

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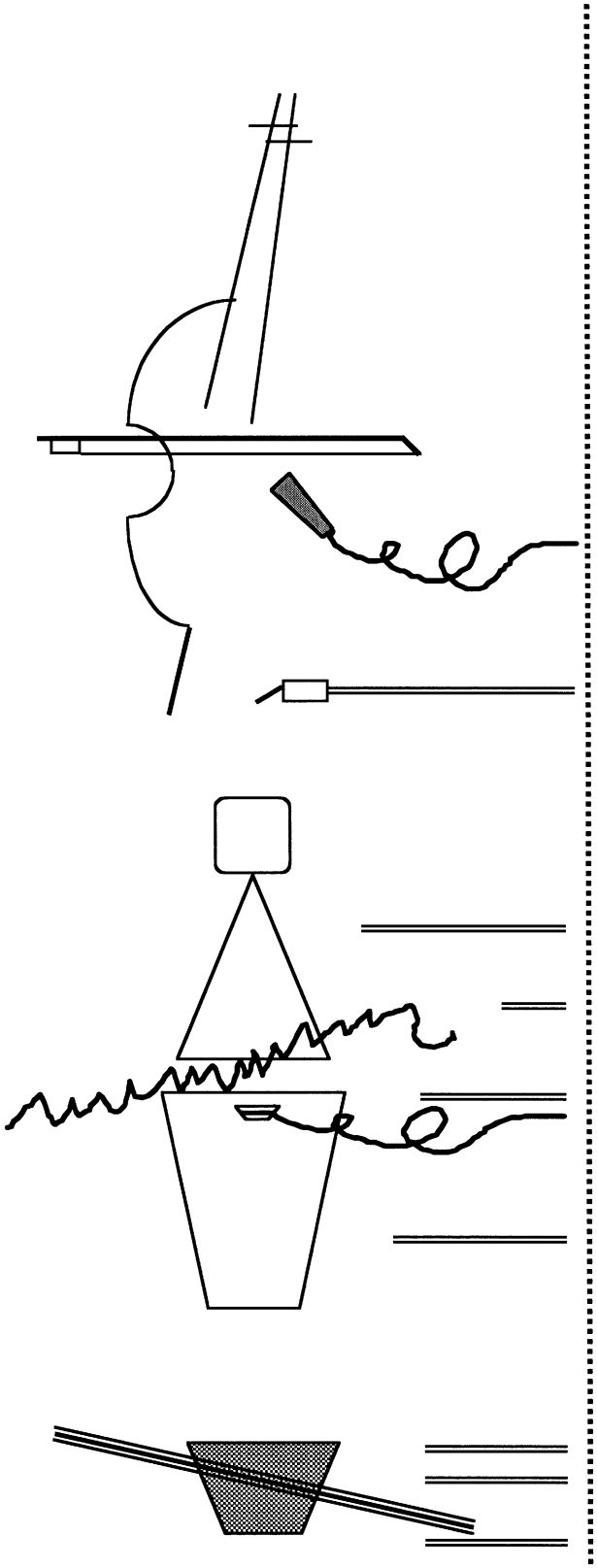


Figure 4. The Upstream.

design. It includes software and hardware elements of an environment tailored for digital signal processing, particularly pitch-tracking and feature recognition. For the Natural Instrument, the downstream preserves the sound capacity and control inherent in the triggering instrument, and focuses on realtime processing of an audio signal. For the Representational and Virtual Instruments, aspects of control are isolated to provide channels of information for an arbitrarily complex sound world. As roughly depicted in the sketches, these include pedals, sensors, separated or filtered audio input.

The definition of Downstream processing is, of course, almost anything that might occur to an input stream, which is then modified for production of a unified audio stream. For clarity, the possibilities of both a personal computer-based environment (hardware platform plus interactive/digital signal processing software such as Max/MSP or SuperCollider), and of off-the-shelf sound processing devices are depicted as available to the sound designer.

In an idealised design environment, a collaborative team of engineers, composers and performers – all sharing their customary roles with each other – create both sides of the interactive musical environment. Compositional possibilities should drive the instrumental design, and while limitations of processing power may suggest that the Downstream environment must share tasks with the Upstream, both sides are left open to future technological advances.

5. ISSUES IN NATURAL INSTRUMENT DESIGN AND PERFORMANCE

Figure 6 enumerates in succinct form advantages and disadvantages of each of the three instrumental models, dividing the issues into those on the Upstream, or instrumental design side, and those on the Downstream, processing side handled by a hardware and software environment.

The primary advantage of the Natural Instrument is of course its nearly unbounded expressivity. While performers have evolved characteristic instrumental techniques, we can recognise a continual process of refinement and extension of the sound. The highly developed skills that a player acquires after years of dedication to a particular instrument cannot easily be replicated on a Representational Instrument (figure 2), and the intimate knowledge of an environment is a primary strength of the performer relationship with the Natural Instrument.

The disadvantages, of course, we are well familiar with, and the usual litany of complaints about machine-irreproducible complexities of sound applies. The nonlinearities which make the instrument so flexible may make observation impossible. The instrumentalist may have to adapt deeply ingrained playing styles to match the requirements of a processing computer. Adaptations forced may include tuning to an equidistant ideal,

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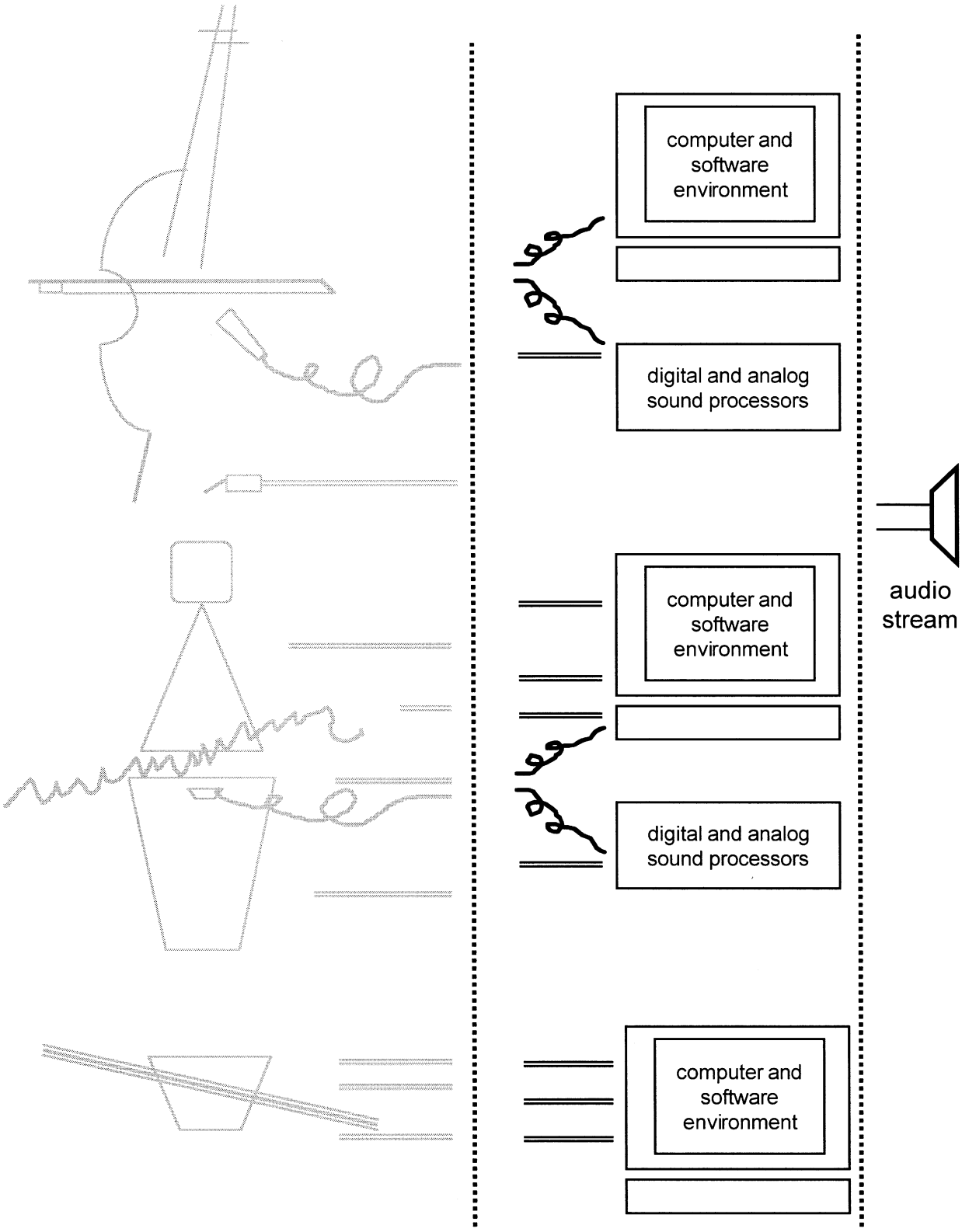


Figure 5. The Downstream.

idealising the attack of a bow stroke, playing neither above nor below a given amplitude threshold, averaging the width and speed of vibrato.

In addition, there is no pitch-tracker with good ability to resolve double, much less triple stops under any playing situation. The overtones mesh and reinforce, even without body resonance, so that isolating the fundamental is a very complex problem. The violin has a low

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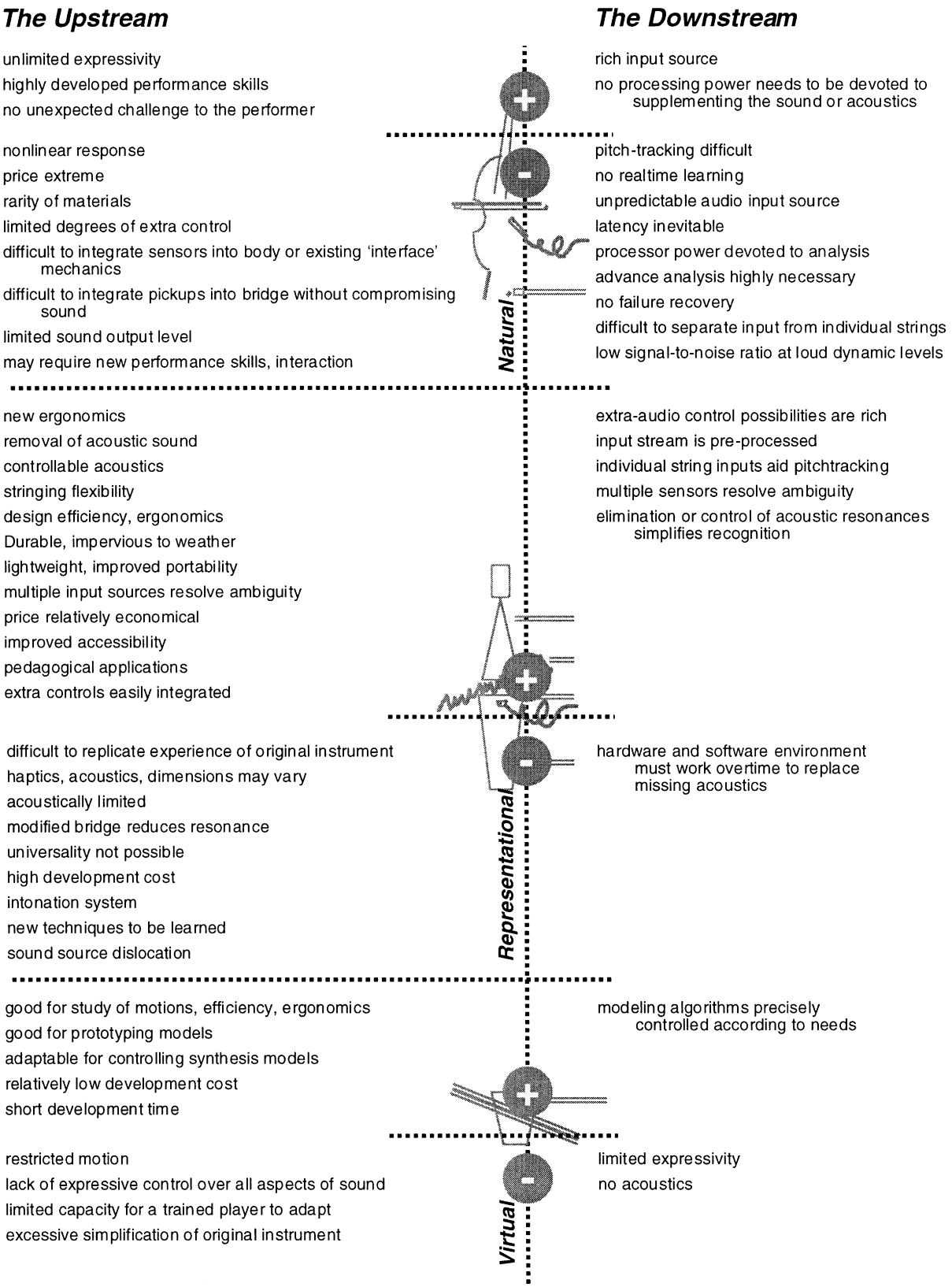


Figure 6. Evaluating the Instrument.

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bridge curvature relative to the resistance of the strings, so true triple stops are possible. On the cello and bass, they must be rolled, or played with an extremely forceful attack to convey the sense of three pitches sounding together. Even in the realisation of double stops, tricks are carefully employed to convey a suggestion of balance. The note on the upper string will tend to have more presence, so the player uses the balance of the bow to adjust the relative sound of each pitch. A useful trick in the execution of stopped fifths (a considerable demand on the left hand, to stop two strings in exactly the same place on a fretless fingerboard with a changing curve) is to rock the hand slightly along the axis of the forearm to alter the contact of the finger with the strings. A note played individually with this technique would sound fuzzy and inarticulate due to the partial pressure in the left hand; summed up the two notes provide a perfect open fifth resonance. This partial pressure would be bound to confuse almost any physical measurement system (pressure sensors on the fingerboard, fingertip pressure sensors, string inductance recorders) and any acoustic measurement system (quality of notes, timbral characteristics, prominence of fundamental).

It is certainly necessary to give due consideration to price factors in the future of instrumental design. A modern cello costs at least $20,000 to build; bows at least $2,000. Older instruments with a more developed sound (sixty years is a conventional threshold for measuring the potential of a string instrument) have no real limits, with pedigreed cellos fetching five million dollars. A truly universal string instrument will have to cost less, especially at the median price, to be accessible. The increasing rarity of construction components has been addressed under the topic of materials technology, so it is worth bearing in mind that sheer shortages of ebony (for fingerboards) could limit the future of the string family's traditional design more than any other factor.

Finally, the acoustic instrument does not lend itself well to adaptation to a hybrid approach. Most string pickup devices which perform significantly better than an 'air microphone' require modification of the bridge to isolate the individual strings and lower the noise. Special string material may also be required, limiting the player's options. Adding knobs and controllers in easy reach of the player's hands is not practical, and the issue of pedalling for cellists and bassists is also a consideration.

The cellist faces a unique problem (along with the double bass player) in that in designing a control system, a foot pedal controller is not as convenient as with other instruments. For both players, the body of the instrument or of the player blocks the sight-line to the pedals. The cellist is furthermore anchored, if in good playing posture, with both feet on the floor and the cello firmly secure between the legs, so lateral movement is difficult. I have found that if I exactly spot one pedal to the left of my right foot (taping the pedal to the floor), I can keep my foot on the floor in constant contact, and then lift up and over to the left when it is necessary to trigger the computer. I cannot see what I am doing, so a multi-pedal set-up, easy for a violinist or clarinettist to stomp on, would be perilous. Likewise, the pedal display available on some models would not be visible. The cut-out body of most electric cello models helps somewhat, but the anchoring principle of the feet still applies, reducing an ideal freedom of movement. This does not make pedalling impossible, but reduces the flexibility of this as a control mechanism and requires a certain adaptation by the performer.

6. ISSUES IN REPRESENTATIONAL INSTRUMENT DESIGN AND PERFORMANCE

The idealised Representational Instrument (figure 2) attempts to solve these problems, and provide enhancements that, while of necessity simplifying the sonic possibilities of the instrumental model, nevertheless create a valuable performing tool. With the presumed elimination of the resonating body, many acoustic nonlinearities and unpredictabilities are no longer a factor. The removal of the acoustics allows the sound designer to completely control the output; it need not sound at all like the inspiring instrument.

The elimination of the resonating body is the first step in the liberation of the electric string instrument. The left shoulder of the violin family creates a special problem in accessing the high notes. While the strategies for changes in positions are different from the shoulder instruments to the upright ones, both require a change of hand position which considerably alters the technique due to the much sharper angle required. Particularly on the violin – where the thumb largely should remain anchored to avoid stressing the player's neck supporting its entire weight – unusual strain may be exerted on the left wrist and hand reaching for the high notes. Without the left shoulder of the instrument, high positions can be reached smoothly with minimal transition in the profile of the hand. Trills and fast passages become easier as the fingers now move in the axis which is most comfortable, i.e. from the centre of the palm. While the cello and bass player take the arm over the instrument's shoulder (freeing the thumb) and thus do not have the same stresses as a violin player, there is nonetheless a substantial change required in profile. The elimination of the shoulder of the cello enables the player to assume a more relaxed profile, with the elbow down and the shoulder back. Left-hand fingering strength is aided in the lower positions on the cello primarily by the weight of the elbow pulling down, and now this is possible in the upper positions as well.

The science of ergonomics can be applied with more of a free hand in Representational design, since the evolved proportions of the last three centuries need not be preserved. Some particular lacunae come to mind:

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changing the curve of the bridge, removing the side bouts of the instrument, changing the length of the fingerboard. In brief detail, I describe what these possibilities afford. The curve of the bridge, if augmented, could allow for increased pressure with the bow on each string, without risk of striking adjacent strings. Presuming that the curve of the fingerboard is increased to match, stopping adjacent strings with the same finger (barring) is easier. The curve of the bridge, if decreased, allows triple and quadruple stops to become more natural, although the left hand is now at a disadvantage for barring. As a clarification, think of the flat fingerboard of the guitar and Chinese *pipa*, and consider how hard these instruments would be to play without frets, which allow for more tolerant hand positions.

The side bouts of the string family are often prohibitively in the path of the bow when a loud dynamic or sharp attack is required on the outer strings, and naturally are the first things eliminated in new instrument design. The fingerboard can be shortened or lengthened to modify the availability of higher notes; neither is better for certain kinds of playing, only resulting in different sound qualities and technical requirements.

We assume that technical studies of playing styles employed in the design of the new instrument could result in increased efficiencies: shorter strokes, less pressure, less extension of the arms, minimal twisting of the limbs and torso, easier reaching for the extremes. As bows evolve, it may turn out that precise, computer-modelled shaping of the mass distribution could result in a bow that turns physically advantageous towards the tip. Many current pedagogical methods instruct a substantial pronation of the right arm as the bow moves towards the tip and away from the mechanical advantage afforded by the weight of the arm. All current physiological models warn against this stress on the body. While upbow and downbow will never be equal, the idealised instrument could minimise the physical effort in producing arbitrarily imagined sounds.

Other benefits of an adapted cello worth mentioning include portability and new materials: the elimination of the body can produce a lighter, smaller instrument which can fit in the overhead bin on an airplane. The body of the cello, or what remains of it, can be constructed of anything from wood to fibreglass to graphite, as the electric guitar market shows. This can produce a custom-designed, portable fashion statement with the added attraction of being weather-proof, where an acoustic string instrument cannot be exposed to sunlight, excessive dryness, excessive humidity, changes in air pressure, or wet weather. The effects of humidity on the sound of the cello are dramatic: as the wood absorbs water its ability to vibrate is affected; in addition, the sound post expands, tightening against the plates of the instrument, tightening the sound. The bridge becomes noticeably taller, raising the strings and increasing their tension, which results in a brassier projecting sound. An instrument that is durable, lightweight, impervious to weather conditions, and portable is naturally the dream of every player. We accept the inconstancy of our instruments as a necessary by-product of their acoustic brilliance, but these are not design models for future exploration.

The ability to add numerous types of sensors and controllers is a significant advantage for the Representational Instrument. Specifically, multiple sensing devices can help resolve ambiguity in pitch-tracking, hand location, and other observational requirements. The controller knobs, sliders and switches can be mounted anywhere on the instrument, at the fingertips of the player, a difficult task with a resonating body.

Finally, although development costs tend to be high and there is virtually no economy of scale for a Representational Instrument, the cost can end up relatively low for the flexibility in control afforded. Increased accessibility to students and new performers is a natural goal of new instrument design, and the pedagogical applications of the Representational Instrument deserve to be developed further. Particularly, I envision an instrument where the beginner need focus only on one aspect of the execution: bowing, for example. The electronic interface generates a scale or a melody; the rhythm is created by the player using the right hand only. Or the system could be switched to another mode: left-hand detection. In this exercise, the player touches the fingerboard without employing the bow. If the location is correct, the note sounds, avoiding the tense initial learning curve where the player must match ideal bow stroke with perfect left-hand contact.

The concomitant disadvantages of the Representational Instrumental system are in many cases obvious, but a short enumeration is provided. It is naturally difficult to precisely replicate the experience of playing a traditional instrument, from the feedback that reaches the hand and ear to the accustomed physical proportions. The most flexible Representational Instrument would be tailored to match the fingerboard curve and length, bridge height, bow weight and momentary density, and string performance of an individual player's model Natural Instrument. Even the idiosyncratic wolf tones are a necessary part of our physical feedback mechanism!

The instrument without a full resonating body will be acoustically limited, and many pick-ups will miss the full range of audio that is produced by a skilled cellist. Any alteration to the mass and density of the bridge, as is necessary for many audio signal systems, will dramatically alter the playing experience. The displacement of the instrument's sound, from its local creation to a distant set of speakers, is bound to require adjustment by the player. Even the tinny sound of a string which is not coupled to the bridge and plates of an instrument can be disorienting.

Any MIDI pitch-tracking scheme requires equal-tempered tuning, far from the reality for any string

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player, and especially problematic for ensemble playing. It is even necessary to calibrate the tuning of each open string to the machine's preferences. Then the fingers must relearn the spacing, with an enharmonic pitch absolutism regardless of the demands of the music. This can only wreak havoc on the ear and the mechanism of ear–finger interaction which a good player has spent decades developing. The preference in string chords (both on one instrument and in ensemble) is for closer to just interval intonation, but it is difficult to build an adaptable scheme for this.

When designing a replacement instrument, especially one without the full body form, it will be difficult to find a solution which suits all players. The universality of any design incorporating a representation of the original instrument plus supplementary controllers will never be guaranteed. This is of course why so many one-of-a-kind instruments exist, although it is rare that they would terminate influencing a commercial instrument. And the exciting possibilities afforded by the addition of supplementary controls are of course extensions for which new techniques must be learned if they are to be effectively employed. Finally, the development cost is relatively high with respect to the market for such a new instrument, the audience's price point being quite limited in contrast to the antiquarian and investment market for older Natural Instruments.

7. ISSUES IN VIRTUAL INSTRUMENT DESIGN AND PERFORMANCE

The Virtual Instrument (figure 3) inherits many of the plusses and minuses described for the Representational Instrument, but its uses are so specific that these tradeoffs are accepted within the paradigm of a test bed environment. The Virtual Instrument, isolating a single feature of instrumental control, is excellent for study of the player's motions, the physical efficiencies, and the ergonomics. The implicit short development time and minimised development cost result in an excellent framework for prototyping concepts to be used in the design of more complete Representational Instruments, as well as observing behaviours which could be used to modify the efficiencies of the Natural Instrument. Also, materials technology can be evaluated for deployment in full-scale Representational or Natural Instruments.

A particular advantage of this niche of instrument design is its synergy with certain kinds of physical modelling synthesis algorithms, where a hypothesis built in a software environment can be triggered with only the control information considered most significant.

The shortcomings of the virtual sphere of instrument designs are their restrictions on motion, expressive control over the sound, and capacity to adapt to nuances of player style. Fortunately, while an excessive simplification of the Natural Instrument, the Virtual Instrument is the seed for future evolution, along any track that manifests itself as appropriate.

8. ISSUES IN THE DOWNSTREAM OF INSTRUMENTAL DESIGN

Many of the pros and cons of the Downstream portion of the interaction equation are tied to the features mentioned in the Upstream analysis, but a few tasks of the computational processing side should be discussed. The rich signal source of the Natural Instrument provides plenty of raw material for processing, without the need for processor-intensive re-creation. On the other hand, the processor is taxed with realtime signal analysis, an inevitable latency, limited ability to recover from failure or learn from it. While increasingly adaptive systems are developed, these issues are diminished but never evaporate, and the behaviour of the input can never be predicted.

The Representational system is designed primarily to solve these key issues from the Downstream side, doing so primarily with 'pre-processing' of the audio stream, as for example using individual pick-ups for each string. Multiple sensors can aid pitch-tracking by observing the left-hand location, string vibration, and audio signal. And the complexity of the whole acoustic system can be 'dumbed down' with the elimination of the body resonances, simplifying feature recognition. One final caveat for pitch-tracking was discussed as an Upstream issue for Representational systems: Who decides what is in tune?

Finally, we can imagine a high degree of control with inputs other than the audio signal, as for example with sliders and switches mounted on the body of the cello, on the fingers, on the player's clothes. But this Downstream system must compensate for the acoustic richness missing from the signal source, whether with interactive processing that restores sonic dimensions or dynamic synthesis.

The Virtual Instrument serves such a particular purpose that one can succinctly aver its benefit as the control over a synthesis algorithm with predictable data and its detriment as the limitation on expressivity and degree of adaptable sonic richness under the performer's realtime control.

9. THE SOUND WORLD FOR COMPOSITIONS, PAST, PRESENT AND FUTURE

I am positing that an essential element of instrumental technology-enhanced music is the compositional imperative leading to an aesthetic sonic instantiation. One assumes that the performer should be awarded maximum control, expressivity, awareness and interaction with the results. Building an electric cello that has a simplified physical playing model serves very little musical purpose. The performer should play their own instrument,

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or play a controller which isolates certain degrees of freedom to provide wide bandwidth channels of control, with strong interactivity between the motion and the ear.

Performers are most comfortable with their own instrument, not a copy, and maximal performance flexibility and expressivity certainly are conveyed through an original instrument. So one envisions truly expressive electroacoustic music as the attempt to enhance this natural sound with sound-processing tools. An important component of compositional sophistication is of course sound recognition, and one assumes that this is achieved primarily through software. Sound recognition is most commonly implemented as pitch-tracking, a notoriously difficult problem for mechanical devices, and one which is most effectively confronted with a combination of software 'listening' algorithms and mechanical sensors.

But sound recognition can and must go beyond the basic compositional nature of pitch-tracking, used for score-following. The software patches should be designed to recognise complexity and subtle changes in the sound as an important element of compositional or improvisational development. The complexity of overtones – sometimes many, sometimes few, sometimes clustered, sometimes dispersed, sometimes varying, sometimes static – that emerge when the bow is placed near the bridge of a string instrument represent a degree of intricate control that a player can have over the sound. A DSP response system that can recognise these differences can be part of genuinely giving the player increased control over the elements of the sonic composition.

There are so many subtle variations of pizzicato technique, for example derived from Asian instruments, that are open to the modern player. As an illustration, the Chinese *gu qin* has over 300 different playing techniques. Use of the fingernails of both hands, different fingers, tremolo, proximity to the bridge, above the left hand, stopping the string with the nail, glissandos, buzzing effects, snaps and so on, are available to any string player, and can be catalogued for compositional deployment. The ability of a response system to recognise these subtle differences can produce music of maximum complexity, with a high degree of realtime input from the player. Advancing techniques of instrumental performance while advancing sophistication and imagination in the interface are appropriate goals of interactive music.

The phrase 'extending the extended techniques' was suggested by the composer Bruce Bennett to describe the use of electronics to enhance an unusual aspect of the instrumental sound, the essential nature of our work together. This philosophy epitomises the essence of a collaborative work and one which advances a musical goal. One can imagine that the digital signal-processing techniques serve as an enhancement of a particular sonic input. The sound produced on the instrument is designed in the same way that a DSP output process might be designed. Again, this is a shared process between experimental performer and experimental composer. Finally, the DSP technique is designed to provide an appropriate enhancement which puts the sound in yet another uniquely created sound world. The player always has the sense of reaching in and sculpting aspects of the output sound, even as the hands sculpt the instrumental technique.

10. A LIBRARY OF TOOLS FOR DSP ENVIRONMENTS

I have attempted to create a collaborative environment where a composer's imagination of sound intersects with the performer's range of technique. As seed sonic material for present and future collaborations, I have recorded a sixty-track CD with 366 examples of assorted cello technique. Mostly focusing on pizzicato, it includes examples of tremolo, trills, glissandos and harmonics. The conception was to suggest areas for exploration in the context of strings and electronics. Specifically, I hope to create a library of digital techniques which supplement the performance techniques. The first problem in the employment of new sounds is detection, and to that end the sounds will be submitted to a battery of analytical methods to determine the best methods for realtime response. I invite all readers to examine those techniques which they find most interesting. The intention is to make the results available immediately to other participants, so that the project is segmented and solutions quickly reached.

The second issue with new techniques is how the electronics might be used in realtime interactive situations to extend the sounds further. While this is traditionally considered a composer's proprietary decision, I posit that being able to examine a patch developed in response to a particular technique should be useful to all participants in this project. There may be many ways to develop a response system to varying tremolo speeds or to pizzicato glissandos, but it is also imaginable that several compositions could share not only the original techniques but the processing algorithms. The Website at http://www.stringsandmachines.com will serve as a clearing house for developments in analysis, detection, and processing of the chosen techniques. Also, extensive information will be provided about notation and execution of the cello sounds. I am also interested to explore the creation of a library useful for all string instruments, when the techniques are adaptable.

A limited selection of techniques from the first volume of the *Hugh Livingston New Technique Series* is included on this volume's Organised Sound CD.

10.1. Descriptions

Each technique is described briefly, followed by the track number on the CD, the filename from the original

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disc (CTxx), and the duration in minutes and seconds. Volume I contains 366 techniques, of which the following is a sampling (Livingston 2000).

10.1.1. Changing vertical position

The open G-string is heard bowed continuously, with considerable variation in the 'vertical position', i.e. the distance from the bridge. The bow begins in the ordinary playing position, moves to the bridge, then back through the whole range to an extreme sul tasto position (the deliberate presence of sub-tones should be clear), and back to the bridge again. The left hand is never used. However, the bow pressure (downward force) and contact of hair with the string (from 'flat' maximum cross-section of hair to one edge) are manipulated to produce maximum variation in the sound [Track 1 (CT42), one example, 2:26].

10.1.2. Buzz

Pizzicato where the hand is rocked after the note is struck to create a buzzing in the decay, like the *sawari* effect on a Japanese shamisen [Track 2 (CT18), 0:50].

10.1.3. Thumb scrape

The thumb travels rapidly along the side of the string, covering 6–12 inches. No particular pitch [Track 3 (CT20), 0:23].

10.1.4. Pizzicato glissando, slow

The pizzicato with one second of sustain, five seconds of glissando, five seconds of decay. On Track 11, it is very clear that the last five examples use the fingernail to stop the string, providing a clearer sound, a sharper stopping point and less friction. But the noise of the nail against the string is also apparent. The resonance of example 8 on Track 51 is due to the sympathy of an open string; it is an aberration. On Track 6, there is lots of left-hand friction. On Track 7, what is heard is not clipping, but left-hand distortion of the sound [Track 4 (CT28), up, narrow, 1:15; Track 5 (CT29), up, wide, 1:25; Track 6 (CT30), down, narrow, 1:24; Track 7 (CT31), down, wide, 0:51].

10.1.5. Pizzicato tremolo octave-shift illusion

Pizzicato tremolo in which the striking finger moves from a point one octave above the stopped note to a point a major ninth above. The second partial becomes incredibly prominent as the striking point intersects with a point a major seventh or a major ninth above the stopping point, and disappears on the node which divides the stopped portion of the string in half [Track 8 (CT33b), 0:14; Track 9 (CT33d), 0:35].

10.1.6. Hammer-on

Striking the string with the left hand only. Note that two pitches are likely to sound, along with the percussion [Track 10 (CT07), 0:53].

10.2. Notes about the sound examples

The audio examples on the *Organised Sound* CD are Copyright 2000 by Hugh Livingston. The CD of test sounds was created for the benefit of testing digital signal processing techniques for analysis, recognition and extension of the sound. The sounds are not available for use in any type of compositional texture. The examples were performed by Hugh Livingston on 28 July 2000 in the studios of Maxis, Walnut Creek, CA, engineered by Robert Kauker. The microphone was an AKG 414, set for cardioid and placed 16 inches from the bridge, angled 15° downwards and aimed at the bridge. The pre-amp was a TC Electronics Gold Channel, operating at 44.1 kHz, 16-bit, passed through the dbx 160SL compressor/limiter, set to peak stop limit at −1 db to avoid clips on the snap pizzicato and percussive effects. It was recorded directly to hard disk using the Digidesign 888|24 ProTools system, in 44.1 kHz, 16-bit. No further processing was done. All samples are single channel. If importing the CD audio to Peak™, click *Set Import Times* in the dialogue box and switch the radio button to Mono.

11. THE MUSICAL FUTURE

The workshop presented at ICMC 2000 in Berlin was intended as the launch of the Strings and Machines III project, developing collaborative compositions for cello and interactive electronics. The idea is not determination to create a masterwork, but experimentation with techniques of instruments and techniques of sound. Composers with whom I am already working are creating short studies, some involving improvisation, all using extended techniques, and attempting to build software techniques that complement the instrument.

The Strings and Machines project is designed to be highly collaborative, eliminating the conventional boundaries between roles of composer and performer. The paradigm begins with individualised studio recording sessions. I inject a few techniques and ideas; the composers and engineers suggest some things and push me in different directions. Then we have a record of our initial interaction and can plan the direction in terms of DSP tools. We meet again and start looking at patches, so I stay involved. We funnel the direction together, sharing the hats of composer and engineer in solving these problems. The intent is also to work only with easily portable software patches, avoiding the labour of carrying hardware and the plague of obsolescence. Strings and Machines is ongoing in the sense that I

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maintain frequent contact with the composers, and after some initial public presentation the music can continue to evolve. In some cases the initial sketches are now fleshed out into solid compositions. Finally, the project is public: working to organise a consortium of companies in technological areas which overlap with the issues of musical DSP has been a primary task recently. The results are to be shared with industries whose own work deals with the tenuous confrontation of technology's impact on humanity.

It is agreed that the work is of an experimental nature, with trial and error inherent and a high degree of risk accepted. An open forum is provided for composers to show their work and performers to show their technique; others provide criticism and comments on works in progress. With these goals, I hope that the International Computer Music Conference serves as the seed for creative work; initiated at the annual meeting, and sustained through consecutive meetings, with an initial collaboration one year leading to performance of a completed work during the next. The core aspect of this ongoing project is of a truly collaborative nature, between the roles of composer, performer, engineer and programmer: all musicians and all technologists. Furthermore, there is intended to be considerable trial and error: not focusing on creating the ultimate new masterwork, but instead on working with some sketches, involving improvisation, adjusting the patches and the direction of the composition with various collaborative sessions extended over time.

12. SOURCES FOR MORE INFORMATION

As extensive bibliographic information is widely available, listing dozens of years of research in the highly malleable field of instrument design is redundant. And in the context of the material discussed, I am proposing a theoretical framework for today's work on instrumental technology, rather than citing previous studies. As an example of the wealth of reference material available, view the history of American contributions to controller design assembled by Joseph Paradiso and its satisfyingly extensive collection of links to other sites (Paradiso 1999).

There are many sources for information about materials employed in building natural instruments, particularly the rapid twentieth-century evolution of those materials. A most relevant one is the collection of interesting notes on technology of Chinese zither string material compiled by John Thompson, comparing silk and synthetics.

For the design of electronic representational (and hybrid) string instruments, the most interesting developments of the last ten years are the Celletto built by Chris Chafe at Stanford and the Hyperinstruments (Hyperviolin, Hyperviola, Hypercello) built and engineered by Tod Machover, Joseph Paradiso and Neil Gershenfeld at the MIT Media Lab. Max Mathews' work on aspects of violin design (including bridge coupling and simulation of formant resonances for the body of the instrument) is also a contribution to the state of the art (Mathews 1984).

The Media Lab now has a new group of researchers developing the next generation of string instruments, some as an evolution of the Hyperinstruments, and others with a new design paradigm. Bernd Schoner, for example, has developed the Digital Stradivarius. The interface is designed to record gesture data from a reduced cello-like controller, driving a real-time synthesis algorithm. Metal contact strips pick up finger location and a broadcast–receiver system detects bow location in two dimensions. The player actually bows in the air or against the body, since no actual contact is needed. These designs are crossing over from the 'fully functional' Representational Instruments which characterised the Hyperinstrument project into the Virtual Instrumental paradigm.

The concept of feature-focused virtual instruments is well illustrated by the new working group at Stanford's CCRMA, which is developing a stringless violin using concepts of haptic feedback originally developed for a mouse-like tracking device to be used by the blind. The bow, simply a straight rod, is drawn through a periodically resisting device which simulates the stick/slip action of the string. This constrained instrument has a particular purpose in driving the physical modelling synthesis algorithm also being developed at CCRMA.

The work of Curtis Bahn, Dan Trueman and Perry Cook is also a significant contribution to the field of instrument design. The instruments known as Fangerbored, Bonge, R-Bow and BoSSA, capture the essence of the virtual instrument, and are particularly important in the attempt to locate an instrument within its time and place, musically and technologically. Dan Trueman's dissertation, 'Reinventing the violin', is an essential reference to the abstraction of a natural instrument, studied and deconstructed, with features extracted for the design of a focused Representational or Virtual Instrument. He presents a theory of how the instrument's evolving physics may be considered matched with contemporary musical styles (examples are from Corelli, Schubert and Bartok), and then extrapolates that to the design of a new instrument and its new music. Similar to my schema, he also proposes classes of instruments, particularly the meta-instrument, an archetype of 'violin-ness'. The adaptation of playing styles and skills, from Stradivarius to Norwegian fiddle to electric violin, is a particular focus of this research, and is an excellent illustration of a performer's confrontation with the issues I have raised in instrumental design (Trueman 1999).

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