The Man and Machine Robot Orchestra at Logos

Laura Maes,*† Godfried-Willem Raes,*† and Troy Rogers**
*University College Ghent
Department of Music
Hoogpoort 64, 9000 Ghent, Belgium
†Ghent University
Department of Art, Music
and Theatre Sciences
Blandijnberg 2, 9000 Ghent, Belgium
laura.maes@hogent.be
godfriedwillem.raes@logosfoundation.org
**University of Virginia
McIntire Department of Music
112 Old Cabell Hall, P.O. Box 400176
Charlottesville, Virginia 22904-4176 USA
tsr9f@virginia.edu

This article provides an overview of the various automata of the Man and Machine robot orchestra found at the Logos Foundation in Ghent, Belgium (see Figure 1). The motivation for their creation is discussed, as well as the way in which these automations of existing and new instruments distinguish themselves from precursors and other contemporary musical robots. This extensive orchestra features over 45 organ-like instruments, monophonic wind instruments, string instruments, percussion instruments, and noise generators. In this article, at least one automaton of each instrument family is discussed in depth; the design, construction, expressive capabilities, and limitations are treated; and the various ways in which the automata are controlled is discussed. Descriptions of six compositions that demonstrate the wide usability of the automata are included. Finally, this article provides a glance behind the scenes and unveils future plans for the ensemble. [Editor's note: video examples appear in the DVD accompanying this issue.]

The Orchestra's Origin

The Logos Foundation started in 1968 as a collective of experimental composers and musicians. In the first two decades of its existence, Logos's main focus was on the design and use of analog, digital, and hybrid electronic sound generation devices. In 1990, the construction of Autosax, an automated acoustic saxophone, marked a shift towards a new era: the design and development of music robots. Over 45 robots have been realized. Together they form an impressive orchestra.

The motivation for Logos's interest and involvement in robotics stems from the view that loudspeakers as sound sources (a necessity for all electronically generated sound) are virtualizations of an acoustic reality. Therefore, they tend to undermine the raison d'être of concerts as social rituals. The dissociation between musicians' gestures and sonic results makes the rhetoric so typical of—if not essential to—live performance nearly impossible. With automated acoustic instruments, virtualization is eschewed in exchange for rich acoustic sound sources under precise computer control; the coupling between gestures and produced sounds is thus inherent.

Precursors

The idea of automating musical instruments is in no way novel. With increased frequency since around the second half of the 18th century, the pursuit of automated musical instruments has fascinated both instrument builders and musicians. Until the middle of the 20th century, almost all musical automata were either purely mechanical or pneumatic (Kapur 2005). The mechanics used were discrete: sounds could be programmed to go on or off at fairly precise timings, but nuances, dynamics,

Computer Music Journal, 35:4, pp. 28–48, Winter 2011

Figure 1. The Man and Machine orchestra at the Logos Tetrahedron.

and timbral possibilities—and thus the expressive musical potential of these instruments—were extremely limited. The advent of electromechanics and their electronic control possibilities greatly extended the versatility of automated musical instruments. Many of the early attempts achieved only flat approximations of music performed by humans, but contemporary computer-controlled instruments can be designed to offer finer control over musical parameters (e.g., pitch, level, timbre, timing) than humans could ever hope to achieve. These instruments demand the creation of new music written specifically to take advantage of their unique capabilities. The Logos orchestra is situated within this territory.

The Contemporary Field of Musical Robotics

Contemporary developments in the growing field of musical robotics fall into several overlapping categories. Perhaps most familiar to the general public are industrial anthropomorphic robots, developed as human companions and service providers that play music as a way of demonstrating their dexterity and technological advancement. The trumpet-playing Toyota partner robot is an example (Toyota Motor Corporation 2003). Next, there are a number of robots produced specifically as musical automata. They are also anthropomorphic to varying degrees, and seek either to replicate the mechanics of human performance (Solis et al. 2006; Petersen et al. 2009) or to serve as interactive physical agents for the exploration of human–machine interaction in improvisational musical contexts (Weinberg and Driscoll 2006). Finally, there are growing numbers of automated acoustic instruments created by composers and sound artists seeking to exploit the unique capabilities of these machines. The Logos Man and Machine Ensemble, one of the oldest robotic orchestras, falls squarely in this category.

Various other artists and collectives are also active in the same field. Logos's Player Piano I builds further on Trimpin's, with the playing mechanism similarly placed directly onto the keyboard, in contrast to the Bösendorfer SE and Yamaha Disklavier where the playing mechanism is integrated inside the piano (Coenen 1992). Trimpin originally designed a player piano to salvage the player-piano music of Conlon Nancarrow, as it is difficult to maintain mechanical player pianos, and Nancarrow's cardboard piano rolls have a limited lifespan. Whereas Nancarrow specified only seven gradations of velocity control (applied to musical characteristics such as crescendo or intensity) for each half of the keyboard (bass and treble), on Trimpin's player piano each key can be controlled separately (Raes 1994). In Raes's version, the exact height of each solenoid above the piano key can be adjusted. This adaptation makes it easier to precisely control the velocity sensitivity.

Trimpin's work inspired not only Raes's Player Piano I: Similar circuits were used in other instruments of the Man and Machine robot orchestra, such as Harma, QT, Troms, Tubi, Vibi, Simba, Xy, Rotomoton, and Toypi.

Trimpin and Raes both focus on acoustically produced sounds and avoid amplified and synthesized sounds (Louie 2002). Whereas Trimpin's designs lean more towards sound art and are often presented in exhibition environments, Raes's Man and Machine ensemble more frequently will be found on the stage of a concert hall. This is perfectly illustrated by the fact that both creators have made MIDI-controlled water valves. Trimpin integrated 100 of these valves in his installation *Liquid Percussion* (Trimpin 2011), in which water drops fall on hand-blown glass vessels. Raes created Dripper, an automaton that can control not only the frequency, but also the size of water drops. Raes used this instrument to realize an act of his music-theatre production *TechnoFaustus*. Just like Raes, Trimpin made an automated toy piano. His sound-work *Klavier Nonette* groups nine toy pianos that can play 41 original compositions. To hear and see them play, the spectator drops a quarter in a jukebox and dials in the number of the composition he or she wants to hear (Chang 2003). Whereas Trimpin makes use of the original toy piano soundboard, Raes created a new free-swinging soundboard constructed out of hardened brass. Both use wooden hammers, but Raes replaced the keyboard and action with a tubular solenoid assembly. On the outside, Trimpin's player pianos look exactly like non-automated player pianos, and the polycarbonate plate and visible electronics give Raes's Toypi a futuristic look.

Trimpin gave advice for the construction of a percussion robot and a marimba/bell robot. Together with a drum robot they form the Karmetik Machine Orchestra (Karmetik 2010). This collective of engineers, visual artists, and musicians does not confine themselves to acoustically produced sounds. Loudspeakers were integrated in the drum robot to create an effect like a rotating Leslie speaker, and in performance settings the sounds produced by the robots are amplified. On stage, musicians use custom-built musical interfaces to interact with the automata. In contrast to the Man and Machine orchestra, most of these interfaces take the form of a musical instrument equipped with sensors.

Jacques Rémus's Concertomatique n°2 is a collection of eleven mechanic automata and comprises, among others, two organs, percussion instruments, a string quartet, and machines with ringed pipes (Rémus 2011b). Besides Concertomatique n°2, Rémus has also created Carillon n°3, which consists of 40 automated tubular bells (Rémus 2011a) and Les Pic Verts, a collection of six automated woodblocks (Rémus 2011c). In contrast to Raes's robots, Rémus's carillon and woodblocks are mainly presented as an installation, whereby the various elements are spread throughout the space. It is not the performer, as is the case in the Man and Machine orchestra, but a visitor who interacts with the automata. The performed melodies can be chosen through various interfaces, ranging from a keyboard or microphone to Rémus's own *caméra musicale*, an interface he developed that detects the position and movements of hands and translates those to MIDI commands (Rémus 2006).

Christof Schläger's Electric Motion Orchestra does not focus on the automation of existing musical instruments, but on the creation of new instruments. Schläger is inspired by the sound world of machines and searches for rhythms and timbres not found in traditional instruments. The orchestra contains 26 automata that all use elements that were originally designed for purposes other than the creation of music, such as doorbells, magnets from weaving machines, sewing machine motors, radiator valves, electric staplers, signal horns, ventilation valves, servomotors, and record player motors (Schläger 2010). Small instruments, such as Toypi, are not found in Schläger's orchestra; all his instruments have monumental shapes. Both Raes's and Schläger's orchestras are MIDI-controlled, but the precision of control in Schläger's Electric Motion Orchestra is less fine.

In 2000 Eric Singer founded the League of Electronic Musical Urban Robots (LEMUR). This group of musicians, robotics experts, artists, and designers creates MIDI-controlled musical automata, including a xylophone, shakers, Tibetan singing bowls, goat-hoof rattles, gamelan, and guitars. Most of the automata are acoustic, but some, such as the Guitarbot, are electrified. Like the Man and Machine automata, LEMUR's robots aim to augment the capabilities of human performers, not to replace them. LEMUR's robots also utilize peripheral interface controllers (PICs), microcontrollers used to receive MIDI commands and to control the steering of the electromechanical components (Singer et al. 2004).

Singer has also built instruments for other people, for example, Pat Metheny has recently travelled the world with the Orchestrion. On stage, Metheny is accompanied by over 40 automated instruments, mostly percussion instruments and automated guitars. Metheny uses a guitar interface, a keyboard, or software programs running on his computer (Chinen 2010) to send MIDI commands to the various automata.

Universities are a breeding ground for new robotic instrument builders. Not only do Ajay Kapur's students at the California Institute of the Arts expand the Karmetic Machine Orchestra with modified instruments and new robots, new organizations are also being formed. In 2007, Troy Rogers, Scott Barton, and Steven Kemper, three PhD students at the University of Virginia, founded Expressive Machines Musical Instruments (EMMI). They have built two percussion robots and one monochord robot (EMMI 2011), and they aspire to create a huge orchestra (McNeill 2008). In 2010, Troy Rogers worked at the Logos Foundation.

Founded by MIT alumnae Christine Southworth and Leila Hasan, the Ensemble Robot unites artists and engineers. The ensemble comprises five musical automata, all utilizing acoustic sources such as whirlies, pipes, and strings (Southworth 2010). As with the Man and Machine ensemble, the automata of Ensemble Robot frequently play together with musicians, but in contrast to the Man and Machine ensemble, the musicians' actions have no influence on the output of the automata.

The underground pop world is also not immune to robotic charms. Jason Vance, the driving force, guitarist, and singer of Captured! by Robots, is accompanied on stage by a guitar robot, pneumatic horns, and various percussion robots (Captured! by Robots 2011). The garage rock band The Trons go one step further: Only robots populate the stage (The Trons 2011).

Design

This section illustrates the design principles of various instruments in the Logos Man and Machine orchestra. The electronics and actuators are discussed, as well as the frames that hold them.

Principles

The durability, usability, acoustic quality, capabilities, and "readability" of the automata are addressed in the following paragraphs.

Durability

A well-made acoustic instrument is expected to hold up to decades or even centuries of regular usage. In the tradition of quality acoustic instruments, the instruments of the Man and Machine orchestra are designed with longevity in mind. Welded steel frames, over-specified electronic and electrical components, and high-performance actuators are utilized to ensure maximal lifetime and minimal maintenance.

Usability

The instruments are designed with the intention that any composer who possesses a basic knowledge of sequencing, notation, or other MIDI software, and who is familiar with the specifics of controlling the automata (Raes 2010a), will be able to write for them.

All of the automata are permanently set up in Logos's tetrahedron-shaped concert hall. Although the instruments are sometimes presented at other venues, they always return to the Logos concert hall, where they stand set up and ready to be used with the simple flip of a power switch.

Acoustic Quality

The orchestra is completely acoustic, and therefore joins a long tradition in the construction of musical automata. Unlike some elements in automated dance organs (orchestrions), where certain elements only have a visual function, the Logos automata have no non-functioning components and no electrical amplification.

Capabilities

Raes's point of departure is that his machines can outperform humans. His intention is not to replace human performers, but to expand musical possibilities. Most automata can play faster, and produce more simultaneous notes, than a human performer could ever achieve, each with precisely controlled dynamics. Most of the orchestra's robots are tuned to twelve-tone equal temperament. Four instruments (Qt, Tubi, Xy, and Puff) are tuned to equal-tempered quarter tones. Sire, as well as all of the monophonic wind instruments, can be tuned with sub-cent precision and can thus be used with nearly any tuning system.

Readability

The machines are "readable," meaning that the audience can visually comprehend them because they feature as many visible components as possible. Additionally, extensive design and construction information, and even the programming and electronic schemes of the instruments, are published with an open-source license on the Logos Web site.

Frames

All Logos automated instruments are supported by sturdy welded steel frames. AISI304 stainless steel is used for its numerous desirable properties. It is easy to weld and shape, is durable, rust-free, and nonmagnetic, and it is a poor transmitter of acoustic vibrations (which is important for preventing unwanted resonances). As the automata are heavy (up to more than 250 kg for Qt) and regularly travel, most of the instruments are equipped with sturdy wheels.

Electronics

PIC microcontrollers are used to control all of the automata. Several varieties of custom printed circuit boards (PCBs) have been developed for various aspects of machine control.

Custom PCBs

On the instruments that utilize solenoids to drive percussive beaters, depress piano or organ keys, or operate valves or tone holes, custom "pulse/hold" circuit boards are used. For instruments (such as pitched and nonpitched percussion instruments) that require a single pulse to drive the solenoid and strike percussively, the over-voltage pulse portion of the board is utilized. The 16-bit timers of the PIC microcontrollers allow for 27-microsecond resolution of the pulse durations for each of the 16 solenoids that are "steered" from a single chip. Lookup tables programmed into the PICs via MIDI system-exclusive commands ensure that the received note velocities (from 1–127) will produce linear gradations of striking forces, from the softest to the loudest possible for the given instrument and striking mechanism. For instruments that do not require velocity control, but instead require that a note-on activates the solenoid and that a note-off releases it (such as for organs without velocity control), the hold circuitry is utilized. For instruments requiring both velocity and duration control (such as the player piano and velocity-sensitive organs), both the pulse and hold circuitry are used in combination.

Instruments requiring audio signal generation for mechanical activation, such as the monophonic winds and the electromagnetically bowed string instruments, utilize custom boards based on

Microchip Technology's dsPIC microcontroller to generate the requisite waveforms. All instruments are equipped with a custom MIDI hub board to buffer the input and distribute MIDI messages to the various actuators and lights.

Actuators

A range of solenoid types is used in the orchestra, carefully chosen according to performance and longevity characteristics. Tubular push and pull, dual-coil push–pull, rotary, and pivoting anchor types are all used, in sizes ranging from the tiny Lucas Ledex push solenoids used in Toypi to the large bi-directional slider action August Laukhuff actuators (capable of 6.3-kg pull force) used in Klung and So.

There is a strong preference for three-phase brushless servos whenever speed or position control is required. These high-performance motors are precisely controllable and have the desirable characteristics of silent operation and extended life cycle. Three-phase alternating current motors, operated with commercial motor controllers, are used to supply wind to the organs. Large stepper motors are used to control the pitch of *Rotomoton* (automated rototoms), while smaller steppers are used, for instance, to raise and lower the swells and to open and close the wind valve on Harmo (an automated 440 Hz, six-octave harmonium). Small, brushed direct current (DC) motors, typically high-performance types that have been extracted from tape recorders, are also used in some automata.

Voice coils remain the audio-rate actuators of choice for Logos automata. The Sousaphone's (So's) silicone "lips" are actuated at audio and sub-audio rates by a modified loudspeaker. Compression drivers are outfitted with appropriate acoustic impedance converters to drive the other monophonic wind instruments.

Families

The orchestra is composed of different acoustic instrument families: organ-like instruments, monophonic wind instruments, string instruments, percussion instruments, and noise generators (see Table 1). Although most of these robots are automations of existing instruments, many of them offer broader musical possibilities than their manual equivalents. The following sections provides an overview of the various robots of the orchestra. For at least one robot from each musical family, the design, construction, expressive capabilities, and limitations will be discussed in detail.

Organ-Like Instruments

The Logos orchestra includes various automated pipe organs that are equipped with flue and reed pipes as well as several free reeds. The ambitus of the flue pipe organs ranges from bass (Bourdonola) to soprano (Piperola). Qt, a quarter tone organ, expands the tuning possibilities of the flue pipe section. An automated organ with reed pipes (Krum), an automated organ trumpet (Trump), a Vox Humana (Vox humanola), and a percussive quarter tone organ (Puff) provide a range of timbral possibilities. Control of the wind pressure envelope of each closed wooden flue pipe is being implemented in the brand-new automaton Bomi. Two automated accordions—Ake and Bako (a bass accordion)—and two reed organs—Harma and his big brother Harmo—constitute the free reed section.

Puff, A Quarter Tone Percussive Organ

The mechanism of the Puff organ has no equivalent in existing musical instruments. Each of the 84 closed brass pipes of this percussive organ is articulated by an individual solenoid-driven piston with a Pyrex glass housing (see Figure 2). On each stroke of the solenoid, a precisely controllable puff of wind is produced. Because of this approach, a fully polyphonic touch sensitivity is realized.

Because of Puff's extended range in the high treble and its quarter-tone tuning, it is particularly well suited for music using spectral harmony. If enough energy is sent to the solenoids, it is possible to over-blow the pipes (because closed brass pipes are used, the *duodecimo* will sound).

Table 1. Automated Instruments of the Man and Machine Orchestra

Category		Instrument Name	Short Description	Year of Production	Pitch Range	Tuning System	Tuning of A4 (Hz)	Web page
Organ-Like Instruments	Flue Pipes	Bourdonola	Pipe organ (8′ register, open wood pipes)	1998–2008	C2–D4	Twelve-tone equal temperament (12-TET)	440	logosfoundation.org/instrum_gwr/bourdonola.html
		Piperola	Pipe organ (open and stopped metal flue pipes)	1998–2007	C4–C8	12-TET	440	.../piperola.html
		Puff	Percussive organ (brass pipes)	2003–2007	G3–C7	24-TET	442	.../puff.html
		Qt	Pipe organ (stopped metal flue pipes)	2005–2008	C2–C8	24-TET	440	.../qt.html
		Bomi	Pipe organ (gedeckt register)	2009–2010	G3–G6	12-TET	440	.../Bomi.html
	Reed Pipes	Vox Humanola	Reed pipe organ (Vox Humana register)	1996–2005	C2–G6	12-TET	440	.../voxhumanola.html
		Trump	Reed pipe organ (modified trumpet register)	1999–2005	G#1–G#4	12-TET	440	.../trump.html
		Krum	Reed pipe organ (Krummhorn register)	2005–2006	C2–G6	12-TET	440	.../krum.html
	Free Reeds	Harma	Reed organ	2000–2005	F1–F6	12-TET	435	.../harma.html
		Ake	Accordion	2003–2009	left hand: G0–F#2 / right hand: C#3–A#6	12-TET	440	.../ake.html
		Bako	Bass accordion	2006–2008	C1–A3	12-TET	440	.../bako.html
		Harmo	Reed organ	2009–2010	F0–F8	12-TET	440	.../harmo.html
Monophonic Wind	Instruments Brass	So	Sousaphone	2003–2007	C0–A2	Any tuning system	440–454	.../so.html
		Bono	Valve trombone	2005–2010	A#0–F#5	Any tuning system	440–454	.../bono.html
		Heli	Helicon	2007–2008	A#0–G6	Any tuning system	426–454	.../heli.html
		Korn	Cornet	2008–2010	E3–C7	Any tuning system	426–454	.../korn.html
	Woodwind	Autosax	Saxophone	1991–2010	A2–C5	Any tuning system	426–454	.../autosax.html

Table 1. Continued.

		Ob	Oboe	2008–2010	A#3–C7	Any tuning system	426–454	.../ob.html
		Fa	Bassoon	2009–2011	A#1–G5	Any tuning system	426–454	.../fa.html
String Instruments		Hurdy	Hurdy gurdy	2004–2008	E2–E6, depending on the tension of the strings	Any tuning system, mechanically moving the tangents	N/A	.../hurdygurdy.html
		Aeio	Aeolian cello	2007–2010	C2–G9	By default: 12-TET, various tuning systems depending on string overtone series and string material	N/A	.../aeio.html
Percussion Intruments	Idiophones	Simba	Cymbals, bass castanets and tambourine	2007	N/A	Not tuned	N/A	.../simba.html
		Casta uno	Castanets	2005	N/A	Not tuned	N/A	.../casta.html
		Casta due	Castanets	2007	N/A	Not tuned	N/A	.../casta.html
		Belly	Carillon	2002–2006	455–3200 Hz	Specific tuning	N/A	.../belly.html
		Vacca	Cow bells	2005–2006	A2–E6	Specific tuning	N/A	.../vacca.html
		Vitello	Cow bells	2005–2006	G#2–D6	Specific tuning	N/A	.../vitello.html
		Llor	Shell carillon	2004	highly inharmonic pitches	Specific tuning	N/A	.../Llor.html
		Tubi	Tubophone	2003–2005	C5–C8	24-TET	442	.../tubi.html
		Xy	Xylophone	2006–2007	F4–C8	24-TET	442	.../xy.html
		Klung	Anklung	2000–2006	C#3–A4	12-TET	440	.../klung.html
		Vibi	Vibraphone	2001–2010	C4–C7	12-TET	442	.../vibi.html
		Toypi	Toy piano	2008	C5–B7	12-TET	440	.../toypi.html
	Membranophones	Rotomoton	Rototoms	2000–2007	N/A	The tension of the drum skin of each rotomoton can be MIDI-controlled	N/A	.../rotomoton.html
		Troms	Single skin drums	2000–2004	N/A	Not tuned	N/A	.../troms.html

Table 1. Continued.

		Snar	Snare drum	2006	N/A	Not tuned	N/A	…/snar.html
	Chordophones	Player Piano I	An automaton designed to be placed on the keyboard of a piano	1994–1995	A0–C8	Depends on the tuning of the piano	N/A	…/playerpiano.html
		PP2	An automaton designed to be placed on the keyboard as well as on the pedals of a piano	2004–2006	A0–C8	Depends on the tuning of the piano	N/A	…/playerpiano.html
	Mixed	HAT	A hit anything percussion robot	2009	N/A	Not tuned	N/A	…/HAT.html
Noise Generators		Springers	Springs, a large siren, and shakers	2000–2008	siren: C1–C8	Not tuned	N/A	…/springers.html
		Thunderwood	Wood blocks, ratchet, wind chimes, thunder sheet, and various other nature related sounds	2000–2010	N/A	Not tuned	N/A	…/thunderwood.html
		Dripper	Droppers	2002–2005	N/A	Not tuned	N/A	…/dripper.html
		Flex	Dual automated singing saws and flexatone	2002–2007	N/A	Any tuning, not always predictable	N/A	…/flex.html
		Sire	Sirens	2003–2005	C3–C6	Any tuning	N/A	…/sire.html
		Psch	Thunder sheets	2006	N/A	Not tuned	N/A	…/psch.html

Although steady notes are impossible by design, flutter-tonguing is possible but can be dangerous if the repetition rate is higher than the mechanics allow.

Harmo, an Automated Harmonium

Harmo is a computer-controlled, six-octave reed organ with touch control, swells, and nine registers (see Figure 3). Harmo's point of departure was an old Emile Kerkhoff (1887–1956) suction reed organ. The 305 reeds and the key springs were kept from the original instrument. The bellows was replaced by an electric compressor. The organ was also equipped with two swells and a reflective tremulant mechanism.

Figure 2. Piston with Pyrex glass housing, detail of Puff.

Figure 3. The registers and the reflective tremulant mechanism of Harmo.

Figure 2.

Figure 3.

As this robot is tuned to 440 Hz, rather than 435 Hz as in Harma, it is more suitable for integration into the robot orchestra. Tubular solenoids with a diameter of 20 mm were used to activate the keys. They serve as levers to reduce the required force to push the pallets down. Because the magnets are wider than the distance between the keys (13.5 mm), they were mounted in alternating rows.

Experiments showed that the gradual opening of the dynamic shutters led to interesting sonic results. To achieve this, linear stepper motors with a threaded shaft were used. Although this approach makes a smooth movement possible, some extra noise is caused by the audible stepping frequency. The main advantage of this mechanism is that it draws no current to hold its position. The whole trajectory, from closed to fully open, takes about 500 msec, a sufficient rate for swell effects. For faster wind pressure changes, a stepper motor-driven wind valve is used.

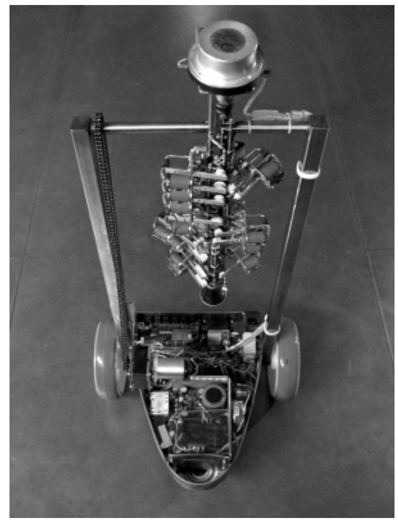
Various possibilities were explored for the design of the tremulant. The operation of the original tremulant is based on the acoustic reflection of sound on the large cardboard blades of a rotator. This approach makes use of the Doppler effect to create a subtle, but real, vibrato. Because autonomous control over the modulation frequency was desired, the original mechanism had to be redesigned and a reflector mechanism, driven by a variable-speed motor, was built. A low-power, low-noise DC motor from an old cassette recorder is used to drive the reflector.

Because full 73-note polyphony would have required the use of a 45-amp, 12-V DC power supply, and because the compressor would never supply enough wind to make all the reeds sound, the polyphony of Harmo is limited to 32 notes.

In contrast to Harma (the first automated reed organ), Harmo retains its original keyboard. As a consequence, it became possible to play the organ in the traditional way, either combined with automated playing or without. However, no manual alternatives for registration and expression control are planned.

The velocity control is less effective than, for example, on Bomi, as the speed by which the valves open in a reed organ is generally much faster than the rather slow build-up of a sound from the reeds.

Figure 4. Ob.



Monophonic Wind Instruments

Autosax, an automated saxophone developed in 1989, was the first member of the robot orchestra. Various other monophonic wind instruments followed: So, an automated sousaphone; Bono, an automated valve trombone; Heli, an automated Helicon; Korn, an automated cornet, Ob, an automated oboe, and Fa, an automated bassoon.

Previous attempts at Logos and elsewhere have, with varying levels of success, created artificial reeds and lips to act as computer-controlled pressure-regulated valves driving air column resonance (Toyota Motor Corporation 2003; Solis et al. 2006; Petersen et al. 2009; Wolfe 2011). After many experiments, all of Logos's monophonic winds except the Sousaphone (So) were outfitted with compression drivers and acoustic impedance converters that feed the drive signal to the instrument via a capillary, as suggested by Benade (1990) and others.

Ob, an Automated Oboe

A concert instrument made by the Belgian instrument builder F. Debert, probably dating from the first half of the 20th century, is the basis for Ob (see Figure 4). The general concept is to realistically automate an existing, unmodified instrument.

During the automation of Ob, the main concern was the silent operation of the electromechanical control of the levers. The fingerings were simplified in order to use as few solenoids as possible: six were used to close the open holes and seven were used for the essential levers. This simplification was possible because, although some levers are essential for performers, they are far less important in an automated version, as the attack of the tone is guaranteed by the nature of the sound mechanism. In the case of some levers, it was decided to automate the closing pad directly, instead of implementing a solenoid to activate them in the same manner as human fingers would. Special fingering tables for quarter-tone and other microtonal applications were developed, as were alternative fingerings to achieve different sound colors.

Several experiments were conducted to activate the double reed. Double reeds made of piezoelectric material glued to brass plates did not live up to expectations, as the sound pressure obtained was very low, even when driving the piezo-material well above its rated maximum voltage (35 V). For a second experiment, a double-faced piece of piezoceramic was bonded to a central brass plate and placed just touching an absolutely flat, thick brass plate with a 4.2-mm diameter orifice. This approach delivered a strong buzz, but with the sound quality dependent on the frequency as well as on the applied air pressure. A small, DC motor–driven vacuum-cleaner type of compressor produced the required pressure of about 15 to 30 mBar, but it was very noisy. Because this did not provide the desired results, a third experiment was conducted. A tweeter motor driver, made for driving an exponential horn, was coupled to an acoustic impedance converter modeled after a real reed in a human mouth cavity. The 12-mm-long cylindrical part fits inside the outlet of the RCA pressure driver, without touching the titanium dome inside. The other side fits nicely into the oboe, replacing the reed. The realism of the produced sound becomes highly dependent on the waveform applied to the driver. A trapezoidal wave shape, in combination with the proper articulation (frequency modulation of at least the first two partials above the fundamental as well as some amplitude modulation), delivers the most realistic result.

The entire automated oboe construction was suspended in a cradle so that the instrument is free to move in different inclinations and, in this way, mimic the behavior of a human oboist. To be able to control and, if desired, to hold a specific inclination, the axis of suspension is provided with a dented wheel driven by a chain and a DC motor with reduction gears. Movement is limited to an angle of about 90°. Multiphonics are not currently implemented in the firmware, although experiments have proven that they can be created via amplitude modulation of the driver signal.

String Instruments

At present only two string instruments have been developed: Hurdy, a two stringed automated bass hurdy gurdy and Aeio, an Aeolian cello.

Aeio, an Automated Aeolian Cello

The problems encountered during the construction of Hurdy led to many new ideas and experiments regarding acoustic sound production from bowed strings. In contrast to Hurdy, where the string is bowed, the strings on Aeio are activated through a magnetic drive (see Figure 5). Therefore, it is not necessary to send complex commands to specify envelopes for bow pressure, bowing speed, finger pressure, and bowing angle to determine the pitch, dynamics, and timbre of the notes.

Aeio has twelve hardened spring steel strings with a diameter of 1.5 mm. The strings are arranged chromatically and each can be individually "bowed" via the electromagnetic system. The soundboard was made from hardened brass mounted in a steel frame.

The strings are tuned from MIDI note 36 to 47, and each string is equipped with a felt-covered, solenoid-driven damper to enhance the expression possibilities. Each string can sound the fundamental, as well as the entire series of slightly inharmonic partials. Therefore, the range covers at least the ambitus of a classical cello, from MIDI notes 36 to 127. Aeio utilizes the same principle as an Ebow, but here the strings are brought to vibrate by

Figure 5. Aeio.

two electromagnets, driven by a two-phase signal on opposite sides of the string. The Ebow is an electronic device that generates an electromagnetic field, commonly used to move a string, such as on an electric guitar (Raes 2010d).

All the strings, or any combination of them, can play simultaneously. Vibrato and glissandi, although common on bowed instruments, are impossible on Aeio. It is also impossible to play fast staccatos or pizzicatos, as stronger electromagnets would be necessary and the operation depends on the excitation speed of the string, which always takes a certain amount of time.

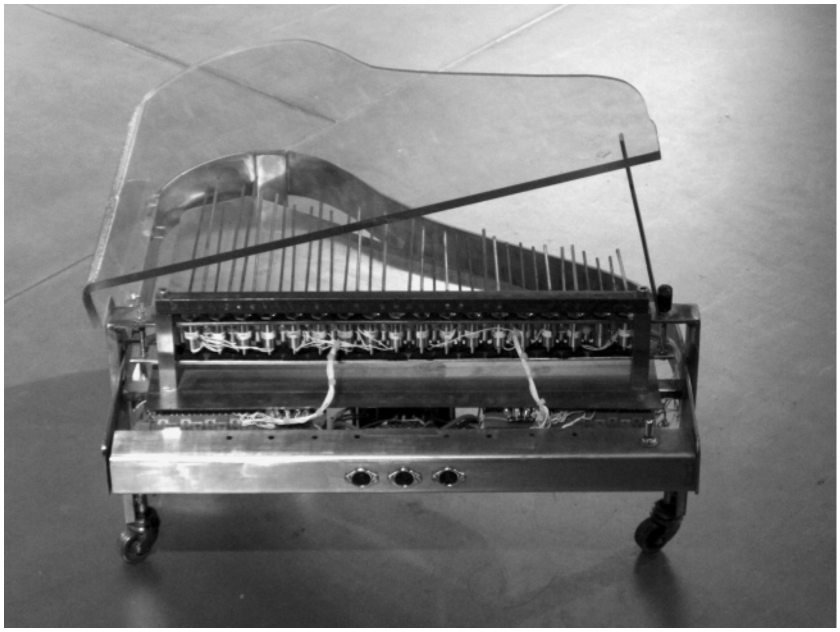
Percussion Instruments

The orchestra holds a wide range of non-pitched percussion instruments. The Rotomoton consists of five automatically tunable and playable rototoms of various sizes. Troms has a collection of seven single-skin drums from 7 to 70 cm in diameter. Each drum has different beaters. Hat is the most recent percussion instrument, and also the only robot that was commissioned for another artist, Aphex Twin. Various objects can be clamped onto this "hit-anything" robot, which will hit whatever is placed on it. Simba consists of a bronze bell cymbal, a couple of bass castanets, and a bell-rim tambourine without drum skin. One of the smallest automata, Snar, has a snare drum automated with 13 beaters from the inside and two drum sticks from the outside. One of the percussion instruments is integrated in another automaton: Casta Uno, consisting of 15 automated castanets, can be found on top of Vox Humanola. A separate automated castanet was built a few years later, Casta Due, as it was impractical to take Casta Uno in and out of Vox Humanola for specific setups.

Automated bells form the largest chunk of the pitched percussion family. For example: Belly, consisting of 34 automated brass bells; Vacca, consisting of 48 automated cow bells and its smaller brother Vitello, consisting of 36 automated cow bells; and Llor, the automatization of 11 stainless steel shells of various diameters and a single antique bronze bell of similar shape. This family also houses two quarter-tone instruments, Tubi, an automated quarter-tone tubophone, and Xy, an automated quarter-tone xylophone, as well as Klung, an automated brass angklung, and Vibi, an automated vibraphone.

Two player pianos, as well as a player toy piano, complete the pitched percussion section of the orchestra. The first player piano, Player Piano I, was developed in 1994. It is one of the oldest musical robots of the orchestra. As described previously, its design was based on the player piano of Trimpin (Perkis 1999) but whose the sturdiness and reliability were improved. In 2004 a new type of player piano, PP2, was designed. Like its predecessor, the PP2 is a mechanism that is placed on top of the keyboard

Figure 6. Toypi.



of a regular piano. It uses look-up tables to access a variety of velocity scales found in different brands of grand pianos. Different tables can be uploaded to the instrument. As the velocity sensitivity of a piano depends on its brand and condition, variable look-up tables allow PP2 to adapt to a specific brand of piano. With this instrument, the repetition rate, and the continuous control of the sustain pedal, exceed the capabilities of a conventional piano. The full 88 polyphony surpasses other player pianos such as Yamaha's Disklavier, whose polyphony is limited to 32 notes (Yamaha Corporation 2011).

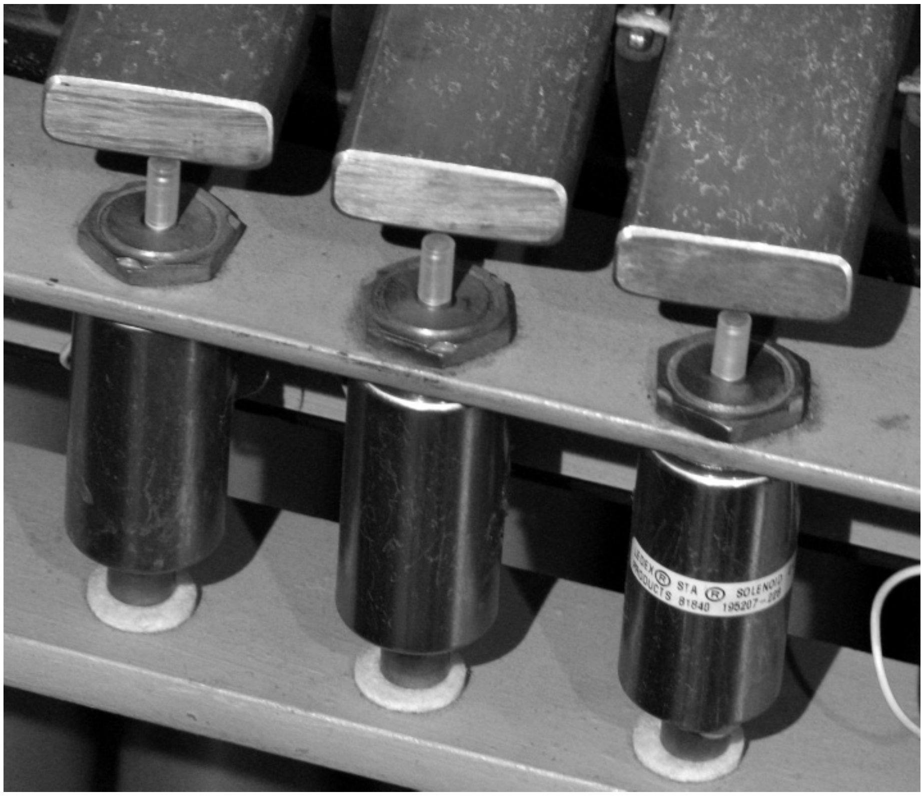
Toypi, an Automated Chromatic Toy Piano

Toypi, an automated chromatic toy piano, keeps the idea of the original instrument while doing away with the mechanics (see Figure 6). Toypi was created from a 35-note chromatic toy piano produced by Antonelli in Italy. Once the cover had been lifted, the clamped rods that were mounted on a cast iron bar were carefully removed. A new brass soundboard was created to replace the original plastic one. To preserve the typical sound, the original small wooden hammers were integrated into the new design. The keyboard and action were replaced by a tubular solenoid assembly. The general shape of the instrument's stainless steel chassis closely follows the typical shape of a normal grand piano. This automaton enables very precise velocity control and extremely fast repetition speeds, opening up new sonic worlds. The maximum sound volume is limited due to the nature of the instrument. As sound volume is inherently connected to the size of the rod assembly, louder sound would dictate thicker as well as longer rods.

Vibi, an Automated Vibraphone

Much similar work of instrument builders preceded Logos's Vibi (Darge and Soetaert 1994), and automations of vibraphones, xylophones, or glockenspiel can even be found in the large dance organs (orchestrions) from the interbellum. Vibi makes an appeal to these prior experiments and improves them by adding computer control, touch control, and individual dampers for each bar. At least one builder, Tim O'Keefe, has based his automatization of the vibraphone on Logos's Vibi (O'Keefe 2009).

Figure 7. Several Lukas Ledex solenoids that drive the beaters of Vibi.



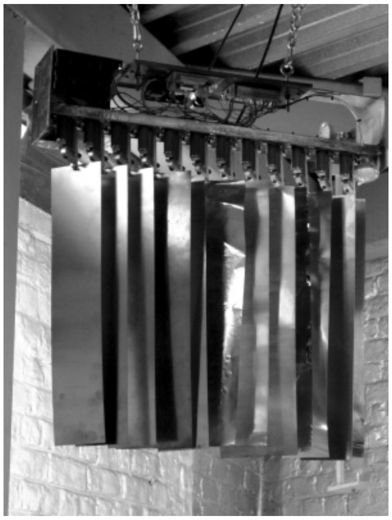
The construction of Vibi departed from a small-model Yamaha vibraphone (type YV-600B, serial number 1977) of which only the tuned aluminum bars and resonators were kept (37 notes, from C4 to C7). A new electric circuit was designed for the vibrato mechanism, as the original was too noisy and could not easily be computer controlled. The beaters are driven by Lukas Ledex solenoids mounted under the extremities of the sound bars (see Figure 7). The dampers were made with the same type of solenoids, but rubber and felt pads were mounted on the anchors as dampers. Because the anchors fall back on the felt-covered steel bars by gravity, there is no need to use springs.

Vibi enhances the musical possibilities of a vibraphone. As each individual beater has complete autonomy, the polyphony far exceeds that of a human performer, in which the number of notes that can be played equals the number of sticks. Each bar features individual velocity control and dampers. A new element, damper-hold mode, whereby the felt covered dampers can be pushed against the bars with a continuously variable force, was implemented for the first time in Vibi. This mode allows the bars to be struck while being damped to varying degrees.

Each row of resonators has its own rotating shaft. Two stepping motors were provided in order to control the rotational speed of the upper row (corresponding to the black keys of a piano) and the lower row (the white keys of a piano) independently over a wide range.

The ability to change sticks, as musicians are often required to do in contemporary music, was not implemented. This would have required at least another row of solenoids with softer beaters, and there was not enough space under the bars to allow for such an undertaking. Placing the solenoids above the bars would eliminate the possibility of manually playing the instrument in conjunction with the automated player.

Figure 8. Psch suspended from the ceiling of the Logos Tetrahedron.



Noise Generators

The orchestra has a large section of noise generators, many of which are newly designed instruments. The automaton Springers has a selection of shakers, springs, and one siren. Thunderwood automates, among other things, various nature sounds such as rain thunder, wind, and woodpeckers. Twelve small automated thunder sheets form Psch. Various singing saw or flexatone-like sounds can be produced by Flex, which can be considered a realization of Luigi Russolo's fifth category of "intonarumori": sounds obtained by percussion on materials such as metal, wood, skin, and stone. Another noise machine, described earlier, is Dripper, a MIDI-controlled rain machine that can precisely control the size and frequency of each drip. Sire is composed of 24 motor-driven sirens. The three-octave range of each siren is controllable with a resolution of 14 bits, which provides many possibilities for microtonal music.

Psch, an Electromechanical Noise Generator

Psch has a variety of small thunder sheets of graduated thicknesses that can be precisely shaken and can create a "reversed cymbal" sound and similar explosive noises, as are typically found in various types of contemporary music (see Figure 8).

The design consists of twelve driving solenoids with individual metal sheets of various thicknesses and sizes. Experiments showed that Martensitic stainless steel produced the most desirable sound. Hasberg and Lamifold stainless steel sheets were used in the final construction of the automaton. The maximum sound level is a function of the size of the sheets or foils used. The noise characteristics are merely a function of the material's thickness and stiffness, and the shaking speed is limited by the mechanical properties of the solenoids.

Psch can produce a steady noise by shaking the sheets at speeds exceeding the mechanical and very low resonant frequency of the pendulum system formed by the combination of sheet and solenoid anchor. Single strokes at high activation forces produce noise shots. However, when one strokes a thicker sheet, flexatone-like sounds with clear, sliding pitch content can occur.

Compositions

In addition to performances at external venues, the Man and Machine robot orchestra puts on a new thematic program at the Logos Tetrahedron every month. These concerts contain orchestrations of existing compositions and new pieces from Logos members or composers worldwide. A mix of sequenced, algorithmic, and interactive compositions is featured. Nearly all algorithmic pieces written for the orchestra are conceived for live performance, where the course of the piece can be adjusted in real time. Experimental dance is almost always an integral part of the performance.

The Man and Machine robot orchestra is designed with the idea of motivating other composers to write for the orchestra. MIDI templates are available to make composing for the orchestra more accessible.

Logos has premiered interactive, algorithmic, and MIDI-file-based pieces from national and international composers (see Table 2).

User Feedback

What makes the Logos orchestra unique is that a group of composers intensively and regularly

Table 2. Compositions Written for the Man and Machine Orchestra

Composer	*Number of Pieces*	*Interactive and/or Algorithmic (IA) or MIDI file (M)*
Mark Applebaum	1	M
Clarence Barlow	3	IA
Scott Barton	2	M
Rainer Boesch	1	M
Joachim Brackx	1	M
Sebastian Bradt	53	M
Barbara Buchowiec	31	M
Warren Burt	4	IA
Peter Castine	1	M
Claude Coppens	1	M
Moniek Darge	3	M
Kris De Baerdemacker	24	M
Joris De Laet	2	IA
Hanne Deneire	1	M
Ellen Denolf	1	IA
Giacomo Di Tollo	2	M
Moritz Eggert	4	M
Hiroshi Fukumara	10	M
Joe Futrelle	1	M
Frans Geysen	1	M
Piotr Groen-Korab	1	M
Carlos Guedes	1	IA
Bernd Haerpfer	1	M
Martin Herraiz	1	M
Dick Higgins	1	M
Aurie Hsu	1	M
Lukas Huisman	6	M
Jonas Jurkunas	2	M
Steven Kemper	1	M
Jonathon Kirk	1	M
Siegfried Koepf	1	M
Juan Sebastián Lach Lau	1	M
Kristof Lauwers	52	IA
Roeland Luyten	2	M
Michael Manion	2	M
David Maranha	3	M
Rytis Mazulis	1	M
Jelle Meander	4	M
Rene Mogensen	1	M
Fred Momotenko	5	M
Kostas Moschos	1	IA
Knut Müller	1	M
Phill Niblock	1	M
Frank Nuyts	1	M
Abraham Ortiz	1	M

Table 2. Continued.

Composer	*Number of Pieces*	*Interactive and/or Algorithmic (IA) or MIDI file (M)*
Daniel Pastene	2	M
Adrian Pertout	1	M
Godfried-Willem Raes	61	IA
Jaime Reis	3	IA
Jacques Rémus	3	M
Hans Roels	7	M
Troy Rogers	1	IA
Jeremiah Runnels	1	IA
Stephan Schleiermacher	9	M
Stefaan Smagghe	1	M
Thomas Smetryns	3	M
Ricardo Spiritini	1	M
Bruno Spoerri	1	IA
Yvan Vander Sanden	11	IA
Celio Vasconcellos	2	M
Jasna Velickovic	1	M
Francesca Verbauwhede	1	M
Xavier Verhelst	1	M
Maya Verlaak	1	IA
Dirk Veulemans	3	M
Brent Wetters	2	M
Caroline Wilkins	1	M

works with the orchestra, providing the builder with immediate feedback on how to improve the automata.

Sometimes adaptations of the hardware are necessary to fulfill the composers' requests. For example, the motor of Vibi, in its original design, stopped in an arbitrary position, but the final placement of the valves had an influence on the volume of the sounds produced. Position sensors were added to the rotating vibrato mechanism in order to always stop the motor in a position where the resonators are fully opened.

At other times, extra hardware is added. On a composers' request, squeakers were mounted on Thunderwood to create a larger variety of non-musical sounds, and audio inputs were added to the brass instruments in order to generate vocal instrumental sounds and multiphonics.

In some cases, adaptations of the software are sufficient. Initially, the woodwind instruments had a new fingering for each note. In the case of repeated notes, the fingering was released after each note and replaced for the following note. These unnecessary movements caused unwanted noises that could easily be avoided. Composer feedback led to an adaptation of the fingering, which is now maintained after each note until a new pitch is played. Not only did this adaptation remove the unwanted noises, but it also greatly improved the resonance.

Sometimes the adaptations increase user-friendliness. Instead of requiring the user to input the wind modulation separately for each note, Bomi's tremulant speed is now automatically repeated across notes, and the user only has to determine the modulation frequency as well as the range of pitches to which it applies. A similar adaptation is currently being implemented in the percussion instruments to facilitate drum rolls.

In the following paragraphs we will discuss six compositions demonstrating various ways that the automata can be controlled.

Kristof Lauwers's *Burden Birds* was composed as a soundtrack to a film by Lieve Vanderschaeve in which two birds fly through a mountain landscape, with light and weather conditions in constant flux. The light changes are musically reflected in the shifting overtone structure of the organs Piperola and Bourdonola, obtained by varying the wind pressure of each. The flapping of the birds' wings is translated into arpeggiated patterns with varying dynamics on Vibi, Puff, and Psch in a manner that emphasizes the essence of each instrument.

Like *Burden Birds,* Sebastian Bradt's *Intron Wenn* explores the novel capabilities of the instruments. At times, Bradt uses extended techniques to produce timbres uncharacteristic of individual instruments. At other moments, Bradt combines these uncommon timbres to create otherworldly composite textures. *Intron Wenn* takes advantage of the instruments' fixed positions to construct spatial gestures.

Xavier Verhelst has created many inventive orchestrations that highlight the unique sound colors of the robot orchestra. *La Romanesca* (from the 1575 *Dublin Virginal Book*) was a very popular song in the late Renaissance. Verhelst illuminates the different melodic or rhythmic ideas of each section of *La Romanesca* by using different groups of automata.

In Yvan Vander Sandens's *Hyperfolly*, an AKAI Ableton Performance Controller (APC-40), combined with his custom written software PIMP (Pike's Interactive Music Programme), is used to steer the automata. His aim was to use the APC as an integral part of the performance. Each button of the APC is mapped to a specific automaton. The performer's actions resemble those of an action-gamer, leading to a ritualistic performance wherein the audience tries to grasp the meaning of the performed gestures and their relation to the audible result.

Kristof Lauwers has worked together with Moniek Darge on a series of pieces in which audio signals and gesture data determine the resulting sound. As the title suggests, *Horizon for Three* features three performers on stage: Moniek Darge, Marian De Schryver, and Zam Ebele. Audio signals from Darge's electric violin and gestures of all three performers were mapped in the software program Pure Data to control the automata in various ways. The pitches played on the violin are mapped to pitches on the organ, piano, and vibraphone. Movements by the performers determine the wind pressure in the organs and the rhythms of the percussive instruments.

Raes's *Schroeder's Second Dream* highlights the advanced capabilities of Toypi in an interactive context. The extremely high repetition speeds of Toypi are thoroughly explored. The viola mimics the perceived pitches, which are not always equivalent to the scored notes owing to the high inharmonicity typical of toy pianos. The performers' gestures are captured by the Invisible Instrument, an array of radar/sonar sensing devices developed at Logos (Raes 1993, 2010b, 2010c). The captured gestures are mapped to various wind sounds produced by Thunderwood. As with all of Raes's compositions, *Schroeder's Second Dream* was realized with the real-time composition programming language General MultiTasker, which was developed at Logos.

Conclusion

Because of its reliability, its usability, and its "readability," we feel that the Man and Machine robot orchestra lies at the forefront of the development of musical robotics. The orchestra will further expand through the development of more monophonic wind and string instruments, as well as the development of instruments that use ribbons to replace strings, making acoustic, string-like instruments possible without an amplifying soundboard. Along with the addition of new automata, new devices in the field of gesture sensing and recognition will be developed. In this way the orchestra's tone color will be extended and the control possibilities will reach even further.

Acknowledgments

The Logos foundation is funded by the Flemish government, the city of Ghent, and the

Province of East Flanders. The authors wish to thank the various people working at Logos for their input. Troy Rogers's involvement was made possible by a 2009–2010 Fulbright Research Grant.

References

Benade, A. H. 1990. *Fundamentals of Musical Acoustics*. Mineola, New York: Courier Dover.

Captured! By Robots. 2011 "Captured! By Robots." Available on-line at www.capturedbyrobots.com/index.htm. Accessed March 2011.

Chang, Y. 2003. "(Toy) Piano Man Makes a Big Sound from Tiny Keys." Available on-line at community.seattletimes.nwsource.com/archive/?date=20030331 &slug=toypiano310. Accessed March 2011.

Chinen, N. 2010. "One-man band—Pat Metheny upgrades a 19th century concept." Available on-line at www.nytimes.com/2010/01/31/arts/music/31metheny.html. Accessed March 2011.

Coenen, A. 1992. "Computer-Controlled Player Pianos." *Computer Music Journal* 16(4):104–111.

Darge, M., and H. Soetaert. 1994. "Automatic Music." *Logos-blad* 16(8):5–10.

EMMI. 2011. Instruments. Available on-line at www.expressivemachines.org. Accessed March 2011.

Kapur, A. 2005. "A History of Robotic Musical Instruments." *Proceedings of the International Computer Music Conference*, pp. 21–28.

Karmetik. 2010. "Robotics." Available on-line at www.karmetik.com/labs/robotics. Accessed March 2011.

Louie, G. 2002. "Trimpin: Computers and Music—Meeting Held February 12, 2002." Available on-line at www.aes.org/sections/pnw/pnwrecaps/2002/trimpin. Accessed March 2011.

McNeill, B. 2008. "Instrument Beginning of 'Huge Robot Orchestra'." Available on-line at www2.dailyprogress.com/news/cdp-news-local/2008/jan/24/instrument_beginning_of_huge_robot_orchestra__01_2-ar-66848. Accessed March 2011.

O'Keefe, T. 2009. "Marv Web site." Available on-line at www.robovibes.com/physical. Accessed March 2011.

Perkis, T. 1999. "Taming the Elements with MIDI." *Electronic Musician* 15(12):110–113.

Petersen, K. J., et al. 2009. "Development of the anthropomorphic saxophonist robot WAS-1: mechanical design of the lip, tonguing, fingers and air pump mechanisms." *Proceedings of the 2009 IEEE International Conference on Robotics and Automation*, pp. 847–852.

Raes, G.-W. 1993. *Een onzichtbaar muziekinstrument*. PhD Thesis, Faculty of Arts and Philosophy, Ghent University.

Raes, G.-W. 1994. Spoken conversation with Trimpin. 24 October.

Raes, G.-W. 2010a. "A Composers Guide to the Logos Robot Orchestra." Available on-line at www.logosfoundation.org/instrum_gwr/manual.html. Accessed March 2011.

Raes, G.-W. 2010b. "Expression Control in Automated Musical Instruments. A Survey (1987–2010)." Available on-line at www.logosfoundation.org/g_texts/expression-control.html. Accessed March 2011.

Raes, G.-W. 2010c. "Namuda: Gesture Recognition for Musical Practice." Available on-line at www.logosfoundation.org/ii/Namuda_123.pdf. Accessed March 2011.

Raes, G.-W. 2010d. "4047 Ebow." Available on-line at www.logosfoundation.org/kursus/4047.html. Accessed June 2011.

Rémus, J. 2006. "Non Haptic Control of Music by Video Analysis of Hand Movements: 14 Years of Experience with the 'Camera Musicale'." *Proceedings of the 2006 International Conference on New Interfaces for Musical Expression*, pp. 250–253.

Rémus, J. 2011a. "Carillon n°3." Available on-line at jacques-remus.fr/carillon-3.htm. Accessed March 2011.

Rémus, J. 2011b. "Concertomatique n°2." Available on-line at jacques-remus.fr/concertomatique-2.htm. Accessed March 2011.

Rémus, J. 2011c. "Les Pic Verts." Available on-line at jacques-remus.fr/pic-verts.htm. Accessed March 2011.

Schläger, C. 2010. "Electric Motion Orchesters." Available on-line at www.christofschlaeger.de/instrumente.htm. Accessed March 2011.

Singer, E., et al. 2004. "LEMUR's Musical Robots." *Proceedings of the 2004 Conference on New Interfaces for Musical Expression*, pp. 181–184.

Solis, J., et al. 2006. "The Waseda Flutist Robot WF-4RII in Comparison with a Professional Flutist." *Computer Music Journal* 30(4):12–27.

Southworth, C. 2010. "Robots." Available on-line at www.ensemblerobot.org/robots.shtml. Accessed March 2011.

The Trons. 2011. "The Trons." Available on-line at www.myspace.com/thtrons. Accessed March 2011.

Toyota Motor Corporation. 2003. "Toyota Partner Robot." Available on-line at www.toyota.co.jp/en/special/robot. Accessed March 2011.

Trimpin. 2011. "Liquid Percussion." Available on-line at www.trimpinmovie.com/#/selectedworks. Accessed March 2011.

Weinberg, G., and S. Driscoll. 2006. "Toward Robotic Musicianship." *Computer Music Journal* 30(4):28–45.

Wolfe, J. 2011 "NICTA-UNSW Robot Clarinet." Available on-line at www.phys.unsw.edu.au/jw/clarinetrobot.html. Accessed March 2011.

Yamaha Corporation. 2011. "DC2M4 PE."Available on-line at usa.yamaha.com/products/musical-instruments/keyboards/disklaviers/grand_pianos/dc2mm4_pe/?mode=model#psort=hightolow. Accessed March 2011.