Distributed Control in a Mechatronic Musical Instrument

Michael Gurevich
University of Michigan
Department of Performing Arts Technology
School of Music, Theatre & Dance
Ann Arbor, Michigan
mdgurev@umich.edu

ABSTRACT

Drawing on concepts from systemics, cybernetics, and musical automata, this paper proposes a mechatronic, electroacoustic instrument that allows for shared control between programmed, mechanized motion and a human interactor. We suggest that such an instrument, situated somewhere between a robotic musical instrument and a passive controller, will foster the emergence of new, complex, and meaningful modes of musical interaction. Adopting a practice-led research approach, the development and design of one such instrument—Stringtrees—is described. The design process reflects the notion of ambiguity as a resource: The instrument was endowed with a collection of sensors, controls, and actuators without a highly specific or prescriptive model for how a musician would interact with it.

Keywords

robot, cybernetics, automata, ambiguity, interpretation

1. INTRODUCTION

There has been substantial recent interest in mechatronic music systems: instruments, devices, or assemblages that integrate electronic controls, mechanical motion, and acoustic systems intended to create music. Most prominently, these have taken the form of robotic instruments and ensembles thereof [12, 13, 16, 25, 26, 29]. Purely mechanical automatic musical instruments, or musical automata—instruments that play preprogrammed music on their own with negligible human intervention—date back at least to 9th century [14], and became quite fashionable beginning in 17th century Europe [8]. Perhaps the most familiar musical automata, player pianos were among the first to successfully integrate digital electronic control systems in the late 20th century. Facilitated in part by the availability of accessible and affordable rapid fabrication systems, programmable embedded computers, sensors, and actuators, a 21st century resurgence of musical automata is undoubtedly underway.

Yet for all the deserved attention they have received, musical automata represent only a subset of possible paradigms of mechatronic music systems. The focus of this paper is specifically mechatronic music systems that are not wholly automatic, that is, instruments that feature electronically controlled mechanized motion but afford substantial human involvement in the sound production process. Fundamental to this investigation is the notion that the human performer and mechatronic instrument are part of a dynamic system in which they mutually influence each other's behavior. This paper proposes a class of instruments that occupy a middle ground between digitally controlled musical automata on one hand, and essentially passive "controllers" on the other.

2. HUMAN-INSTRUMENT RELATIONSHIPS

Our approach to a mechatronic instrument is situated through a brief survey of perspectives on human-instrument relationships in NIME and allied disciplines.

2.1 Cybernetics

Usually associated with Norbert Wiener, cybernetics is a suite of concepts that initially framed the interaction between humans and machines in terms of communication and exchange of information. These principles were subsequently extended to other domains such as economics, biology, ecology, and social science, and, especially due to the contributions of Ashby, were simultaneously expanded to broadly integrate the ideas of systemics [5]. The concept of complex, highly interconnected systems, especially on biological and planetary scales, has become rather commonplace these days, but has roots in cybernetics.

Later authors, most notably Maturana and Varela, shifted attention toward the abilities of systems to organize themselves [18]. This so-called "new cybernetics" represents in part a philosophical rejection of the notions of control and design in favor of those of emergence and self-production [5]. That is to say, systems, including living biological ones, cannot be autonomous unless their behaviors are produced spontaneously from their internal dynamics and interaction with other systems. The repercussions for robotics and artificial intelligence are significant: it would be impossible to design an autonomous, intelligent system by exhaustively specifying sets of input-output rules or comprehensively enumerating all possible outcomes. Rather, a system must be imbued with the possibility to dynamically generate its own knowledge, if not meanings.

A number of early (pre-NIME) authors considered the relationship between human performers and music controllers in terms of first-generation (information processing) cybernetics, specifically examining the properties of controllers that can facilitate effective control given the constraints of human abilities [19, 23, 28]. Mulder [20], however, highlights limitations of a strictly cybernetic model of the human-instrument relationship, suggesting that other representations—semiotic models or those involving energetic exchange—may be simultaneously valid. He argues that instrument designers must therefore consider these multiple models and be able to effectively translate between them.

2.2 Haptics

Mulder's "energetic exchange" model is consistent with Cadoz's concept of an "ergotic" human-machine relation-

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ship, which he sees as a prerequisite for "instrumental" interactions [3]. Cadoz argues that interactions with physical devices having real-time influence over digital sound synthesis (i.e., "music controllers" to which I have previously referred as "passive") are frequently not instrumental, because there is no physically meaningful exchange of energy between the performer and the sound-producing mechanism. That is, by not mechanically transmitting energy back to the human performer in response to their gestures (as, say, a piano or a violin does), the interface and synthesis system do not reveal their physical or acoustic properties.

Cadoz and others propose that one way to overcome this problem without abandoning the whole enterprise of real-time digital music is through active force-feedback or haptics (a comprehensive list of citations would be too long to list, but see, e.g. [1, 2, 3, 22, 27]). Haptic systems are generally mechatronic, but on a continuum of mechatronic music systems in terms of their degree of autonomy, haptic systems would be at the opposite end as musical automata. Haptics are seen as a way to promote tighter and more meaningful coupling between a human performer and a digital sound synthesis system, frequently—but not always—by computationally modeling the forces exchanged between real mechano-acoustic systems.

2.3 Semiotics

Mulder's third representation of human-instrument relationships—a semiotic model—points explicitly to the fact many digital music systems afford linguistic or symbolic interfaces. Significantly, tangible or physical interfaces to digital music systems may still be essentially semiotic, especially when generic inputs are mapped directly to symbolic properties of the system, e.g., a tempo knob or a transposition button. Based on qualitative studies of performers and spectators, recent authors have pointed to the potential for multiple modes of engagement or skill development with interactive music systems, specifically highlighting the predisposition of digital tools toward intellectual engagement [7]. Magnusson takes a stronger position regarding semiotic relationships, arguing that a digital musical instrument is necessarily an *epistemic tool*—a device that encapsulates a system of knowledge and thought in its own right [17].

2.3.1 Intelligent Systems

The impulse to endow computer-based music systems with intelligence is as old as computer music itself [9]. A generation later, Lewis frames now-interactive and responsive intelligent music systems explicitly in terms of "latter day musical automata" [15]. Whereas Lewis's work has been confined to synthetic sounds and digitally-controlled player pianos, others, most notably Weinberg, have developed responsive musical robots [10, 29]. Although aspects of their behavior are automatic, these systems represent another interesting model of human-instrument relationship in that a human can substantially affect the system's response in real-time, but only indirectly and not entirely predictably. Furthermore, the interaction is through an abstract, high-level, symbolic ("musical") language. This is to say that unlike digital musical automata, a performer cannot control the mechanical motions of these intelligent systems directly; to cause a particular note to be played at a particular time, for instance. What's more, the interface to these systems is generally acoustic: it is the sonic quality of another instrumentalist's performance that influences their behavior.

2.4 Dynamic Systems

In one of the most interesting recent qualitative studies of performer-instrument relationships, Johnston et al. identify three different modes of interaction with a purely virtual musical instrument—one that responds to acoustic input from a performer with dynamic behavior according to a physical model [11]. The authors identify what they call instrumental, ornamental, and conversational modes of interaction with the system, again suggesting a continuum of possibly overlapping types of relationships. Although it lacks a physical interface, Johnston's system might be considered ergotic according to Cadoz's criteria in that there is a degree of proportional energetic exchange—acoustic inputs interact with a computational model of a physical dynamic system, which in turn provides multisensory (audio and visual) feedback to the performer.

Perhaps the most significant feature of this system is that its input, like that of the intelligent robotic instruments described above, is acoustic; but the virtual instrument in this case does not model musical intelligence, it models a physical dynamic system. It is thus noteworthy that a model of a virtual dynamic system could facilitate a conversational interaction style, which would typically be associated with symbolic communication. In one sense, we can consider this an example of the transformations between representations that Mulder describes [20].

3. DESIGN APPROACH

As designers, the team behind Stringtrees was struck by the fact that in [11], a single dynamic system—even a virtual one—with physically meaningful behaviors could engender such rich, diverse, and fluid modes of interaction. Other authors, e.g., [4] have highlighted the utility of physically meaningful metaphors in the design of musical interactions, but we are interested specifically in systems the contain explicit, rather than metaphorical, representations of physical dynamic systems. We are furthermore interested in systems that "move at slower, 'haptic' rates (up to around 20 Hz)" [11], as opposed to computational acoustic models used in sound synthesis. However, instead of a virtual dynamic system, we sought to integrate concepts of cybernetics by employing real, physical motion and an acoustic sound source.

Our interest is in examining the potential for a mechatronic instrument to facilitate new modes of music making. The underlying hypothesis is that bestowing the instrument with dynamic behavior, while distributing real-time control between a human performer and programmed automatic motion, will allow for the emergence of rich and meaningful musical interaction.

The concept of emergence is significant here, reflecting the notion of self-organization from cybernetics, but also concepts from design theory, specifically those of designing for ambiguity and facilitating interpretation advocated by Sengers and Gaver [6, 24]. These ideas suggest that systems can be designed to afford multiple, heterogeneous interpretations, styles or modes or interaction, which may in turn engender more rewarding and meaningful experiences for their users. In our case, the specific ways that a performer would interact with the instrument were not prescribed in advance; rather we sought to equip the instrument with useful capabilities without excessively constraining a particular way in which it would be used [24].

The approach in developing a hybrid mechatronic instrument falls under the umbrella practice-as-research [21]. The design process was theoretically motivated, but this was seen to be an instance which demanded exploration through reflective practice with a "real," functional instrument, as opposed to experimentation in a laboratory setting or user studies. Furthermore, approaching the design as a creative exercise allowed for what we consider appropriate freedom to make artistic judgments, given that the ultimate application of the design is a musical one.

4. STRINGTREES

Below we describe the general design concept of Stringtrees, and document its development into its current form. In the spirit of practice-as-research, at each major stage of the process the developing design was holistically evaluated with regard to the goals laid out above. Those reflections are presented here alongside the account of the design.

Stringtrees was initially conceived as a plucked string instrument in which a motorized central rotating plectrum-arm would pluck strings circularly arranged around it. Following the "tree" metaphor, the central shaft would be the "trunk" and the strings branches surrounding it. The initial shape was also inspired by the old practice of plucking the rotating spokes of a bicycle wheel with a card attached to the frame; in this case, the plectrum rotates instead of the spokes. The most obvious inspiration from NIME is the rotating plectrum from LEMUR's GuitarBot [25].

4.1 First Prototype

The first prototype, developed in 2010, has an industrial aesthetic. A 1" steel shaft supports a CNC-machined aluminum "crown," from which guitar strings extend down to a 1m-diameter, circular Delrin base. The strings can be tuned with standard guitar machine heads, which are mounted on machined aluminum brackets that attach to the base with a thumb screw. The crown supports up to 24 strings.

An industrial 12V motor drives a bearing-mounted arm attached to the shaft via a v-belt and pulley. If the motor is driven at a constant speed, the adjustable relative position of the strings along the perimeter of the base allows for continuously variable rhythmic pitch-sequence patterns as the rotating arm plucks the strings.

The prototype was tested without a feedback-control system. A potentiometer connected to an analog input of an Arduino modified the duty cycle of a PWM output connected to an H-bridge motor controller. Development of this version of Stringtrees was suspended after initial testing due primarily to its size and weight; the motor torque involved to operate it required substantial power. It was determined that a smaller, lighter version would be a more effective platform for investigation.

4.1.1 Reflections

Although development of this version was subsequently suspended, initial testing of the first prototype did offer beneficial results that offered some validation of our method and informed the subsequent design. Among the design evaluations, it became clear that spatially reconfiguring the strings "on-the-fly" to achieve predictable rhythmic variation would be nearly impossible; even if it could be done, the string tunings would be altered to a greater degree than anticipated in the process of moving them.

The hub-and-spokes model didn't appear to offer feasible rhythmic variation by the human performer. It could be achieved by programming the motion of the arm: A solenoid at the end of the arm could be programmed to retract or extend the plectrum to bypass or pluck strings as desired. This of course would have deviated from our goal of sharing control between human and automatic behaviors, placing the instrument squarely in the realm of automata. This would furthermore defeat the purpose of the tree-like configuration which presents an attractive spatial mapping of rhythm to points on a circle.

With regard to the design method, it was encouraging to witness spontaneous, unanticipated interactions with the prototype. Upon switching on the power for the first time in the laboratory, a colleague who was uninvolved in the project, and unaware of its aims or theoretical foundations, almost instantly picked up a nearby wrench and began using it like a guitar slide along the strings to change their pitch. It appeared that the open-ended design would indeed facilitate multiple interpretations.

4.2 Current Version

The current version of Stringtrees is smaller and lighter, with a wooden, 18" square by 36" high frame and 1/4" shaft (Figure 1a). It elaborates on the strictly tree-like shape by replacing the array of individual strings around the base with four equally-spaced rotating spindles supporting four strings each. A spring-loaded mechanism locks each spindle into place, with buttons on each of the 4 side panels to release them (Figure 2a). This allows strings to be moved into and out of the path of the arm easily, and without altering their tuning as in the first version. The machine-head tuning attachments from the first version were reused from the first prototype (Figure 1b).

Figure 1: Stringtrees January 2014. a) Full instrument, b) Tuning mechanism, c) Multiple arms

This version uses a direct drive in which the shaft itself rotates, with a 12V DC motor coupled directly to it. The plectrum arm is made of threaded rod that screws into a shaft collar. This simple and inexpensive mechanism allows for the possibility of multiple plectrum arms (Figure 1c). At the end of the arm, a laser-cut fitting allows for plectra of different materials to be mounted and precisely positioned.

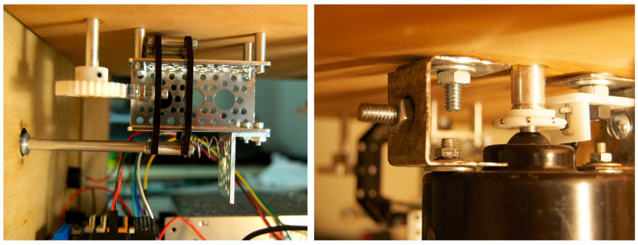

Figure 2: Inner detail. a) Spindle Lock, b) Motor mount and magnetic speed sensing system

A shaft-mounted collar made of laser-cut acrylic holds 8 equally-spaced neodymium magnets that pass a linear hall-effect sensor as the shaft rotates (Figure 2b). This is currently used to calculate the rotation speed, shown on a numerical display on the front panel, which provides a means of feedback the performer can use to modulate their control. The speed-control potentiometer system is retained from the first version. The magnetic rotation sensing system is deliberately excessive for just displaying speed; in keeping with the design philosophy, we left open the possibility of further automating the motion of the arm to explore the distribution of control.

4.2.1 Reflections

As with any instrument, our practice with Stringtrees will evolve over time. Although we are only near the beginning of our journey together, several important features are apparent. Moving individual strings to spindles provided the ability to easily change the tuning of a note at a particular rhythmic position (or stop it from playing) by rotating the spindle. This has enabled more effective note-level control. The spatial configuration around the shaft suggests a collaborative performance. With one person at each spindle, we are able to create coordinated harmonic progressions. This suggests a new dimension for the distribution of control—among several performers and an automated system.

The speed control system needs to be more refined. This is an instance where giving more control to the system will be effective. Instead of having the potentiometer control the PWM duty cycle of the motor driver directly, we are working toward programming it to set a desired speed, and using the speed sensing mechanism to regulate the motor drive to achieve that speed. In the current configuration, the dynamics of the motor drive require too much human intervention to maintain a constant speed.

Perhaps the most significant musical discovery has been that varying the motor speed can put Stringtrees into perceptually distinctive modes which suggest different styles of interaction. At low speeds, the effect is that of looping pitch sequences or arpeggios, which can be varied by rotating in different notes. At high speeds, the sustained string sounds create a more of a harmonic texture than a note sequence. One observer compared it to a hyper-tanpura. With multiple plucking arms, the textural effect is amplified.

As with the distribution of control between the instrument and performer, we are finding the space in the middle—where Stringtrees can be heard alternately as textural, harmonic, or melodic—to be the richest area for further exploration and musical development.

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