<Robodies>

At many occasions a have been asked how I came into starting to build musical robots as well as why the performances using them always involve nudity. So the time might have come to dig into the past, excavating personal memory a bit.

Presumably my oldest exposure to new music dates back to 1958 at the occasion of the World Exhibition held that year in Brussels. I was only a six years old boy than, but my parents did sing in a choir that had to perform many times in concerts organised at the exhibition. They took me along and dropped me in the kindergarten there for the duration of the rehearsals and performances. The ladies that took care of the children there however happened to only speak French. I remember very well that I started crying as soon as they addressed me. I spoke only Dutch and German. As they had no idea as to how to handle me in their kindergarten, they took the initiative to send me off to the Dutch pavilion on the exhibition grounds as there for sure, Dutch was spoken. And, sure enough the ladies there could handle me. They posted me on the first row in the pavilion and thus I had the extreme privilege of experiencing -through eyes and ears- Edgar Varese's Poeme Symphonique many times in a row and on different days. This was the famous Philips Pavilion designed by Le Corbusier but in reality realised by Iannis Xenakis. Needless to say I didn't know these names at the time but the environment left me deeply impressed.

Also in 1958 it was that I got enrolled in the Ghent music conservatory to study the piano. At home we had two pianos -tuned a quarter-tone different, not for the sake of performing quarter tone music, but by accident as one of them was and old but expensive instrument with a wooden frame that could not be tuned to A=440Hz properly whereas the other one was newly bought, for my parents were convinced that listening to the old piano and playing it, would ruin my hearing. Hence the old piano was taboo and I had to do all practising on the newer instrument. I wasn't too bright at it and remember very well that I only wanted to practice if the lid of the piano was taken off completely. I wanted to see the little ducks -my vision as a child on the felt hammers striking the strings- moving as my hands were touching the keys. Mechanics must have fascinated me from early on.

The year 1958 had some importance for yet another unrelated reason: it was the year the Russians launched their Sputnik, the first human object in outer space. I found the idea that it was sending beep-beep messages to planet earth puzzling. Also, I had seen the Sputnik in the Russian pavilion on the world exhibition, as well as the American H-bombs in the USA building... The Russian Sputnik looked so much more friendly than anything I remember from the Americans.

A year later, we moved to a new very large house right across where the laboratories of the Ghent University were situated. I sat for long hours in front of their halfway below street-level windows, just watching the technicians soldering components, performing all sorts of measurements as well as glass-blowing for the chemistry labs. One day, I got a present from one of the engineers. A nice looking component with two wires and coloured rings. I still remember them: red, red, yellow, silver. I asked the man what it was and what it served for. He answered me that it was something as used in the Sputnik. I was all euphoric and made a holstered box to store the component as if it were a precious jewel. I started getting really interested and intrigued by electronics. Soon enough I got to learn that my precious component was a resistor, 220k Ohms in value. By reading typical do-it-yourself boys books, I learned how to build my first radio. With a gallenium crystal, a self wound coil, a crystal earphone and some capacitors and resistors.

Not too many years later, I had build vacuum tube radio's, a tape recorder, amplifiers and, together with some friends at school, a broadcast station working on the FM band... We got it up and working but soon enough the police fell in and confiscated the device. We learned broadcasting was illegal. As we were young boys, the case was closed without further consequences except a talk with the parents, who could barely believe we succeeded doing such things...

As the house we were living in was really large, my parents rented out a room to a university student. That student, Raymond Van Soens, was enrolled for engineering and in his spare time worked quite a bit in the electronic music studio of the university. At some point the entire wall in his room was filled with suspended pieces of 1/4" recording tape. That's how I came in contact with the studio itself as well as with the electronic equipment involved. The IPEM studio, as it was called, organised also new music concerts that I never failed to assist. They deeply influenced my musical preferences and sense for sonic adventure.

At the conservatory at the other hand, things were going very slowly. There was not the slightest trace of adventurous new music there. It was another and very narrow world, unrelated to the real and lively world outside. I gradually lost interest in the piano for two distinct reasons: first of all, the piano teacher, Maurits Deroo, couldn't refrain from sliding his hands into my pants whilst 'teaching' me to play – he was clearly a paedophile abusing me- and secondly, I developed a strong preference for mechanical playing as opposed to the 'emotional' and 'romantic' way I was supposed to use. Technically I went only as far as learning to play Bach's 3-part inventions pretty well and furthermore Bartok's Microcosm. I hated anything romantic and refused to play it. Later on, I made a move towards the clarinet and later to percussion.

The academic year 1968-69 however caused quite a stir. A small group of students gathered together around ideas radically opposed to these underlying the conservatory. We found that the conservatory -and with it the entire world of so called classical music- was merely reproducing the past. There was not even the slightest concern about newly created music. At the academy of fine arts however, it was considered trivial that students would paint their own paintings rather than attempting to copy and/or reinterpret the great masters of the past. Why weren't things going like this at the conservatory? Thus I took the risky decision to refuse to recreate the past and instead called out the will to play exclusively contemporary music from that moment on. I started delving into contemporary music scores from abroad and took contacts with young and experimental composers in other countries. Thus we started performing music by people such as Robert Ashley, David Behrman, Cornelius Cardew, John Cage, Frederic Rzewski, Karlheinz Stockhausen, Richard Orton, Mauricio Kagel...
Soon we concluded that writing our own music would be even a step further and the most radical move into the contemporary we could make. Thus I wrote a composition for the ensemble called 'Logos 3:5'. That piece, scored for five musicians (piano, cello, violin, oboe, flute) required all musicians to play in a different tempo. The five tempi were only related to each other by prime number relationships. As it was nearly impossible to perform the piece without some form of strict coordination, I designed an electronic conducting machine. As came out later on, in fact my very first robot in a way. The tempi -fully programmable on the machine- were indicated to the performers using flashing coloured lights on stage. The performance looked a bit like a disco, although that phenomenon didn't quite exist yet at that time. The piece caused a big controversy at the conservatory, a controversy that did even resonate in the local newspaper. Its music critic headlined 'In cauda venenum...', as my composition was performed at the very end of the concert. The musicians were nicknamed the Logos group and there were even protests of teachers and conservative students against us. However we went on and started working under the name 'Logos workshop'. The conflicts with the conservatory increased and finally, around 1970, we were all kicked out. Logos was born.

So, I had decided to devote my life to new music. Not only did Logos study, create and play it, but also we though that we could not undertake this in isolation. Therefore we also started organising concerts wherefore we could invite artists working along similar lines from abroad. At that time I was elected president of the University Music Club and thus could make use of some subsidy to make this possible. In 1969 I enrolled at the University for studies in musicology and got the degree in 1973.

Several years in a row, from 1970 on, we followed the Ferienkurse fuer Neue Musik in Darmstadt. It's there that we made intense contacts with people such as Warren Burt, Horatio Radulescu (+), Claude Vivier (+), Ladislav Kupkovic and many others.

Although we had made the decision to go for new music, more and more as time went by, we started realising that we were doing this mainly making use of instruments of the past. We came to the insight that this was pretty absurd: as if in our time the perfect tools for musical expression could still be violins, oboes... all instruments developed in the 18th and 19th century. Moreover, the kinds of sounds we were to produce on our instruments more often than not seemed to contradict the nature of these instruments. After all, knocking on a violin sound board isn't really too healthy for the instrument, neither is preparing piano's at the end a valid solution in the quest for new sonic materials... As a consequence we developed the idea that new music calls for new tools for musical expression, read new instruments. And here it is that the knowledge I had acquired in electronic design came in. It seemed obvious that the material to use for new instruments had to be electronics. Not the kind of electronic equipment they had in the studio for electronic music, as that equipment was not useful for performing, but only for the realisation of tape-music. Live-electronics were what dictated the show. So I went off designing all sorts of analogue electronic equipment: voltage controlled oscillators, filter banks, ring modulators, envelope shapers, sequencers, delay lines, programmable mixing boards... I took them on the road and the Logos group used them extensively although not exclusively during our many concerts in the seventies.

By the end of the seventies though a new insight arose, in part also caused by the admiration we often got from audience members for the apparent fact that we could handle all that complicated equipment. Such praise had nothing to do with the music we wanted to make heard and it made us think critically about our endeavours. Two main problems came floating above after a thorough analysis. First the actions we were performing whilst playing on stage (changing patch cords, turning knows, pushing switches and moving sliders) were completely unrelated in any intuitive way to what could be heard. As a matter of fact, in analogue electronics you often have to prepare a patch by setting all sorts of knobs -without auditive result- and only after that you move the volume slider up and the result can be presented. Such actions lack even the slightest bit of gestural involvement in sound production and thus undermine the rhetoric inherent to musicianship. After all, if we would have play-backed all our concerts, it would probably not have made a difference to the audience and it would have saved us all the hassles of setting the equipment up properly. But a second criticism went even deeper into the problems inherent to live-electronic music. By necessity all sound has to come from loudspeakers. Now a loudspeaker is nothing but a piece of cardboard set into motion by a coil placed in the magnetic field of a strong permanent magnet. If you hear an intriguing sound from a loudspeaker, watching the speaker does not bring you the slightest step further into deciphering the nature of the sound heard. The loudspeaker virtualises the sound. The use of loudspeakers on stage, in particular in the case of electronically generated sound, causes a dissociation between the musician and his utterances. This undermines again the rhetoric of the concert as a social ritual. It undermines the musicians chances to convince, let alone to seduce. . A loudspeaker can merely be undergone.

As a radical outcome of these insights, Logos decided to give all electronic equipment used hitherto a fixed place in our electronic music studio and to use it only for the production of tape music, records and radio broadcasts. That was around 1977.

But rather than going back to using old and classical instruments, we decided to point our research into the direction of acoustic projects and instruments. This lead in the late seventies and early eighties to the creation of projects such as the Singing Bicycle Symphony and the large scale 'Pneumaphone' project.

These projects, although very successful, however left me with a frustration. The instrument and the composition in these cases in fact coincide and cannot me separated. Read, it is barely possible to imagine any other piece to be performed using the Pneumaphones than exactly the Pneumaphone project. The same for the singing bicycles: just about any project imaginable using these devices would sound like my symphony.

What these project lacked was the universality of the musical instrument as a tool for musical expression. With this aim in mind, I started considering the construction of musical robots: acoustical sound sources controlled by electronic circuitry. But, before starting to build the robots as they are known today, I made a side-step somewhere in between: the 'Hex' project. For this project I made a set of about twelve pretty small electro-acoustic modules, to be suspended very near to the audience. Each module contains real physical objects (pieces of spring, membrane, tines, string, plates...) set into motion and vibration via computer controlled electronic circuitry. The Hex project was build up with portability in mind and indeed, we did travel all over the world with it. The sounds although purely acoustic in nature, needed to be amplified in order to make them heard. So we couldn't drop the loudspeakers. The main advantage in 'Hex' was in the richness of the sounds as opposed to the inherent poverty and one-dimensionality of purely electronic sound. Also the computer control paved our path towards the development of much larger and fully acoustical robots later on. 'Hex' was in fact a miniaturised robot orchestra for its own sake, although I have used it only for one single full evening show and some audio art installation projects.

In the early nineties, the construction of large scale acoustical robots took off rather slowly. The oldest robot being Autosax, an automated C-melody saxophone, started in 1989. By the end of the 20th century we had only about seven robots up and running.

We were dreaming about the possibilities of these musical robots, but at the same time had to overcome another very fundamental problem. By using robots the problem of musicianship is in no way solved. Although automating the instruments frees the musician from the mediaeval aspects of craftsmanship, it cancels him out to a great extend as a performer. The music itself can be fully automated without a need for a performing musician.

No matter what musical instrument we can think off, invariably it requires bodily involvement from the musician: bowing, pushing keys, blowing, beating, shaking... are all motoric actions essential to cause a traditional musical instrument to sound. No action, no sound. However these motoric actions in the case of traditional instruments are very specific and pretty difficult to master well. The very fact that we move for making sound, is what makes attendance to a live concert performance into a meaningful ritual. Long before we started the project of the robot orchestra, we developed a system capable of detecting body motion and gesture using Doppler sonar as well as radar technology. The 'invisible instrument' is a completely wireless system based on detailed analysis of reflected waves by the naked human body if exposed to ultrasonic or microwave radiation. The recognition software is largely based on fuzzy logic for classification of gesture properties. A defined set of ten to twelve expressive gestures can be recognized. Namuda dance technique requires a mutual adaptation of the performer and the software parameters. Namuda stands for naked music dance. In order to make the study of Namuda dance possible, we have designed a series of études in which each single gesture prototype can be practised. Since visual

feedback to the performer is very problematic in the context of performance, for it greatly hinders freedom of movement and is by nature too slow, we have opted for auditory display. In the early versions of this technology (applied in productions such as 'A Book of Moves' (1992) and 'Songbook' (1995), wherewith we travelled all over the world) we used samplers and DSP voice processors as sound production engines, depending on loudspeakers.
The robot orchestra as we later designed and built, nowadays makes a very good platform for such auditory display, particularly since the sounds are not virtual (loudspeakers) but real acoustic sounds emanating from real physical objects. In fact just about any musical instrument can be seen as an example for auditory display as it by its very nature truthfully converts a certain subset of fine motor skills and gestures into sound. The gestures underlying music practice may very well constitute a basis for the embodiment underlying the intelligibility of music. The motor skills and gestures entailed by playing traditional musical instruments are obviously instrumental in nature. They are dictated by the mechanical construction of the instrument. Therefore, as an extension of the body, an instrument can, at most, be a good prosthesis. By removing the necessity of a physical object, the body becomes the instrument. But this in no way removes the need for motor skill and gestural control. In our software, at the time of this writing, the circa ten gesture prototypes we can clearly distinguish are: speeding up, slowing down, expanding, shrinking, steadiness, constancy of speed, collision, theatrical collision, smoothness, edginess. For exact definitions we refer the reader to our scientific papers on this topic.

Each gesture prototype can be mapped to a different subset of responding robots. In this respect, the study of Namuda gestures is quite similar to the study of any musical instrument. A certain level of fine motor control has to be developed in the player. Only once that level has been reached can the recognition software be modified by changing the parameters slightly. One would never buy a new and better violin for a child every time it makes a handling and playing mistake. Only once it knows the basics reasonably well should buying a better instrument become an option. Fortunately, in the case of the invisible instrument, we do not have to buy a new instrument but we can improve the software and adapt it to the player. This last possibility opens a whole new perspective for future developments in instrument building.

As said, the development of the invisible instrument, both in hardware and software, during the last 25 years ran in parallel with the design and the construction of the robots that make up the robot orchestra, today consisting of 60 robots. The robot orchestra basically consists of two categories of automated musical instruments: at the one hand we have novel sound sources and noise makers and at the other, existing musical instruments that we attempted to automate as fully as possible including many extended possibilities hitherto unimaginable to achieve from the same instruments when played by humans. Classified along organological criteria, this is an inventary listing of the entire robot orchestra as of today:

Pipe-organ robots using flue pipes:

- Piperola (a flute register with some added small percussion, 1996/2005)
- Bourdonola (a bass register with large wooden pipes, 1998-2005)
- Puff (a novel quartertone air-puff driven organ, 2004/2010)
- Qt (quartertone organ with a six octave range, 2005-2007)
- Bomi (closed wood pipes and conical valves, 2009/2010)

Pipe-organ robots using single-reed pipes:

- Vox humanola (vox humana register with castagnets, 1995/2005)
- Trump (trumpet register, 1999-2004)

- Krum (krumhorn register, 2005/2006)

Pipe-organ robots using membrane driven pipes:

- Klaks (an assembly of compressed air ship and car horns, under construction)
- Hybr (hybrid electroacoustic organ using membrane driven pipes, 2014/2015)

Reed organs:

- Harma (harmonium, 2000/2005)
- Ake (accordion-robot, 2004-2008)
- Bako (bass accordion, 2006/2007)
- Melauton (melodica, under construction)
  Harmo (large-scale harmonium, 2009/2010)

Cavity resonator driven pipes:

- Whisper (cavity resonators with some added percussion, 2013)

Tuned percussion robots:

- Klung (automated brass angklung, 1998)
- Vibi (automated vibraphone, 2001)
- Xy (automated quarter-tone xylophone, 2007)
- Tubi (automated quarter-tone tubophone, 2003/2005)

Robotic bells:

- Belly (automated mini carillon, 2002/6)
- Llor (automated stainless steel shells, 2004/2005)
- Vacca (48 automated cowbells, 2005)
- Vitello (36 automated cowbells, 2006)

Plate driven percussion robots:

- ThunderWood (intonarumori robot with nature sounds, 2000/2006)
- Flex – automated singing saws, 2002/2003)
- Psch (12 small thundersheets, 2006)
- Simba (cymbal robot, 2007)
- Ribby (ribbon-string instrument, 2011/201x – under construction)

Rod and spring driven percussion robot:

- Toypi (automated chromatic toy piano, 2008)
- Rodo (31 bronze rods, 2014)
- Springers (very large and long springs as well as a large siren)
- Rumo (noise robot, 2014)

Wooden percussion robots:

- Casta Uno(15 castagnets, 2004, integrated in Vox Humanola)
- Casta Due (16 castagnets, 2007)
- Temblo (12 templeblocks and ratchet, 2013)
- a set of woodblocks is also integrated in Thunderwood.

Drum robots:

- Rotomoton (automated rototoms, 2000-2007)
- Troms (drum robot , 2000/2004)
- Snar (automated snaredrum, 2006)
- Hat (hit anything robot made to the order of Aphex Twin, 2009)
- Snar_2 ('Robosnare', automated snaredrum ordered by Aphex Twin, 2014)

Piano-robots:

- Player piano (piano robot #1, 1994)
- PP2 (piano robot #2, with pedal, 2005)

Robotic bowed string instruments:

Hurdy (dual stringed bass hurdy gurdy, 2004/2007)

- Aeio (aeolian cello, 2007-2011)
- Synchrochord (fretted monochord with synchronous excitation, 2011/2014)

Robotic plucked string instruments:

- Spiro (automated spinet, 2011)
- Zi (plucked zither or Qanun, 2014, under construction)

Robot brass instruments:

- So (sousaphone robot, 2003-2007)
- Bono (automated valve trombone, 2007-2010)
- Heli (automated helicon, 2007-2008)
- Korn (automated cornet, 2008-2010)
- Horny (automated horn, 2013)

Robot single reed wind instruments:

- Autosax (saxophone robot, 1989-2009)
- Klar (automated alto clarinet, 2012)
- Asa (automated alto saxophone, 2013)

Robot double reed wind instruments:

- Ob (automated oboe, 2008-2010)
- Fa (automated bassoon, 2009 - 2012)

Siren robots:

- Sire (24 automated sirens, 2005)

Dripping robot:

- Dripper (a rain and dripping robot, 2002/2005)

Conducting robots and tools:

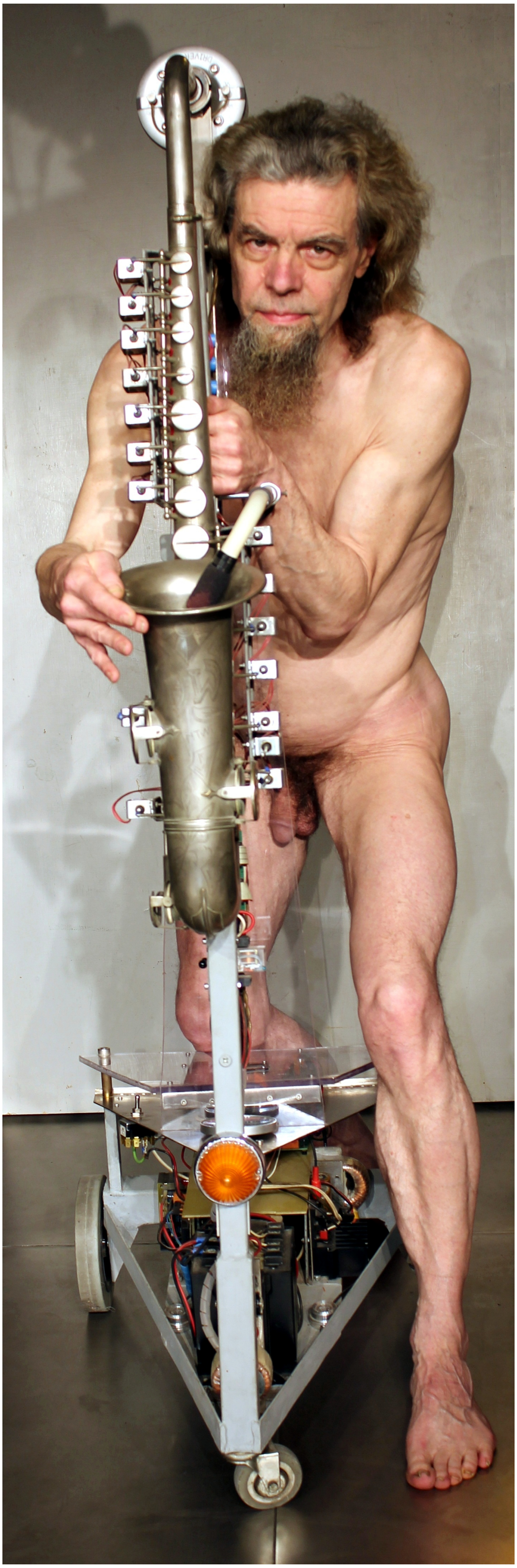
- Polymetronoom (conducting machine, 1969/1994/2012)

- Saf (mains isolated power supply unit for the entire orchestra, 2013)
- Display (two programmable displays, 2014)

As all gesture controlled uses of the robot orchestra require the performers to be naked, we were dreaming for a long time of devoting a book to the idea of 'robodies'. Each of our robots would be photographed together with a human nude, not a photo model. Nudity has always been an important bias in my artistic work, not only for its functional necessity, but also ideologically. All robots are designed by me to be naked, that is, readable in all respects. None of the components are hidden nor boxed but very much on purpose fully exposed to sight. All their functionality is thus revealed to a maximum extend, even if this makes them slightly more vulnerable.

On the pages following, the reader will find, side by side, a single page description of one of the robots as well as a picture of that robot in relation to a human nude. For the present publication we left out all technical details, design considerations, circuit drawings, maintenance instructions and guidelines as these are available in full on the Logos website.

We express our thanks to all people that helped us out to realize this project. As we do not want to tag the people individually in the pictures, we name them here as a group: Dominica Eyckmans, Emilie De Vlam, Marjolijn Zwakman, Moniek Darge, Angela Rawlings, Andrea Urbankova, Sebastian Bradt, Zam Martino Ebale.



<Autosax>

This instrument is an automated and computer controlled acoustical saxophone. It is one of the very first automated instruments we designed and its building history, starting off in 1989, went through four very distinct phases, each realizing a different approach to the problems posed by properly automating a saxophone. In the very first version, the sound production relied on computer controlled acoustical feedback in the bore of the instrument. This version was dropped for the response was sluggish and the pitch produced quite unreliable. The second version used a compression driver driven by a frequency synthesizer. This version was evaluated as very reliable, but soundwize, far away from anything like a realistic and convincing saxophone sound. The thirth version (2007) used a quite sophisticated automated reed mechanism. The sound was indeed very good and it was also capable of producing a wealth of multiphonics, slaptongues and other special effects. The sound production was realized through an acoustical but computer controlled two-phase reed mechanism using a compressor for the wind supply and a fast regulating conical valve for expression control. This version was dropped in 2009 mainly because the ambitus was limited to the lowest octave. The range below the 'normal' range actually sounded best and hence we extended it in the Midi support down to midi note 0. However, we never got the instrument to overblow properly and reliably... The new sounds the mechanism could produce were a bonus, but quite unrelated to the saxophone itself. For this reason, we decided to save the sound production mechanism for a future project and a novel robotic instrument. The fourth version took of shortly after our quite successful realizations of brass instruments (<Korn> the cornet, <So> the sousaphone, <Heli> the helicon and <Bono> the trombone) as well as <Ob> the automated oboe, making use of acoustical impedance converters driven by a compression driver and a capillary conduct. For this version we carried out many experiments using acoustic impedance converters. In a first design we made the acoustic impedance converter such as to mimic as well as possible the behavior of the original mouthpiece with reed. Thus, instead of using a circular capillary channel driving the saxophone, we used a small slit. The whole construction was made from massive staff brass material on the lathe, the slit filed out manually. A quite inexplicable side effect of applying this construction to the saxophone, was that it lowered the whole tuning of the instrument by a minor thirth. Thus the C-melody saxophone came to behaves like an A instrument. In the last and most successfull experiment so far, we used a regular capilary again, but with a much reduced traject as compared to the first version. The saxophone now behaves again as a C instrument...

The lightbulbs -clearly visible on the picture- are not just a visual feature but serve as voltage dependent resistors in series with the solenoid valves controlling the keys, thus preventing overheating of the coils when many keys are opened and stay opened for a long time. Different and non standard fingerings can be applied, leading eventually to multiphonics, particularly if the feedback mechanism is in use.

The instrument uses 3 PIC microcontrollers, one is a DS type used for the reed control, the tuning and the intonation, one taking care of the keys and one for the volume and feedback levels.

The normal note range is 45 to 72, but due the possibilities of the reed mechanism, we provided in an extended range in the low end, descending down to even below midi note 33. Of course users should not expect a realistic C-melody saxophone sound from this range. The sounds produced in this extended range are far too interesting -although not as good as those produced in the thirth version of the robot- to leave them out of the range of possibilities. High notes are implemented up to midi note 93, but again, in this range users should not expect any realism.

The development of this robot took us some 20 years and <Autosax> has known 4 different working realizations in its history. At the time of this writing, 2010, we are at version 4, and version 5 may be coming...

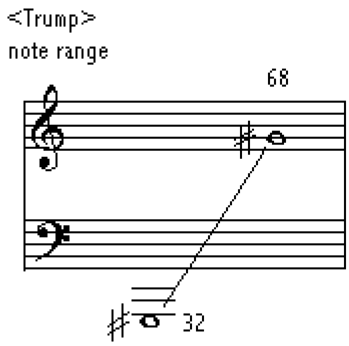
<Trump>

The design of this musical robot started with an old trumpet register taken from an early 19th century organ. Nearly all resonators, made of the infamous as well as anachronistic pipe metal (lead / tin) where smashed, rendering plans for restoration idle. The only parts we kept were the reeds and the shalots. The pipes give out in a large exponential horn constructed from stainless steel, and common for all pipes. The concept of this automaton is more or less the exact opposite of what instrument builders in previous centuries always attempted at: homogeneity of timbre over the entire compass of the instrument. Here we on purpose gave each pitch a timbre of its own. Therefore we calculated a series of small conical horns, such that the lowest sounding notes get the smallest cone, going slowly up in size to middle C and from there on down again up to midi note 68 (A). In the higher part of the register, it sounds very much trumpet like, whereas sharpness of tone color increases with decreasing pitch. The exponential horn homogenizes the sound to a certain extend but, more important, guaranteed a loud and very well projected, slightly agressive sound. The notes are switched in the windchest with electrical pallets, solenoid driven. Wind pressure control is possible, although as can be expected from single reedpipes, does not preserve tuning! Maximum wind pressure is 300mm watercolumn and generated by a Laukhuff Ventus-type organ blower driven by a programmable Hitachi motor controller. The entire circuitry for this robot makes use of a single fast PIC controller: a Microchip PIC18F252 - I/SP type. This controller takes care of the midi input parsing, the note on/offs for the latches, Mosfets and solenoids as well as of the PWM for the 3-phase motor controller, via an optoR (LED/LDR combination) coupler.

The circuit is assembled on a single eurocard and includes the 5V dc power supply (500mA) for this board as well as for the note latch boards.. The component specified as OptoR in the schematic is an encapsulated combination of a LDR and a small bulb or LED. For the housing we used the case of a very ancient 27MHz crystal, since this could be made completely lighttight and yet be opened again for possible replacement of the bulb or bright white LED. The use of an LDR here gives us signal integration for free, since these components are inherently very slow reacting devices. The construction further guarantees us complete galvanic separation between PIC board and associated electronics and the 3-phase motor controller. The use of a microcontroller obviously greatly simplifies the schematic and the circuitry required. The ingenuity is now required on the level of the software design for the PIC controller. We confined this task to our collaborator Johannes Taelman.

The power supply, although designed to cope with peak currents of over 7 A at 15V, was very straightforward, using a linear regulator mounted on a large heatsink.

Midi note range: 32- 68. (G#-g'#)



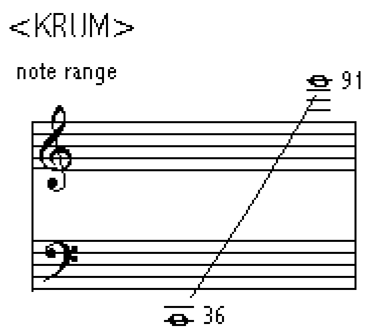
<Krum>

The design of this musical robot started with an offer found on the August Laukhuff website for a Krummhorn 8-feet register made with full length wooden resonators and shallots. Oak and mahagony wood is used for the resonators. The resonators have regulating flaps. As for the Krummhorns with metal resonators, the resonators with narrow scales in the bass must be shortened, while those with large scales can be built in full length. Narrow tapered and cylindrical shallots are suited. Since we desired wooden shallots, the blocks and boots are also made of wood. The sound was designed such as to be soft and reedy, very rich in overtones. It promised to become a viable alternative for our [<Vox Humanola>] at the one side, and an excellent gradation of the latters sound in the orchestral spectrum of the complete <M&M> orchestra.

In the <Krum> robot we designed around this register, the notes are switched inside the windchest with electrical pallets, solenoid driven. Wind pressure control is possible, although as can be expected from single reed pipes, does not preserve tuning! Maximum wind pressure is 85mm watercolumn and generated by a 130Watt Laukhuff Ventus-type organ blower driven by a programmable 3-phase motor controller from Siemens. Air production is 3 cubic meters a minute. Normal working pressure should be 75mm watercolumn. A manometer is mounted on the windchest such that monitoring of pressure is easy.

The entire circuitry for this robot makes use five fast PIC controllers: Microchip PIC18F2520 - I/SP types. For each group of 16 notes, a controller takes care of the midi input parsing and the note on/offs, mosfets and pallet valve solenoids. A fifth PIC microcontroller takes care of the steering of the windvalve as well as of the motor commands and the PWM for the 3-phase motor controller.

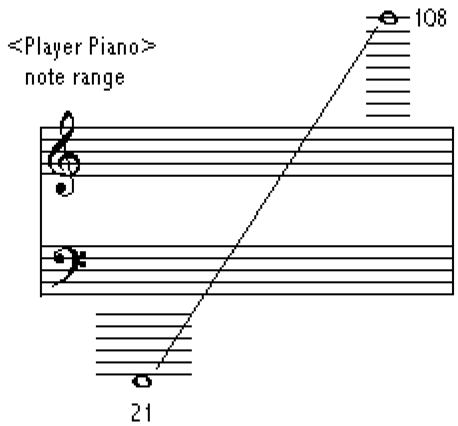
Mapping:



<Player Piano>

The player piano is one of the oldest musical robots build and developed at the Logos Foundation. We spent many years of research into automating pianos. Our designs started with the already very elaborate design by our friend and colleague Trimpin, who worked on his design whilst in Holland at the conservatory with Floris Van Manen. Improvements we realized in our first design are mostly related to sturdiness and reliability. All technical details with regard to building and design of player pianos can be found in our course on experimental music. In 2004 we started the design and construction of a completely new type of piano Vorsetzer (Player Piano II) , of course building further on the experience gained in the first designs. The new model makes use of 9 PIC microcontrollers, one controller for every group of 10 piano keys. It has an even better dynamic resolution and can be adapted via uploadable lookup tables to many different types of grand pianos. Because of the very fast PIC controllers, polyphony is even better than in the previous design, although that also was 88-note polyphonic, but suffered a bit from the serial design bottleneck problem. The only element limiting polyphony in the new design is the capacity of the power supply. A full fff cluster on all keys together requires some 150 Amps of current... The newly designed player piano was finished in July 2005 and baptized <pp2>. In 2006 we improved the PCB's for player pianos by increasing the density. A single board of the new type can take care of 14 notes. So for a complete piano, only 7 boards are required. These boards use a Microchip PIC type 18F4620. Assembled boards with programmed PIC's for player piano are available from the Logos Foundation. The special rubber feet required to fit on the anchors of the solenoids and designed by us in 2006 are available as well. In 2014, a new board as well as new firmware -covering an octave- was designed. These boards are quite a bit cheaper in production.

Musical range:

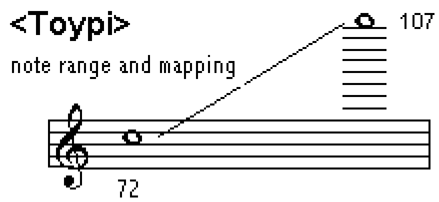


In the latest model, <pp2>, the key controlling electronics could find a place in and on the Vorsetzer chassis itself. Only the hefty power supplies (24V and 12V 1200Watt) remain in a separate box to be placed under or inside the piano. Therefore, the mechanism is slightly heavier than the first model. The power supply is a lot lighter (ca. 5kg) than the control computer used for player piano 1. The new power supply fits in a normal attaché case. A mechanism to operate the right pedal is available as well and is conceived as a separate robot. This pedal can be used both with the first model as with the newest model of our player piano.

<Toypi>

Definitely, I am not the first designer to build an automated toy piano. My friend and colleage Trimpin has -as far as I know- been the first to deliver a good working programmable acoustic toy piano. Our own design presented here, however started completely from scratch. First we removed and saved the internal harp (clamped rods mounted on a cast iron bar) from a 35 note chromatic toy piano made by Antonelli (Italy). We designed a completely new soundboard, replacing the original plastic construction. The new soundboard was made from hardened brass, the same type as we used before in <aeio>, our robotic cello. In contrast to the robotic cello design however, here we did not clamp the soundboard on its circumference, but we mounted it free swinging, using elastic material for mounting in the piano chassis. This lowers the resonant frequency for the mimimal surface dictated by the design here. The soundboard operates more or less as a Chladni plate. It also contributes greatly to the damping of mechanical noises. To preserve the typical sound, we kept the original design for the small wooden hammers. The keywork was completely replaced by a tubular solenoid assembly, controlled by a couple of PIC microprocessors. The maximum sound volume of the instrument is pretty limited. We could not change this, since sound volume is inherently connected to the sizing of the rod assembly. Louder sound would dictate thicker as well as longer rods. As to the electronic hardware, we used the same printed circuit boards here as developed earlier for <Xy>, our robotic quartertone xylophone. The boards were mounted at the spot where you would normally expect the keyboard. The power supplies found a place under the soundboard. The general shape of the instruments chassis follows closely the typical shape of a normal grand piano, although in this case, it was made entirelly using welded stainles steel. It stand on three sturdy legs. The instrument listens to midi commands and very precise velocity control is implemented.

At first sight, it may appear to be a bit silly to spend all the effort and money to automate such a cheap instrument as the toy piano. The building costs are about a hundreth times the cost of the toy piano itself. But at the other end, there appears to be quite some serious music literature for the toy piano... Margareth Leng Tan even devotes a large part of her career to concerts on this instrument! After all, one must confess its sound is quite unique. Realizing this, it is obvious that the toy piano is quite clumsy to play professionally: not only the keys are undersized for normal hands, but also the mechanics are pretty unreliable. By making a robot player toypiano, it becomes possible to play the toy piano via the interface of a normal touch sensitive keyboard, a hitherto unimaginable possibility. Of course, <Toypi> can also be completely computer controlled and used in interactive applications. As an alternative to MIDI control, we also implemented UDP/IP control.



<Rodo>

Rods clamped on one side and free to vibrate at the other side are the acoustical base of quite many musical instruments and sound installations: reed organs, mouth organs, bandoneon, music boxes with a comb, nail violin, toy piano, Fender-Rhodes piano, Waterphones, Harry Bertoia's installations, African lamellophones, clock gongs to name just a few. Two classes of instruments using this sound source should be distinguished: instruments that only use the fundamental resonant tone (reed organs, Fender-Rhodes, music boxes) and that are always considered pitched instruments and at the other hand those that use the broad spectrum of overtones these rods can generate, when tuned to very low fundamental resonant frequencies (clocks, Waterphone, toy piano...). The fundamental resonant frequency of these rods is inversely proportional to the square of the length of the rod.

The <Rodo> robot was designed to be either an extension or a generalization of the toy piano robot <Toypi>. Just like in the toy piano, the sounds all stem from massive rods clamped at one end in a solid cast iron bar. We started the project, as the automation of the small instrument was very successful and appeared to have many more sonic possibilities than we grasped at the start. So we thought of rescaling the design such that the range would extend much lower and the maximum sound level quite a bit higher. At the same time, we aimed at making the instrument a lot more sturdy than the toy instrument, that needed all too many repairs because the tines broke very easily on very fast note-repetition rates. Also quite some new features were added in this design: individual dampers, an e-drive mechanism and a set of radar sensors to allow gesture interactive activation and playing modes.

We started off by doing experiments on different metals and alloys for the tines: martensic stainless steel, hardened spring steel, brass, aluminum, phosfor-bronze, aluminum-bronze. We even experimented with some non metals such as bamboo, glass, carbon-fibre. Those experiments made us drop the nonmetals very fast as the sound was too weak or the rods too fragile. Obviously the evaluation of sonic quality has to remain a quite subjective issue, since there is no standard to compare to as we are designing a new instrument. After all these experiments were performed we decided to go for the aluminum-bronze alloy. These rods produce a very rich tone, though not as brilliant and loud as spring steel rods. In the design of <Rodo> we took into account the possibility for tuning and adaptation to different tuning systems. To allow this, set screws are used to fix the vibrating length of the tone rods. This arrangement makes it possible to exchange the rods for other sets, as long as the diameter is 8 mm. By default the tuning is chromatic, equal temperament. Due to the high inharmonicity of vibrating bars clamped at one end, it is perfectly possible to consider the instrument as 'non-pitched' in the context of orchestra compositions conceived for our robots. In this respect, the instrument would sound like a set of gongs.

An extra and new feature of the <Rodo> design, as compared to <Toypi> is the electromagnetic feedback driver mechanism. To this end we mounted a powerful (100 W) electromagnet very close (leaving just an air gap less than 0.1 mm) to and underneath the cast iron bar. This electromagnet is driven by a high voltage amplifier whose input comes from an ARM processor. The input for the driver can be either a signal picked up with a piezo transducer from the soundboard filtered and processed by the ARM controller, or a drive signal under midi-controll. This mechanism enables bowed and sustained sounds to be produced from this instrument. Rodo can sound very much like a bowed string instrument in this mode, although sound build-up is rather slow due to the inertia of the mass of the rod assembly.

<Klung>

This instrument is a computer controlled acoustical angklung designed and build in 2000. The anklungs themselves are made of hardened brass and tuned to a western scale covering two octaves.

The instrument is very rare and stems from an instrument build in Berlin around 1900 on request of the father of my composition teacher, Norbert Rosseau, who happened to be a circus director. He wanted to show instruments and musicians from other cultures in his circus, in line with wild animals. The role of these natives -in this case indonesians- had to be performed by circus clowns. The original instruments being build from bamboo and tuned to pelog or slendro tunings, he wanted the newly build anklung to be 'corrected' to our civilised tuning system as well as stable for humidity and temperature changes. Hence the construction using brass and the tuning conforming to A=440Hz. The 'modernised' instrument was donated by testament in 1984 to the Ghent conservatory by Norbert Rosseau. However, at a given moment when the conservatory building was under renovation, I found the remnants of this instrument on a big trash container. It was in a state of absolute neglect and parts were missing. However, I didn't hesitate a moment to take it along with me.

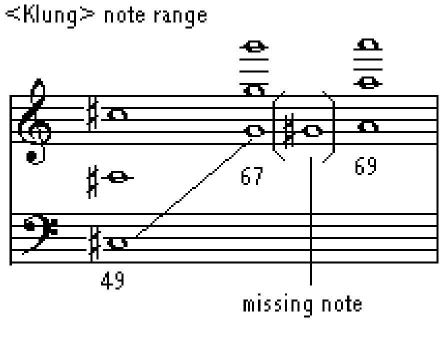
The research I did with regard to the instrument also revealed that in the circus it was used with electric lights, a novelty at that time. When we decided to turn it into a robotic instrument, we definitly wanted to include this original feature.

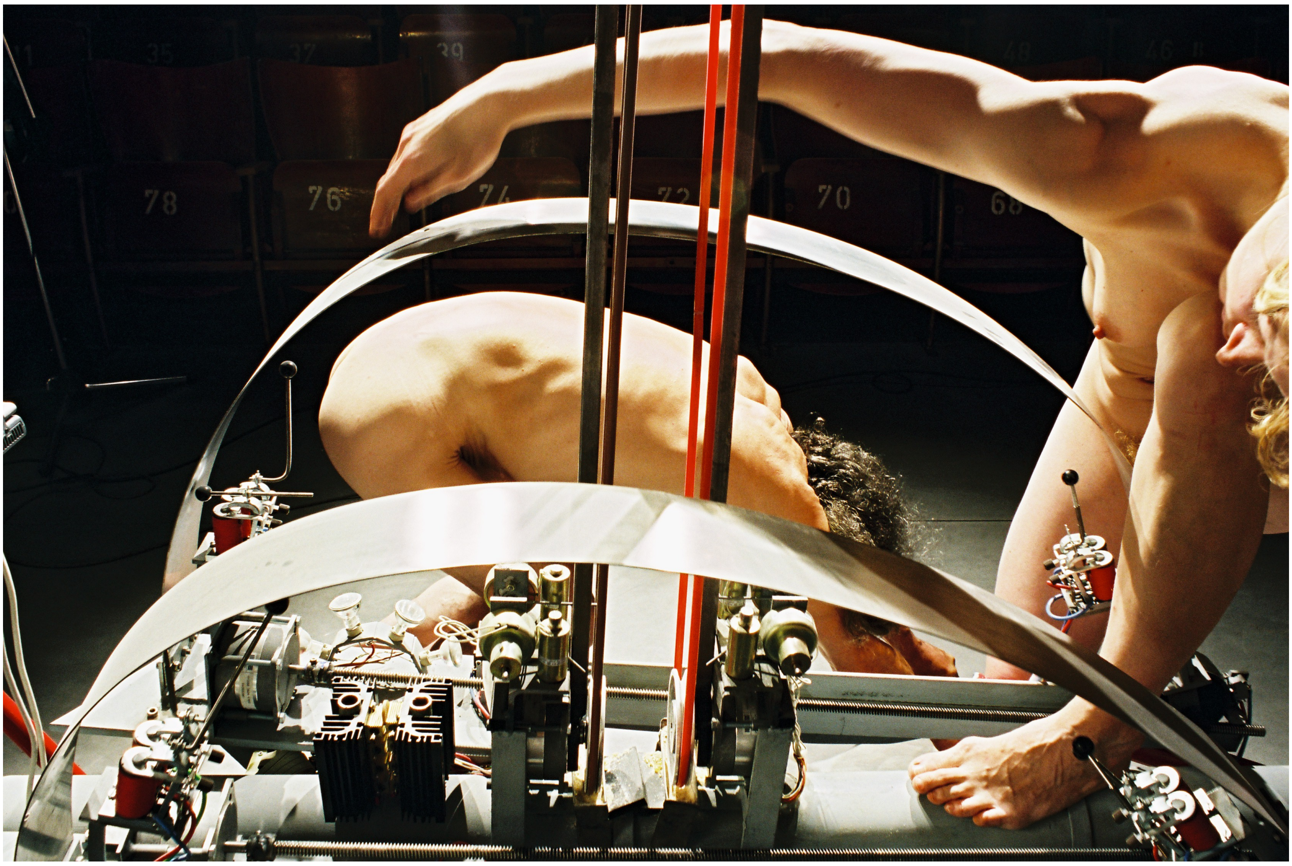
Fot the automation of the anklung shaking, heavy duty bidirectional solenoids were used.

The robot instrument is mounted on a heavy duty trolley and can be taken on the road for street performances. However, it is not rain resistent and should be protected against moisture.

<Klung> played its very first automated scales on sunday the 18th of june 2000. Its first public appearance was at the occasion of the 'Web Strikes Back' project' (Tromp Biannual) in Eindhoven. At that occasion is was played by commands coming from the internet in real time.

The musical range for this robot is:




78
76
70

<Flex>

This musical robot consists of an assembly of singing saw or flexatone like soundsources: blades of hardened stainless steel struck by solenoid driven beaters and bend by a system of heavy duty stepping motors. In this respect it may be considered a realization of Russolo's fifth category in noise makers (intonarumori): sound of metals, stone etc.

The individual beaters for the steel blades are driven by strong solenoids. Musical dynamics are implemented by applying pulse width modulation techniques in the driver circuits. However, the dynamic range is different from blade to blade and also depends on the amount of bending applied by the stepping motors. The circuitry used is very similar to that developed for our <Vibi> and <Rotomoton> automats, although we used a different kind of stepping motor (4-phase, 0.45 Ohm coil resistance, 1.2mH inductance), requiring a much higher current of up to 4.5A per winding. Two PIC microcontrollers are used for the blade steppers.

The stainless steel blades can also be bowed by two individually steerable bowing motors and two attack solenoids. Here again we decided to use stepping motors to drive a round nylon belt with rosin over two aluminium wheels 100mm in diameter. Since motor speed can be controlled by the software in the range of 0.5 Hz to 5 Hz, the bowing speed ranges from 160cm/s to 1.57m/s. The bow assembly is pressed against the blades by the action of a couple of Lucas-Ledex solenoids. The solenoids used are: Ledex STA series push tubular solenoid type nr. 195207-228. They have a cold DC resistance of 19.1 Ohm. The nominal working voltage, at which the coils can be activated indefinitly long is 13.8V. At 10% duty cycle, a voltage of 44V may be applied. The release of the bow follows under gentle springload. Positioning of the bows against the blades is achieved with four softshift solenoids, PWM-controlled by four PIC controllers. The bows, 70cm in length, are mounted vertically, facing each other on the central tube of the robot.

To prevent the all-notes-on on startup bug in the very first versions of earlier automats, this instruments should receive a pincode (241) before the motor and solenoid power supply is switched on. The software does program the microcontrollers and timer chips on board, prior to switching on the high power supply. In total, this automat is equiped with 8 PIC microcontrollers: 4 for each of the stepping motors, 4 for each of the bow movement softshift solenoids.

The instrument is mounted in a TIG-welded triangular structure with three large and sturdy wheels, 40 cm in diameter each.

<Simba>

This robot was build in response to repeated questions and requests we had from many of our collaborating composers working and writing for the Logos robot orchestra, for automated cymbals with extended musical playing possibilities. Only our <Troms> robot sofar had a small cymbal with only a single beater. Its musical weigth was judged to light in the context of the ever growing and pretty symphonic robot orchestra. In this newly designed robot we wanted to implement both the suspended (stand-mount) cymbals, as the hi-hat, where the sound comes from the concussion of two cymbals. Both elements can be played with many different sticks, hitting the cymbals on different spots. The hi-hat can also be played with the cymbals closed. Since the upper cymbal is not moving, the striking distance for the solenoids remains constant, which is essential for the realisation of predictable velocity scalings in such an instrument. As to the suspended cymbals, instead of mounting them horizontaly as usual amongst percussionists, we went for a vertical placement, since that facilitated the mounting of the different striking mechanisms. Also, it made it possible to provide in a good working damping mechanism for each individual cymbal. We did a lot of research into this one, and finally came up with the design implemented here whereby the cymbals are damped with a piece of felt covered neoprene touching the cymbal on the edge over about 1/6th of the diameter of the cymbal. Also these cymbals can be struck whilst damped, thus allowing for a typical dry sound effect.
Some extra features added to this robot are: A small but heavy cast bronze bell cymbal (made by Ufip and sold as 'ice bell') with a single beater. A couple of bass castanets (large wooden clappers, sounding a bit like loud coconuts), driven by strong push type solenoids; a bell-rim tambourine without drumskin driven by a pull-type solenoid. As yet under consideration are a motor driven rainmaker (rainstick), motor driven musical tubes, tubular shakers, a reco reco, a cavity resonator tube...
Some visual features have been added as well: a variety of lights, mapped on midi notes. Four lites are mounted on the front, three on the back.
The entire chassis construction was made from stainless steel AISI304L. The parts were welded together using the manual TIG process. The chassis main frame was bend from a piece of stainless steel 2400mm x 100mm x 10mm and provides more than enough structural strength to withstand abuse in transportation and heavy use. The <Simba> robot has three sturdy wheels: two 400mm diameter frontal wheels and a 200mm steering wheel on the back. The horizontal movement is equiped with ball bearings.

<Rotomoton>

Rototoms are frameless drums that, just because of the lack of a resonator, can be tuned over a range of abouth a fifth. This robot is a computer controlled assembly of five of such rototoms. Each drum is equiped with a set of beaters and the pitch of each rototom can be controlled. The lowest couple of rototoms have 3 beaters each, whereas the upper three suffice with two beaters each. The beaters are velocity sensitive and have a wide range dynamic control. Heavy duty stepping motors are used to achieve pitch control of each individual drum. Instead of rotating the drums on their fixed axis, we fixed the frames of the drums and rotate the threaded axis through a geared construction using dented belts. This also contributes to more silent operation of the mechanics.

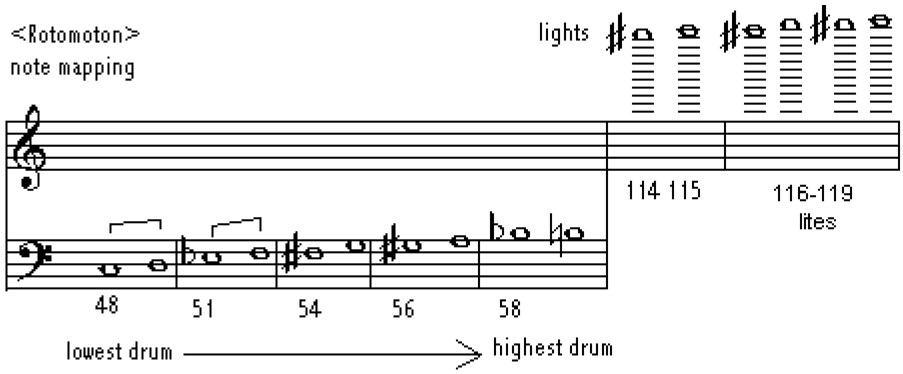
The instrument listens to midi data, however, good control of the pitches requires a lot of midi controllers to be send to the robot.

The original version dating from 2000 used hardware based on a parallel bus controlling Intel 16 bit timer chips with a resolution of a single microsecond, next to motor controllers of our own design. It was not directly controlable using midi but required a separate laptop computer to translate midi (or midi via UDP/IP) commands to the parallel bus commands required. In 2005/2007 we redesigned the hardware such that we could get rid of the laptop. No less than 7 PIC microcontrollers now take care of the control of every detail of the mechanics. The timing resolution suffered a bit under this change and is now limited to 19.2 microseconds.

The stepping motors use special circuitry, and make use of motor controller hybrid power modules. Since in this application, very high force but no holding torque is required from the steppers, we could use many power saving features available from these motor controllers.

Two inputs on each microcontroller for the steppers are used to read the start and end position of the tending mechanism, two bytes for each drum. Inductive proximity sensors with 0.01mm resolution were used to this purpose. Herewith we could obtain a hysteris of ca. 30µm. For precize positioning, it is mandatory to reset all motors first to the lowest and next to the highest end position prior to running music compositions. This calibrates the pitch range for each drum. Software to handle this automatically has been integrated into our <GMT> programming language.

As other instruments belonging to this percussion project (a complete range of robotic percussion instruments), this one also is designed for mobile use and thus mounted on sturdy steerable wheels.



<Llor>

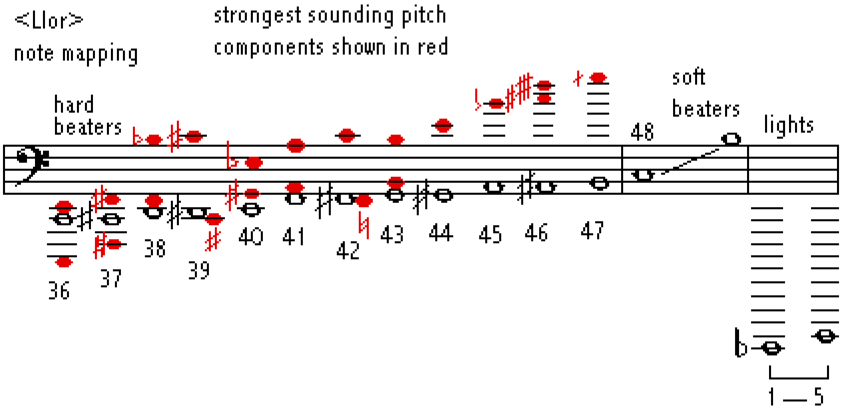
This very heavy musical robot uses eleven large stainless steel (AISI 304L) shells of different diameters as sound sources, as well as a single antique bronze bell of similar shape. These twelve shells are either struck by strong electromagnets with a heavy beater, or with felt covered piano hammers driven by much smaller and less powerfull solenoids. The first method covers the f to fff loudness range, whereas the piano hammers cover ppp to mf and even allow for quasi sustained sounds by grace of their relatively high repetition rate capability. Although the sounds of this automaton have definite pitch content in the inharmonic bell like sound, we do not classify nor use it as a pitched percussion instrument. The name given to this robot is a tribute to Llorenc Barber, who we saw playing shell like bells at so many occasions within the last 25 years. However, Llorenc's bells are made of normal iron (taken from gas containers) and suspended in a light wooden frame.

The constructional parts for this robot, apart from the very sturdy wheel base, are all made from stainless steel. All welding was performed using the full manual TIG process, using pure Argon gas.

The entire circuitry for this robot makes use of three fast PIC controllers: Microchip PIC18F252 - I/SP type. The first one only controls the blue LED lights fitted on different places all over the instrument. The second microcontroller takes care of their largest eight bidirectional solenoids and control not only the striking force, but also the backwards (return) movement. The third micro steers all the smaller solenoids. The power supply is rated 48V/ 12.5A, allowing for full polyphonic operation even at high striking forces and repetition rates. The dynamic range of the instrument is very wide.

<u>Mapping:</u>

Midi note range: 36-59 (hard-beaters on 36-47, soft beaters on 48-59) , lights (blue) mapped on notes 1,2,3,4,5. For those who like to see this in traditional music staff notation in the we we hear it:



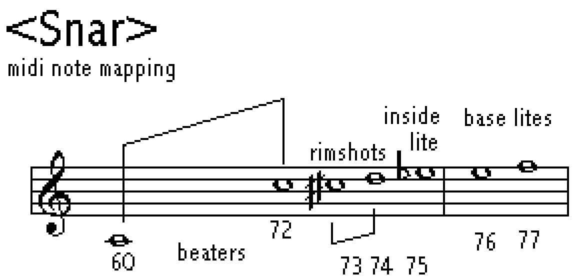
For midi files played by our <GMT> software, there is an 'intelligent' playing modus available, which you can switch on by sending controller 72 with a value higher then zero (value 0 resets to absolute mapping as described here above). In intelligent mode, our software will try to find a note that corresponds to the correct pitch of the given midi note, where the value of the controller determines the allowed deviation in cents. If, in this modus, no matching note is found, nothing will be played.

<Snar>

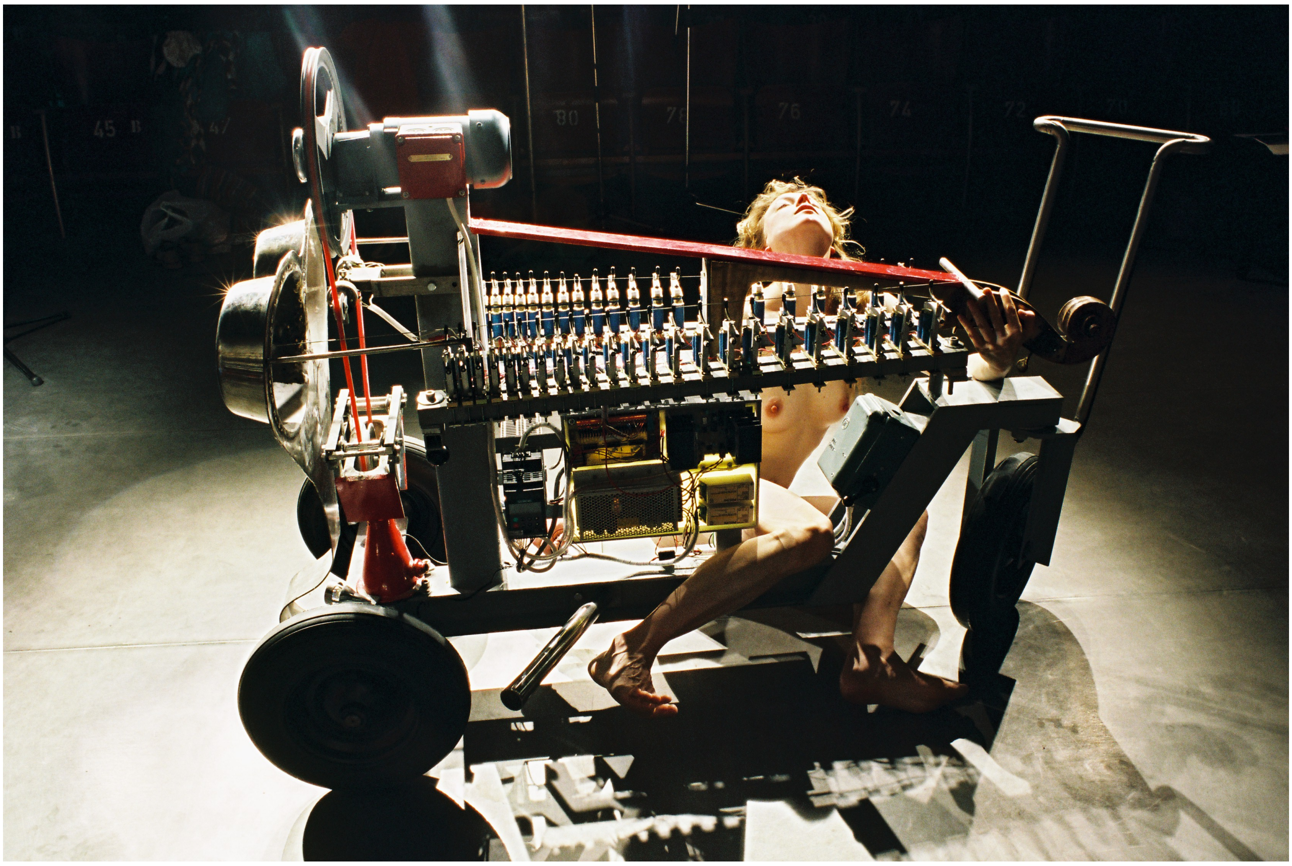
This musical robot consists of a new high quality snare drum automated with 13 beaters hitting different spots of the membrane from the inside. Two solenoid driven drum sticks, mounted externally, take care of the rimshots. Of course, all beaters have a precise and wide range velocity control. The snares can be activated through a special solenoid driven mechanism, offering gradual control. Controlling this robot is realized using a standard midi protocol. It was designed to form an extension of our drumming machine <Troms> and hence it occupies the same midi channel and port.

Musically, the snare drum may be considered to be the most sensitive instrument of the entire percussion section. In classical music however it does'nt play such an important role, the exception being the infamous 'Bolero' by Maurice Ravel, but in the most advanced styles of jazz and improvised musics, it constitutes the touchstone of musicianship for the drummer. We have done our best at rendering all nuances so typical of a good snare drum playing possible with this automate. Of course it will be up to the programmer and/or composer to take benefit of the possibilities offered.

From an electronics point of view, there were no new problems to be solved in the development of this automate, except to a certain extend the snare push and release mechanism, involving gradual control using PWM. We used the same circuit boards and design as we developped for such robots as <Vacca> , <Vitello>, <psch>. The data sets in the PIC lookup tables for the velocity scaling of course are fully different.



In 2014 we finished a second version of the robotic snaredrum. It was designed as a commission from Aphex Twin, who also delivered us the Ludwig snare drum to be automated. One of the elements that forced us to recalculate and redraw the design was in the fact that this snaredrum has ten tuning pegs whereas <Snar> only had eight. Also, this snare drum is equipped with an internal controllable damping felt pad, occupying some space. Although possible, we decided not to automate this component. All these differences made placement of automation components in this snare drum a bit more complicated. From an electronics point of view, there were no new problems to be solved in the development of this automate, except to a certain extend the snare push and release mechanism, involving gradual control using PWM on two separate solenoids.. The mechanics for the rimshot beaters are an improvement over the first design. Here we use heavy duty pull-type solenoids. The height of the final robot is determined by the height of the drum itself, the height of the electronic components -in particular the hefty power supply- and the acoustical requirement that for preservation of the sound integrity of the drum a free space of about half the skin diameter had to be reserved between the resonance skin underneath and the electronic components on the base. For mechanical reasons, the drum should only be used in a fully horizontal position.



<Hurdy>

This robot is a bowed bass instrument with two strings of equal length, covering a range of nearly four octaves. The construction of the bow mechanism is a further development of our first designs in this direction, implemented in <Flex>, our singing saw. The bowing speed, and consequently the loudness, can be controlled as well as the direction of rotation. Bow pressure can also be controlled independently for both strings. The time plot shown further below gives the details of the control possibilities. Rosin is continuously applied to the bow material through a rosin holder wherein the bottom wheel of the bow mechanism rotates. The frets are realized with strong electromagnets equipped with tangents. They are moveable, such that the instrument can be prepared to play in different tuning systems, including just intonation. The resonators for the strings are constructed from thin stainless steel pots, welded on a heart shaped sound board. The metallic and harsh sound the instrument produces when bowed was intended. Softer sounding, almost etheric string sound, including all flageolets, can also be produced using the e-drive mechanism. This machine is fully programmable and can work under midi control.

As it turned out, <Hurdy> proved to be an excellent test- and demonstration tool for classes in the acoustics of musical instruments. Particularly the theory of inharmonicity of strings can be perfectly well demonstrated and proved. The e-drive mechanism provides excitation at a mathematically exact 'harmonic', yet one can easily show that maximum resonance for that overtone only occurs if the string is retuned a bit for every 'harmonic'! It proves clearly that 'harmonic' overtones rather belong to the realms of religion than to those of physics. We used these scientific facts as the underlying compositional base for our composition 'Religionszwang', a solo piece for <Hurdy>. Another version of the same piece is called 'Scientia Vincere Tenebras', using calculations and empirical data for real inharmonic spectral components. These two pieces have been released on our 'Lonely Robots' CD.

<Synchrochord>

The first bowed instrument robot we designed was <Hurdy>, an automated hurdy gurdy, built between 2004 and 2007. The building of that robot had many problems and our attempts to solve these have lead to many new ideas and experiments regarding acoustic sound production from bowed strings. Between 2008 and 2010 we worked very hard on our <Aeio> robot, where we used only two phase electromagnetic excitation of the twelve strings. Although <Aeio> works pretty well, it can not serve as a realistic replacement of the cello as we first envisaged it. The pretty slow build-up of sound was the main problem. The cause being the problematic coupling of the magnetic field to the string material. Thus we went on experimenting with bowing mechanisms until we discovered that it is possible to excite the string mechanically synchronous with the frequency to which it is tuned. For such an approach to work well, we need a very precize synchronous motor with a very high speed. Change of speed ought to be very fast, thus necessitating a low inertia motor as well as a fast braking mechanism. Needless to say, but the motor should also run as quietly as possible. To relax the high speed requirement a bit, we designed a wheel mounted on the motor axis with ten plectrums around the circumference. Thus for every single rotation of the spindle, the string will be plucked ten times. Follows that in order to excite a string tuned to 880Hz, we need a rotational frequency of 88Hz. Or, stated in rotations per minute: 5280 rpm. The motor type ought to be a synchronous reluctance motor, since this type has no slip and can be frequency controlled with high precision. Fortunately we could dig up a suitable precision motor made by Eastern Air Devices. It's a spare part, custom made for an American military airplane.
Since the tuning of the string is very critical, we did strive at making the robot autotuning. Such a mechanism entails yet another motor specification problem. The tension on the string obtainable from the motor ought to be at least 600N. Such force values indicate the use of some kind of gears as well as a motor with slow speed and very high starting torque. This brought another type of motor we had on our shelves into sight: a General Electric synchronous inductor motor. Its torque is specified as 150 Oz.In., the anachronistic imperial equivalent of 1.059 Nm in standard SI units. This motor is used to drive, via an intermediate 1:10 dented wheel construction, a worm gear without backlash, the large wheel being connected to the 12 mm take up spindle for the string. The reduction ratio of the worm gear is 1:4. The maximum force we have available to excert on the string now is 6.6 kN. We estimate that the sum of losses suppers up more than half of this force. Designing an autotune mechanism means that we also need to provide a sensor to measure the string pitch accurately. For strings made of ferromagnetic material, an inductive sensor can be used, but if we want to use other types of strings, either optical sensing or a contact microphone is needed. During the tuning procedure, the string has to be excited. Either the motor-exciter has to run at its lowest possible speed, just plucking the string at its free resonant frequency, or we can use the build-in feedback mechanism if ferromagnetic strings are used. As an electromagnetic string exciter, we used a synchronous shorted cage motor from which we removed the rotor completely. The string comes to run through the circular hole left open now. An extra bonus of this autotune approach is that it now becomes possible to apply vibrato on the string sound during normal operation. However, this makes it essential that the processor steering the string exciter and the processor called in for the autotuning mechanism talk to each other..

Musically <Synchrochord> sounds quite a bit like a mediaeval Tromba Marina. A bit harsh in sound at times. The historical trumpet marine however, did not have any frets and its sounds were restricted to the high overtone series of the single gut string. On our instrument, not that many overtones can be produced due the the fixed position of the exciter with respect to the sounding string length. The fingered vibrato on this instrument came out to be very usefull. On large interval jumps its behaviour is a bit sluggish due to motor inertia and thus the instrument is best suited for relatively slow moving string bass parts.

<Aeio>

The first bowed instrument robot we designed was <Hurdy>, an automated hurdy gurdy, built between 2004 and 2007. The building of that robot had many problems and our attempts to solve these have lead to many new ideas and experiments regarding acoustic sound production from bowed strings. The problems with <Hurdy> were all related to the very complicated controls required for the bowing mechanism: a system with so many degrees of freedom that handling it became far from 'automatic' and the users were left with a very complicated command set in order to make <Hurdy> play the notes he wanted. Bow pressure curve in time, bowing speed, finger pressure, bowing angle all in function of the note to be played and the required dynamic had to be send to the robot. To avoid this we provided the users an alternative way of producing bowed sound from the string: magnetic drive. This worked very well and many aspects of bowing technique in <Hurdy> could be automated in a more user friendly way.
These experiments made us dream of an instrument using twelve strings, in a chromatic arrangement, that would all individually be bowed with our electromagnetic system. So on the drawing table we envisaged an instrument with twelve strings tuned from 36 to 47 and equipped with felt covered solenoid driven dampers. The soundboard could be made from either hardened brass, titanium or Styrofoam mounted in a steel frame. Now one would think the instrument could only play twelve notes, but that's wrong since on each string we can sound the fundamental as well as the entire series of slightly inharmonic partials. In fact the range is extremely extended and covers at least the ambitus of the classical cello. The name of this robot was derived from its working principle, showing some similarity to the aeolian harp, where the strings are struck by the passing wind. <Aeio> lends itself not only as a robotic instrument in the context of our robot orchestra, but can also stand very well on its own as an interactive audio art installation.

When the instrument is used monophonically, there are no limitations. However, when you want to play double strings, these can only be played if the requested notes can be produced on two different strings. That's quite the same with all usual bowed string instruments. The driver software will arbitrate for you but there is an obvious possibility that certain chords will not be sounded in full. All strings can be made to sound simultaneously, if required. Vibrato, as common on bowed instruments, as well as glissando playing, is impossible with <Aeio>.
A scheme for playing string spectra using midi has been worked out. Unfortunately, standard midi has no codification for fractional midi notes nor for 'just' intoned intervals. So the best alternative seemed to implement continuous controllers (nrs. 36-47) for each string, whereby the parameter value corresponds to the number of the overtone to be sounded. To also control the volume or excitation level of the string, we implemented another series of controllers, in the range 49-60.

The constructional parts for this robot are all made from welded stainless steel. The instrument is mounted on a wheel base, as most of our music robots.

The strings are driven by the electromagnets in two phases. By extending the duration of one of the phases the excitation characteristics of the string can be modified to a great extend. The waveform thus obtained comes closer to that of a real bowed string. The firmware in each of the twelve PIC controllers has two cascaded 16 bit timers. Using the thus obtained 32 bit timer, a period time can be programmed with great precision. To make research and development easier, we designed the firmware for the string drivers such that each dsPIC processor responds to its own midi channel, thus using up 12 midi channels. In normal use, the parser microcontroller takes care of string arbitration and the user sends all his commands on the <Aeio> channel solely.

<Bomi>

In 2008 we finished the construction of our automated 6 octave quartertone organ <Qt>. It was the output of a three-year post-doctoral research project on the extension of expressive possibilities by applying modern automation and robotic principles to traditional instrument-building practice. For the realisation of this robot, we were assisted by Ghuislain Potvlieghe (organ builder) and Johannes Taelman (engineer). The research, design and realisation was in our own hands.

The experience gained from the construction of <Qt> continued to intrigue us and raised quite a few new challenges. In <Qt> we achieved touch sensitivity for each pipe by driving the flat solenoid valves in the wind chest with a variable voltage. To what extent could this be improved by using conical or spherical valves? Would it be possible to fully implement aftertouch control? What would be the consequences of designing the organ to operate at very low wind pressure? Qt was designed to work with 14 mBar pressure, which is quite high by traditional organ standards. The modulation characteristics of the sound when modulating the wind pressure are very different when the nominal pressure changes. At low pressure, modulation possibilities appear to be larger.

To obtain an experiment-based answer to these questions, we set up another relatively small building project: <Bomi>, finished by the end of 2010. The design of this musical robot was triggered by an offer found on the August Laukhuff website for a semi-finished and incomplete wooden 4-feet register that seemed perfectly suitable to carry out these experiments. The stopped pipes are made of light oak wood and we made an extra five pipes ourselves, so that the lowest note is now 55 (low G). With 37 pipes in total, we obtained an ambitus of three octaves.

The sound was designed to be soft and gentle, but still pretty rich in overtones and with a clear and slightly spitting attack. This was achieved using traditional techniques of organ pipe intonation and tuning. To aid in adjusting the instrument we added regulating screws in the pipe feet. The wood has been left in its natural and untreated state. The pipes are tightly fitted to the wind chest using easily replaceable Teflon tape (PTFE). Since the instrument is designed for transportation, the pipes are inserted deeper into the upper plate of the wind chest than usual in organ building.

The wind flow to each pipe is controlled inside the wind chest with solenoid-driven conical electrical pallets. Conical valves allow for a much better airflow regulation than the flat pallet valves we had used hitherto. Thanks to these valves, we obtained velocity sensitivity for each individual note as well as individual key pressure modulation (note aftertouch).

Global wind pressure control is possible over a wide range, although as can be expected from flue pipes, tuning cannot be guaranteed under extreme deviation from the normal pressure circumstances. A tremulant, using a softshift solenoid valve on the wind inlet in the wind chest, is also part of the design. Its operation can be seen as we have made the wind chest transparent. The softshift valve used here to steer a large conical valve can be controlled with a midi controller. It is important to the user to know that the velocity byte in the midi note-on command does not control sound volume, but only the way the pipes begin sounding. It is strictly an attack control.

Since its finalisation, many composers have used <Bomi> as a much welcomed sound in the robot orchestra. The robot was also demonstrated at the festive opening of the STAM museum for over 20000 visitors. Due to its flexibility in tone production and modulation, <Bomi> is extremely well suited to real-time interactive playing using our gesture sensing and recognition system. This was convincingly demonstrated in our Namuda studies, a collection of interactive compositions. Study #7 ('RoboBomi') was written for a dancer, the gesture system and <Bomi>. These pieces are performed regularly on the concerts of the robot orchestra at Logos in Ghent.

<HarmO>

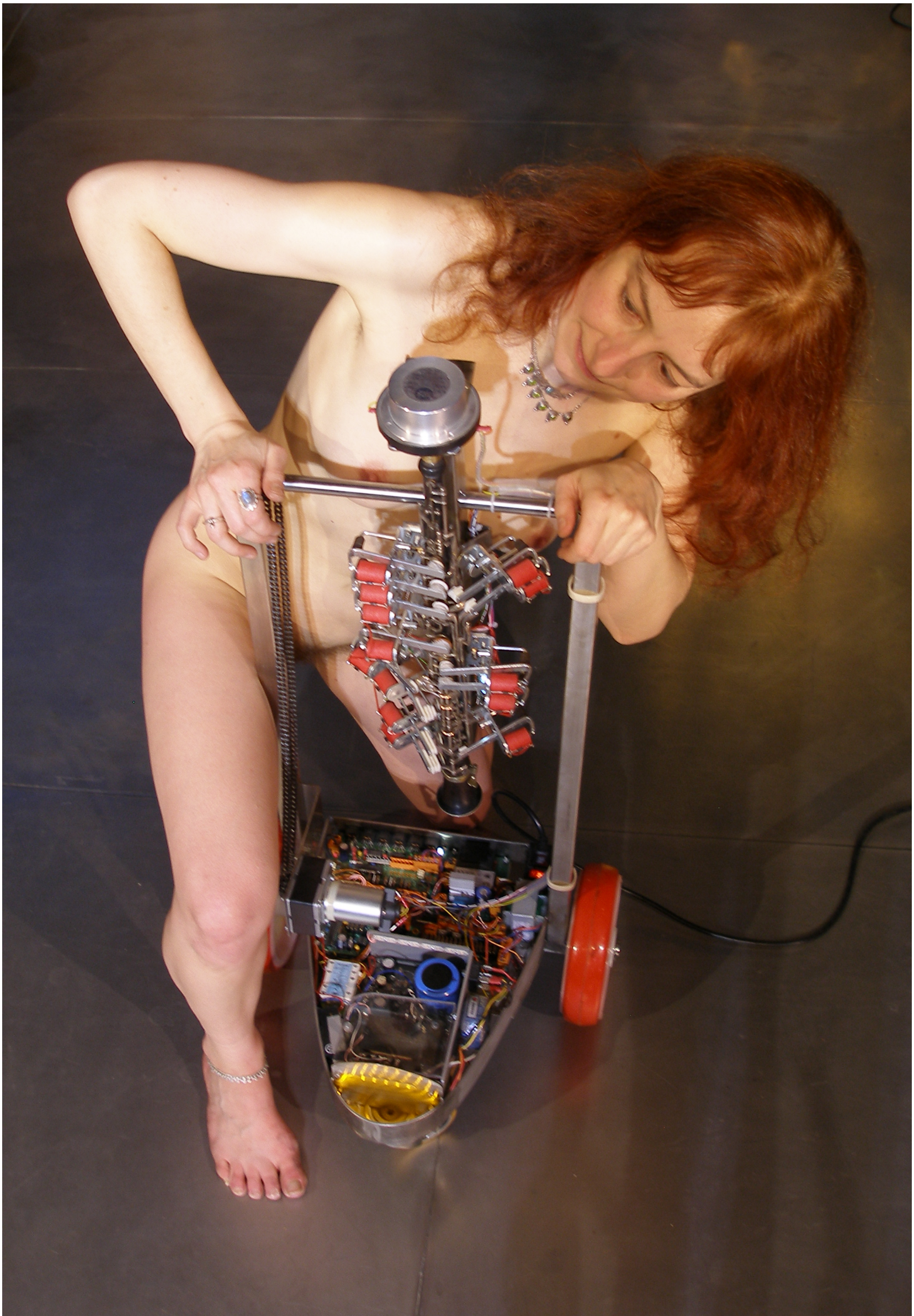
A computer controlled 6-octave reed organ with touch control, swells and individual registration. The starting point for this construction was an old suction reed organ, of which we only kept the reeds and the key springs. A new electric compressor was added (a small Laukhuff Ventola, rated for 80mm H2O pressure (800 Pa) and 3000 l/min) replacing the bellows. The instrument has 4 sets of reeds for the bass side and 4 sets of reeds on the treble side. In addition it is equipped with 1 octave (13 reeds) of reeds for a subbass. These sound the notes 12 -24.Taking the registers into account, the real sounding ambitus ranges from midi note 12 to 113, or an impressive eight and a half octaves! Two swells are provided, as well as a reflective tremulant mechanism. In total the organ has 305 reeds.

As usual in our automated instrument designs, we designed a sturdy welded frame made in stainless steel for the entire magnet and electromechanical assembly. Other than in our first robot reed organ, here we decided to leave the original keyboard in place. As a consequence, it becomes possible to play the organ in the traditional way even in combination with automated playing. We used tubular solenoids, 20mm in diameter, to activate the keys here serving as levers to reduce the required force to push the pallets down. This saved us the work of replacing all pallet springs with lighter ones as we did in <Harma>. Since the magnets are wider then the distance between keys/pallets (13.5mm), we had to mount them on alternating rows. This became another reason for not activating the pallets directly. The eight registers are each divided in a bass and a discant unit. Gradual opening of the dynamic shutters appeared to be an interesting feature worth implementing. Our first attempt using soft shift linear solenoids to this end were not successful because these solenoids did not produce enough pulling force to guarantee a smooth action. Therefore we finally decided to use linear stepper motors with a threaded shaft. This approach makes a smooth action possible at the expense however, of some extra noise caused by the audible stepping frequency. Although this mechanism is relatively slow in action, the big advantage of it is that it draws no current to keep position, but only so on movement. The whole traject from closed to fully opened takes about 500ms.

The tremulant makes use of the Doppler effect to create a slight but real vibrato. Therefore we needed to build a reflector mechanism driven by a variable speed DC motor.

The radial compressor used for the wind supply is equipped with a wind regulating slide mounted on the inlet of the windchest. This slide can also be controlled and allows for faster wind pressure changes than can be achieved by regulation the rotation speed of the motor. This slide is driven by a stepping motor coupled to a dented belt.
Although in the design phase we considered making the instrument fully polyphonic, we finally decided to limit polyphony on this automate to 32 notes. For a full 73 note polyphony would have implied the construction of a hefty 45A / 12V power supply. Even though possible, the compressor would never have enough wind to make all the reeds sound. Thus we decided to forsake full polyphony. Even at 32 notes held simultaneously the wind supply is barely powerful enough.

<HarmO> is controlled by 11 PIC microcontrollers (6 for the notes and the registers, 3 for the linear stepper motor controllers, 1 for the compressor motor, 1 for the lights, the motor control signals and the tremulant) and takes midi input directly. <HarmO> was designed from the beginning on with velocity control but the effect of touch sensitivity is of course by far less effective than it is on our player piano or on the organs equipped with conical windchest valves such as <Bomi>. However, any touch sensitivity a reed organ played by a human might have, is also implemented and at least surpassed in this robot.



<Ob>

This musical robot belongs to the category of our automated classical music instruments: the oboe. The approach here was quite experimental and was an attempt to realistically automate an existing unmodified instrument, and thus it does in fact make use of a fine classical oboe. The instrument used is a Brussels made concert instrument by F.Debert, probably to be dated first half of the 20th century. Electromechanical control of the levers did not confront us with any real problems apart from the quite delicate and differentiated mechanics. Silent operation of these have been our main concern. We simplified the fingerings such that we could suffice with less than 16 solenoids: six closing the open holes, and the strict minimum of seven for the essential levers. Some of the levers (such as the three octaving levers as well as the levers to facilitate trills) are essential for players, but have much less importance in an automated instrument where the attack of the tone is guaranteed by the nature of the sound mechanism and where resonance on partials can freely be used. Alternative fingerings in order to obtain different sound colors are implemented as well.
The double reed however, became the main problem. The first experiments conducted us to the design and building of double reeds made from piezoelectric material glued to brass plates. We got a few prototypes build along this line, up and working and indeed the concept is workable. The main problem here was the very low obtainable sound pressure, even when driving the piezo-material well above its rated maximum voltage (35 V). The second series of experiments was carried out using a double faced piece of piezoceramic bonded to a central brass plate and placed just touching to an absolutely flat thick brass plate with a central perforation of 4.2 mm. This mechanism gives a strong buzz but unfortunately, sound production is very frequency dependent as well as dependent on applied air pressure (after placing the assembly in a closed container). A secondary problem in this approach was the noise generated by the compressor. We used a small DC motor driven vacuum cleaner type compressor capable of producing the required pressure of about 15 to 30 mBar. Therefore a thirth series of experiments was carried out using tweeter motor driver made for driving an exponential horn. Instead of coupling the driver to an exponential horn, we designed an acoustic impedance converter modeled after a real reed in a human mouth cavity. This piece had to be fabricated on the lathe. With this mechanism, the realism of the produced sound becomes highly dependent on the waveform applied to the driver. Something trapezoidal seems to work best. However, in order to come close to original oboe sound, articulation is very essential: frequency modulation, phase modulation of at least the first two partials above the fundamental as well as some amplitude modulation (envelope shaping). The circuit for driving this motor was derived from the circuits designed earlier for robots such as <Korn>, <Bono> and <Aeio>. It uses the same PC-board and the same PIC microcontroller. The firmware however, is quite different. For coupling of the circuit to the motor driver, we use a classical audio output transformer. The two resistors and a capacitor form a simple formant filter tuned together with the inductance of the transformer, to the required strongest formant frequency for oboe sound.
As an extra feature, we suspended the entire automated oboe construction in a cradle. Thus the instrument has freedom to move in different inclinations. The axis of suspension is provided with a dented wheel driven by a chain and a motor with reduction gears. This way, any inclination can be held and controlled. The movement possibility was added since it mimics a bit the behavior of a human oboist. In the software we use for controlling the automate, we are implementing rules such that the robot derives its gestural behavior from the music it gets to play. The circuit secures that the instrument is not allowed to turn fully around, since that would ruin the robot. Movement is limited to an angle of ca. 90 degrees. For the sensor, we decided to call in an analog tilt sensor by Penny & Giles allowing us the read the position of the instrument at all times using an analog input port on the PIC controller. For the motor control we made use of a Trident 4-quadrant DC motor controller.

<Fa>

This musical robot is an automated classical music instrument: the bassoon. The reason for taking up this automation project has to do with the simple fact that bassoon players of quality are getting extremely rare. We do like the bassoon sound and thought it would be a most welcomed timbral component in the Logos robot orchestra. The brass section is well represented and covers the bass side pretty well, but as far as woodwinds go, there was a noticable gap. The sound mechanism is based again on an acoustic impedance convertor with a capilary, driven by a motor compressor. The original crook of the bassoon fits very precisely into this part, made on the lathe from massive brass. As mandatory in such an impedance convertor, we first have an anticonical part driven by the motor compressor leading into a capilary traject, after which follows a conical part adapted to the instrument to be driven, in this case the crook of instrument at the end where normally the double reed is mounted. The longer the length of the capilary and the smaller its diameter, the more the sound is determined by the acoustic properties of the instrument alone, but obviously at the same time, sound pressure goes down. Thus we always have to find a compromise.

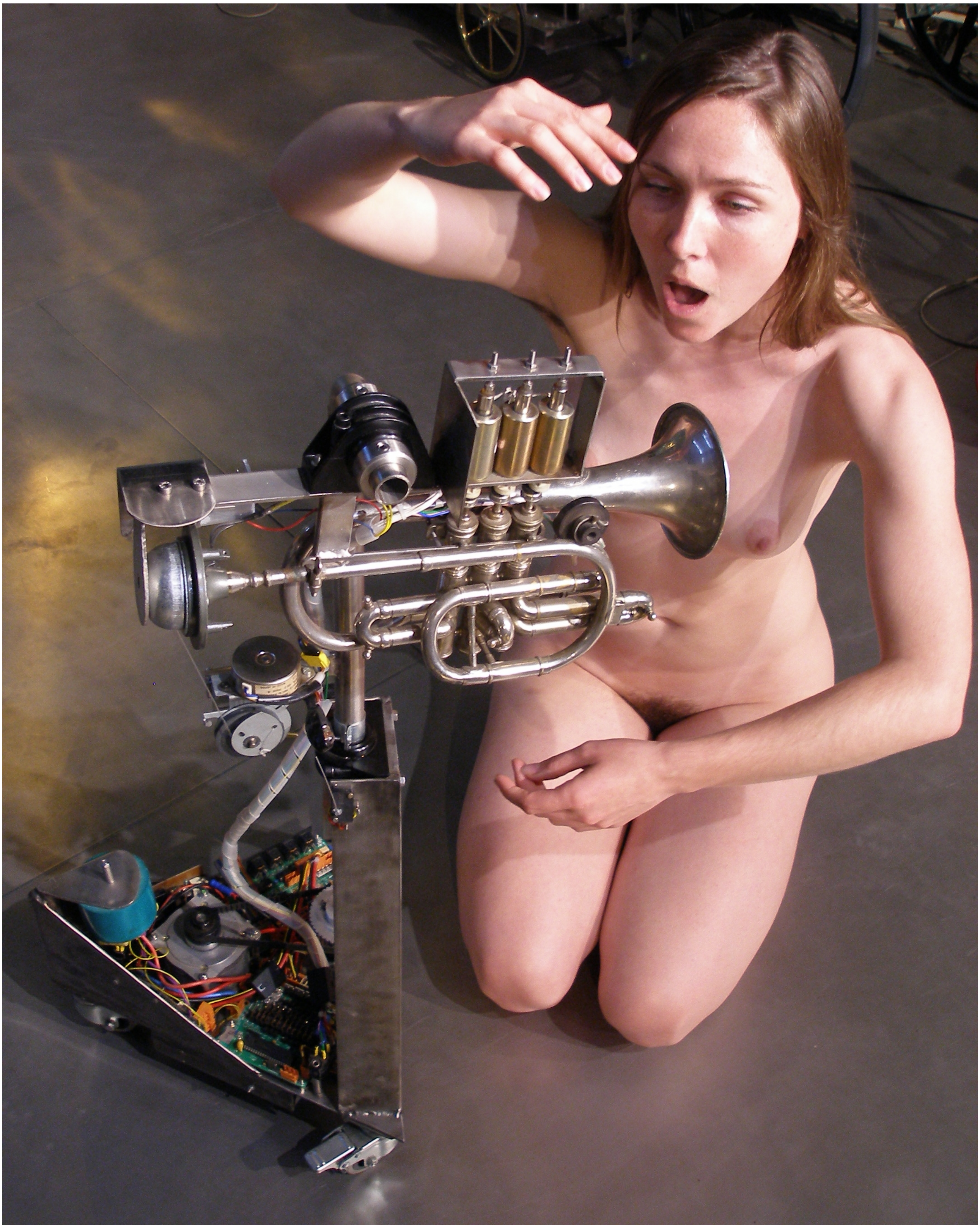
From an acoustical point of view, the bassoon is a pretty poorly designed instrument. It has a narrow conical bore with no less then 27 holes. A pretty complicated valve and lever mechanism renders it possible for a human player to open and close all these holes with just ten fingers. The resonance characteristics show up a pretty low Q-factor for the fundamental note played and therefore playing exactly in tune is pretty demanding for a human player and asks for a very good lip control. Despite the many valves and mechanics. At the other side of the medal though, this makes is possible, in a robotic design, to implement all kinds of tuning and intonation subtleties even without using complicated fingering combinations.

Although we first considered leaving all mechanics on the instrument intact and replacing the human fingers with action solenoids, some early experiments revealed clearly that this would lead to a lot of unwanted clicking noises. Therefore we decided to get rid of all the mechanics and replace them entirelly with flat pallet solenoid valves working directly on the tone holes. We took a risk here by mounting the valves directly on the instrument, knowing that the mechanical load on the wood would be quite a bit higher than in the traditional instrument. To make sure we would not crack the bassoon and ruin the internal bore, we constructed well fitting saddles from 0.8 mm thick stainless steel plate, for each of the solenoid valves and fixed them lightly with very short plate screws into the wood whereby the real sticking force is realised by glueing the assemblies using a special silicone compound. This job alone took almost a month of work, in part also because the silicone compound takes about 24 hours to cure.

An important aspect of the firmware for the ARM processor used here, is that we had to implement a formant around 500Hz in the driving source signal. This conforming to the findings published by F.Fransson in 1966, where he proves clearly that this formant cannot be attributed to the bassoon as a resonator but solely to the action of the double reed. The formant filter implemented affects the lower partials. Note that notes higher than midi 60, do not have this formant, note 71 being at the center of the formant frequency itself.

Since some movement of the bassoon is quite normal in human performance, we wanted to implement that as well. Hence we suspended the entire bassoon and motor drive assembly on a spindle such that it is allowed to rotate over an angle of about 30 degrees.

A novel aspect of the design of this robot is the implementation of a fingered vibrato, conforming to the tradition in vibrato playing up to the second half of the 19th century.



<Korn>

This musical robot was the result of our first experiments with membrane compressor driven sound production on brass instruments. It does in fact make use of an old Bb cornet and the attempt was to get a realistic cornet sound. The driver causes resonance in the cornet tubing, but in this case there is no real one-directional windflow through the instrument, but rather a standing wave. When a note is requested from the cornet, the firmware will calculate the optimum valve combination -including non orthodox fingerings- for the requested pitch. Microtonal pitches are implemented such that the instrument is capable of performing quartertone music, as well as a wide range of different tunings and temperaments with great perfection. The relatively low Q-factor of the horn (compared to strings...) as an acoustic resonator renders this very well possible. The signal generated in the motor was shaped after a physical model of the air pressure waveform in the mouth cavity of a player. Since there is no loop coupling from the resonator to the generator, the sound generation mechanism is a hybrid somewhere between synthetic/electronic and natural/acoustic. The advantage being that the reliability of the robot becomes very high, but this is obtained at the detriment of some realism.

The valves are used in this instrument to tune the fundamental frequency of the instrument. The valves can be controlled independently from the mouth driver frequency. They are mechanically driven by unipolar solenoids and have a return spring. Bi-directional solenoids would have been superior (read, faster and more silent in operation due to the absence of return springs) but we just did not have enough mounting space in this rather small instrument.

High brass instruments in their normal human biotopes tend to move quite a bit in space. The highly directional characteristic of these instruments make this also an expressive valuable parameter. Thus we tried to implement movement in two degrees of freedom in this robot: the cornet can be tilted in the vertical plane over an angle of about 90 degrees and in the horizontal plane, it can rotate over 180 degrees. This conforms pretty well to what human players do in terms of movement on stage. The movements cannot be very fast however, at least not much faster than what a real cornet player could do whilst playing. Horizontal movement is a lot faster than the vertical movement. However, the intention never was to render Doppler effects possible...

The electronic circuitry consists of four printed circuit boards:

1. Midi-hub board: This board, using a Microchip 18F2520 controller, takes care of the Midi I/O handling and communication as well as the control of some of the the lights and the movement of the horizontal movement stepping motor, including the two end sensors. For these we used two Pepperl & Fuchs inductive proximity sensors. Provisions were also made for two PIR-sensors allowing the robot to 'search' in space for moving human bodies.

2. Horizontal stepping motor driver board using a Nanotec SMC42 compact microstep constant current driver. This motor is designed for 360 steps for a complete rotation.

3. Pulse & Hold board: This board steers the three solenoids for the pistons as well as the vertical movement stepping motor and the lights.

4. Sound generator board: This board, using a microchip ds-PIC 30F3010, steers the 15 Watt motor compressor horn driver. Note that the output transformer forms a tuned circuit, tuned to the formant band of the cornet (1.8 kHz). The transformer at high sound pressure levels, operates close to saturation, thus causing a formant shift upwards. When a coil gets into saturation the inductance decreases. This clearly nonlinear behavior of the circuit was part of the design.

<Bono>

This musical robot consists of an old but extremely well made valve trombone, found on the Ghent flea market. It was build by the famous brass instrument builders V.F.Cerveny and Sons in Hradec Kralove (Tchechia) We equipped it with an automated playing head and four automated valves. Normally these valves rotate over a 90 degree angle under finger operation. When we started the automation of this mechanism we had many technical choices with regard to the way the valves could be operated. Our solution consists of using eight pull-type tubular solenoids working on the eccentric pivot point on the valve shafts. Here we get rid of the entire original mechanism and replaces it with newly designed traction elbows. In order to get fast response we drive them using our pulse/hold PIC controller boards as developed for our <player piano> , for <Bako> and for <Qt>. The force they are able to develop is only marginal for smooth operation in this robot.

In total, three PIC-microcontroller boards are used in this robot: A first one placed on the midi-input and hub board, controlling the motor driver functions, the expression valve and the visual effects. A second one takes care of the valve combinations used for resonance on the required notes. A third one, -equipped with a dsPIC, type 30F3010, controlling the artificial mouth assembly and the pitch generation. This board also has two digit decimal displays, showing the midi note playing.

For the construction of the artificial mouth we could build further on the experience gained when realizing our automated sousaphone, <So>. However, we also tried out a few other sound generating mechanisms prior to taking up the <So> design again. Thus we tried a servo motor driven rotary valve working on compressed air. This worked soundwise excellently - we could obtain really impressive fortissimos for instance over the entire compass. We finally rejected the application of this technology because we were unable to control the servo fast enough in going from the one speed to the other as required for proper generation of musical pitches. The second problem had to with the difficulty in finding really silent compressors.

The <Bono> robot was designed to be suspended, thus reducing floor space requirements for the Logos robot orchestra. All mechanical parts were made from stainless steel, welded together using the manual TIG process. All serviceable parts can be taken apart however.

Pitch bend implemented. The range is limited to a semitone, thus a quartertone up or down. Pitch bend can be used for microtonal music as well as for vibrato control.

<Horny>

The design and construction of this automated instrument started with the purchase of a brand new F-horn, made by Arnolds & Sons, model nr. AHR-301, serial number 121267. It came with an extra short piece of tubing, such that it can be turned into a Bb horn as well.

The horn has three rotary valves and force measurement revealed that the minimum force required to start movement of the valves was 2 Newtons. The required movement trajectory is 12 mm and the force required to fully push the valves raises to 2.5 Newtons. This determines the specification of the solenoid valves to be used. The physical placement of the valves on the instrument however, dictates a few more restrictions: the distances between the activation points of the valves are 30mm and 20mm, so the use of standard Lucas Ledex tubular solenoids (diameter 1" (25.4mm)) capable of meeting the specifications becomes problematic. Hence we went for August Laukhuff register magnets with a pivoting action and a force of 10 Newton.. The mounting width of these type is only 18mm. The solenoids are connected in series with a 24V halogen bulb (10W), operating as a voltage dependent resistor

As we power the solenoids from 48V, we now doubled the force developed at the start of the trajectory. The starting force of these solenoids, even after carefull adjustment of the anchor and the trajectory is only marginally large enough otherwize. The solenoids are mechanically coupled to the valves using tractures made of flexible M4 threaded nylon rod. Nuts and felt washers were used to minimalize mechanical noise production. The operation of the valves is controlled by a Microchip PIC controller type 18F2525. There are selectable lookup tables for both the fingering on the F-horn and the Bb horn.

For the excitation of the horn we once again used a compression driver followed with an acoustic impedance convertor. In this case we used the original mouthpiece of the horn without any modification other than the construction of a new clamping system to connect the mouthpiece firmly with the driver. The compression driver is steered -after amplification- by an ARM-microprocessor.

Horns are normally played with the bell pointing backwards. On occasions, composers do ask for the bell to be brought 'cor en haut', pointing to the audience. This request can for instance be found in the score of Strawinsky's 'Le Sacre du Printemps'. In our robot we also wanted to implement some form of control over the sound projection from the instrument. Since the mounting of the horn appeared to be quite complicated it was not possible to perform all calculations and drawings beforehand since for fluent motion it is mandatory to know the axis of equilibrium. Therefore we started by making the essential holding structure including the valve solenoids and the compression driver and only after that job was finished, we empirically found out where to place the balancing point. Unfortunately this balancing point appeared to come too close to the compression driver. Thus for technical reasons such as accessibility of mounting bolts and nuts and for ease of disassembly, we did move the axis of movement slightly to the backpoint. To restore equilibrium we sufficed by adding some extra weight. A stainless steel ladle at the same time serving as a protection cap for the compression driver fullfilled this function very well. As it came out, the final result is a bit crab like as the wheels had to be placed under a weird angle to the instrument.

Very probably this robotic horn is the very first horn player in music history that ever succeeded in playing his musical parts always perfectly in tune. Users and composers that like the 'out of tune-ness' of real hornplayers can always implement this as we gave the instrument ample possibilities to play in just about any imaginable tone system with high precision.

<Klar>

A somewhat rare instrument became the starting point of this robot: an alto clarinet built by Higham in Manchester in the first half of the 20th century. It's an Eb instrument, a fifth lower than the regular Bb clarinet and thus reaching down to G (midi 43) in absolute pitch. In any case it's an instrument that never found its way into the regular symphony orchestra. It has a curved metal bell and is made of coconut wood. The mouthpiece connects to the instrument through a bent neck.

For the design we benefited from the experiences gained with previous wind instruments such as <Korn>, <Autosax> and <Fa>. Our prime concern was to make the mechanical parts as quiet as possible. <Ob> and <Fa> in that respect were the most succesful so far, but in a clarinet the forces needed to open and close the valves are quite a bit higher than on the oboe. On the other hand the solution that has made <Fa>, the bassoon, a success cannot be applied here: in <Fa> we removed all existing valves and replaced them with solenoid driven pallet valves directly mounted on the bassoon. The clarinet body however just does not offer enough space to make that a viable solution. Thus we had to find something in between what we realized for <Ob> and <Fa>. Some original valves were removed and replaced by solenoid driven valves mounted on a separate chassis. For other valves we left the original valves and springs in place, but operated them with felt or rubber padded solenoids replacing the human fingers.

The sound driver follows a recipe that has proven its validity over many previous wind instrument robots: the membrane compression driver followed by a capillary impedance convertor. Obviously the impedance convertor we finally inserted has quite different proportions than the ones used for the brass and double reed instruments. One of the problems was to work out empirically the equivalent acoustical length of the clarinet mouthpiece. There are -so far as we could find out- no mathematical models available. It is known in acoustics that a single reed can be considered to be a flat bar clamped at one end, but if we look at the spectrum produced once the reed is mounted on the mouthpiece and coupled to the resonator, almost nothing of this theory seems to hold true. What we do know is that the pitches that can be produced on the clarinet, must be below the natural frequency of the reed. Thus the reed is the limiting factor for the ambitus of the instrument. As we do not have this limit in our design, we can extend the ambitus of the clarinet way beyond what is possible on a normal instrument with a reed. It is not by accident that the clarinet came to join the robot orchestra much later than all the previously realised robotic instruments. In many respects, the clarinet poses many more implementation problems than brass or double reed instruments, for its expressive possibilities are the widest of all wind instruments. First of all, there is the extreme dynamic range: close to 110dB, well above what is reachable with 16 bit processors. Furthermore, through reed control, the timbre of the sound is modulated continuously. This called for a pretty complex compression driver with many parameters, leading to a wealth of controllers for the user. Then of course, there are the 'special' playing techniques such as vibrato, flatterzunge as well as quartertones and microtonal inflections. Because of these complexities, we called in a true 32-bit ARM processor.

As in some previous robotic wind instruments, here again we implemented some form of movement: the clarinet together with the valve chassis are suspended in a cradle and can perform pendulum-like movement. Seen in the group of monophonic wind instruments designed and build sofar, <Klar> is doubtless the most flexible instrument. The wealth of controllers make it possible to program the instrument such as to sound sounds completely unlike what we expect clarinets to be capable of doing. It can easily surpass the possibilities of human players but at the other hand, human players can produce sounds that this robot is not yet capable of producing, such as some multiphonics, loud slaptongues and vocal-instrumental interfering sounds.

<Asa>

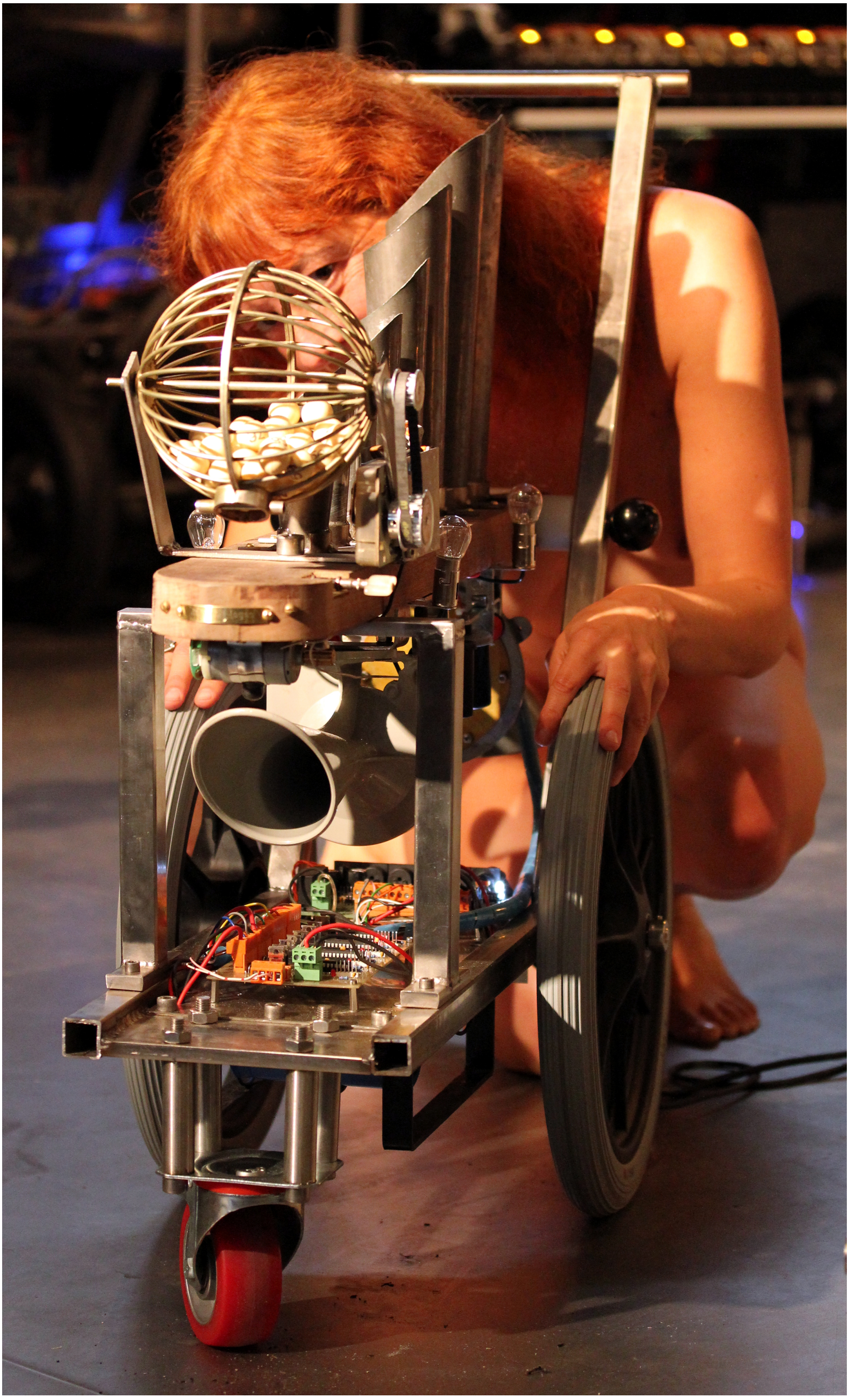
The instrument used to start off this robot building project was an alto saxophone made by Ancienne Maison Muller, Louis Cousin successeurs, in Lyon, France. We presume it dates from the early interbellum, as it must have been made after the death of the late Louis Cousin. Certainly not older than 1890. We started by thoroughly cleaning and restauring the instrument and bringing it back to full playing conditions. As it is a pretty old instrument, it misses some features in the mechanism typical for more modern instruments, such as automatic octave keying, palm keys and a few trill keys. An advantage as it turns out, for an instrument to be automated. Following the recipe applied in most of our wind-instrument robots sofar, we decided to drive the saxophone using a membrane compression driver followed by an acoustic impedance convertor. This convertor with its typical double coned design with a capilary connecting both cones, had to be calculated anew, as it had to fit the drive requirements for an alto saxophone. Our design is an attempt to match as closely as possible the characteristics of a normal mouthpiece with a reed for such an instrument.
For the implementation of the valves, we could build further on the experience we had build up during the realisation of our <Klar> robot. In fact, the case of a saxophone is even a bit easier as there are less valves that have to be operated. The two octave valves appeared to be dispensible, as with our driver mechanism the octaves actually even sound better without activation of these keys. So the double octave valve on the crook as well as the lower thumb operated valve could be left closed all the time. This left us at first sight with no more than 16 valves to be automated. However the native mechanism on a saxophone tends to be rather noisy. Therefore we decided to replace as many of the valves, pads and mechanisms as possible with solenoid driven pads acting directly on the tone holes. Therefore we unsoldered the posts holding the mechanism for many valves. The mechanism on the crook for the double octave, although not required, was left in place as well as valve 8, as we found no place for a directly driven solenoid pad here. The 'automatic' valves thus also required solenoids, bringing the total up to 18 valves.
An extra feature implemented in this robot is gesture: this saxophone can move left-right as well as front-back and thus is capable of mimicing the typical gestures a human performer might make when playing the instrument. This appears to be more than just a visual feature, as gesture in human playing is an essential ingredient of live performance and allows the audience to better capture the embodied meaning of the music.

<Temblo>

Temple blocks are in origin Chinese percussion instruments used in religious ceremonies. The instruments can also be found in this context in Korea and Japan. It is a carved hollow wooden instrument with a large slit. In its traditional form, the wooden fish, the shape is somewhat bulbous. From an acoustic point of view they function much like a tuning fork and their cavity like a Helmholtz resonator. The pitch of both elements should be matched for a good hollow and resonating sound. As such it is a synergetic construction.

Temple blocks are often found in the percussion section of classical orchestras in a simplified (and generally poorly sounding...) rectangular shape. Most commonly one will encounter them in a group of five blocks of different pitches. The original chinese instruments can be found in widely varying sizes: from close to 1 meter for the very largest ones up to really tiny ones not larger than 3 cm. The very small ones have a sharp and very penetrating tone. They are hand carved from a single piece of relatively soft wood and covered with a thick layer of mostly red chinese lacquer. The lacquer not only protects the wood against moisture and the impact of the beater, but also changes the sound somewhat in making the attack sharper. The traditional lacquer is derived from urushiol, a substance from the toxicodendron vernicifluum and has the property to form a natural polymere in the presence of moisture and medium heat. Once cured, it is hard and stable but the fresh substance itself gives cause to quite severe allergic reactions when brought in contact with the skin. In China the temple block is usually placed on a cushion. Mounting them in a stand is a western adaptation. Although they produce a quite distinct tone and pitch they are never used as pitched percussion instruments. Each temple block has its own individual beater, as the weight and hardness of the beater head has to match the size and weight of the block to be struck. The original chinese beaters are rarely used by percussionists in western ensembles and orchestras. Medium hard cloth covered vibraphone or marimba mallets give a good sound. Using too hard mallets (drumsticks, hard nylon beaters...) lead invariably to destruction of the templeblock, first by cracking the lacquer, secondly by destroing the wood itself.

The idea of making an automated set of temple blocks arose from educational needs: In 2012 we were asked to teach a class on modern instrument building and automation for the students enrolled in the instrument building program at the School of Arts (Ghent University College). After discussing the topics to be treated, we decided with the students to set up a building project that could be finished within a single academic year. Hence the choice of a percussion robot, as this seemed to require the minimum of preliminary research, without being a trivial undertaking. The fact that it would constitute a most welcome addition to the robot orchestra and not merely an academic project seemed a challenge to the students involved. The building project was started in october 2012 and the first automated sounds came out in february 2013. By the month may, Temblo made his final entry into the robot orchestra and many composition students wrote a piece for the newborn robot



<Whisper>

This robot is very silent by design. It's sound production is based on the cavity resonator. In daily life people may have run into such sound generators as they are often used as a whistle on some water cookers. They find extensive applications in bird calls of different kinds and in quite a few toys (rubber ducks) and simple toy instruments. All these are designed to be blown (or suck) with the mouth or a small bellow. From an acoustical point of view cavity resonators at first sight appear to be Helmholtz resonators: there is a cavity of air and two orifices on opposing sides of the cavity. However, the math around them does not seem to apply here. Properly speaking a Helmholtz resonator ought to have a single well defined resonant frequency lacking overtones, whereas the cavity resonators under consideration here operate over a range of more than an octave and produce a manifold of non-harmonic sounds and noises, including multiphonics. The main reason for this behavior seems to be that our resonators are driven by turbulent air of very low pressure and hence the dominant sounds produced are edge tones around the orifices. It is known from organ pipes that the frequencies of these edge tones are highly dependent on applied wind pressure.

We started off by constructing a wide variety of cavity resonators. Small flat cans gave good results and had a quite wide pitch range under varying pressure conditions. The addition of a conical secondary resonator increased the sound level quite a bit, although it greatly influences (and limits) the pitches obtainable. After a lot of experimentation we decided to construct these conical resonators with the large end cut under an angle of 45 degrees, this to make the resonant frequency less pronounced. These cones were made from a tin-lead alloy. The cavity resonators were glued inside the tapered end of the cones. We made stainless steel flanges to mount the resonators and their cones on the windchest.

Sofar we have no sound explanation for the observed difference between calculated and measured resonances. We might assume turbulencies play a major role here, and maybe the velocity of sound, taken as a constant in the calculations cannot be considered constant. As measurements on the propagation speed of sound in cavities and coupled cavities seemed to be in order, we performed some initial measurements using a pair of measurement microphones and an oscilloscope set up for delay measurement between two input channels. We used an electronic metronome as pulse source, placed as close as possible behind one of the microphones. The measured propagation speed of sound through constricted channels was ca. 10% lower than the speed in free air. The difference is substantial, but apparently not large enough to thoroughly explain our mystery...

The little fans to cause the turbulent wind work on a 12 V DC voltage but they easily can withstand 16 V. It should be noted that this instrument works on suction wind! We have no clue as to what explains the fact that suction wind works better, given the inherent symmetry of the resonators.

The rubbed string component is based on the same sound generation principles underlying Luigi Russolo's Intonarumori. He used a crank driving a wheel over which a piece of gut string (the tension could be controlled with a hand lever) was led. The other side of the string being attached to a membrane connected to an amplifying horn, a linear cone in most of his instruments. In our design we used a metal membrane coupled to a flared cone taken from an old alarm buzzer. The crank with wheel in the Russolo design, was replaced by a small high torque Johnson motor powered by a variable DC voltage

The three small shakers on this robot were made from empty 35 mm film cans filled with iron or lead granules. The shaking is activated by A.Laukhuff pallet lifting solenoids. On the front of the robot, we mounted two cast bronze sleigh bells activated by a somewhat larger solenoid.