LEMUR GuitarBot: MIDI Robotic String Instrument

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ABSTRACT
This paper describes the LEMUR GuitarBot, a robotic musical instrument composed of four independent MIDI controllable single-stringed movable bridge units. Design methodology, development and fabrication process, control specification and results are discussed.

Keywords
Robotics, interactive, performance, MIDI, string instrument.

1. DESIGN GOALS
In early 2001, LEMUR set out to create an ensemble of robotic musical instruments controllable by MIDI and playable by human musicians or from a computer. GuitarBot, one of several instruments created by LEMUR, was designed to be a responsive robotic stringed instrument controllable via MIDI for the performance of live, generated or sequenced musical works in concert or installed settings.
To help satisfy our goal that it could adopt any number of configurations and aesthetic treatments, the instrument is comprised of 4 identical modules which can be mounted and arranged to suit the needs of a given work. Each module is a monochord under tension suspended between 2 fixed bridges. Pitch variation is achieved by a motorized servo-positioned movable bridge which travels along the length of the string, in a manner similar to a slide guitar. The string is plucked, struck, bowed and otherwise excited by a system of plectra and other mechanical and electromagnetic actuators. A solenoid damper is employed to inhibit string vibration under control.
The sound of the string vibrating is electrified by an electromagnetic pickup positioned above and adjacent to the string, and processing and amplification are used to deliver the instrument's performance to the listener.

In order to maximize GuitarBot's usefulness to the greatest number of users, we adopted the MIDI standard for communication between the modules' onboard microcontroller and the outside world. The instrument module can be set to several MIDI modes which range from offering an external sequencer complete access over all parameters and functions of the robot, to condensed command sets suitable for control of the instrument by a live performer using a keyboard or other, more exotic controller.

General design principles also dictated that the instruments be fabricated in a manner as precise and repeatable as possible, with the goal of producing a series of durable, serviceable, and upgradeable devices. To this end, the iterative design process made heavy use of CAD to model and revise the instruments prior to milling and assembly.

2. DEVELOPMENT
The current version of the GuitarBot is the result of three design iterations. The first prototype was created experimentally, crafting the basic design from aluminum and investigating various mechanisms for the slide and picking systems, modifying and refining parts until we had a working proof of concept.

This unit was then modeled to scale in 3D using the Vectorworks CAD package which allowed us to explore design scenarios before committing to and machining the next version. This second version was built to spec from the CAD model and tested. Additional changes were made to the CAD model, further refining the accuracy and playability of the instrument. As a reflection of our growing understanding of the milling, machining and assembly processes, design enhancements at this stage also served to increase the ease of manufacturing and servicing the unit.

Following this round of changes, the third and current version of GuitarBot was constructed and is described below.

2.1 Mechanical
Each Guitarbot module is assembled on a 36" x 4" aluminum base. A steel electric guitar or bass string, with a diameter range of .01" to .02" for plain strings, and .02" to .1" for flatwound strings, is stretched between 2 fixed bridges and tensioned with a worm drive guitar tuning peg. Open string pitches from E at 41.2Hz through E at 392.6Hz are within the nominal range of the instrument. The effective maximum length of the string is 27.03", occuring when the moving bridge is furthest from the base fixed bridge. The moving bridge has a travel length of 21.44" inches, or 79.3% of the effective length of the string, thus ensuring a pitch range of over 2 octaves.

The moving bridge assembly travels in a ball bearing slide track and is positioned by means of a drive belt affixed to the

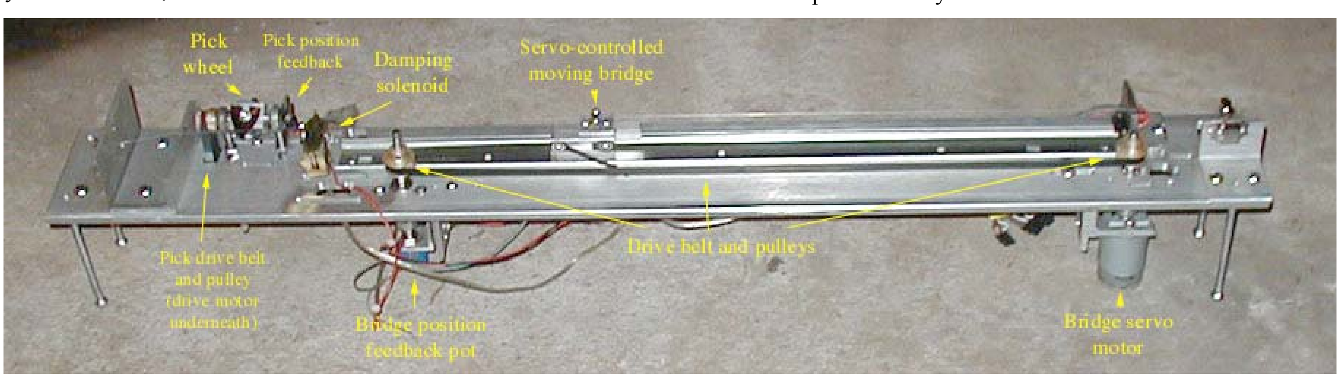

Figure 1. GuitarBot prototype

bridge and riding on pulleys. The drive pulley is driven by a DC servo motor, and the idler pulley is coupled to a 10-turn rotary potentiometer. End-to-end travel time of the slide assembly is under 250ms.

In contrast to previous mechanical guitar-like instruments like Sergi Jorda's 6 string hammer-on fretted robot[1], the string is excited by means of a plectrum mechanism consisting of 4 nylon guitar picks mounted on a block that rotates on a shaft. The shaft is belt and pulley driven by a DC servo motor on the underside of the assembly. Position feedback is derived from an encoder wheel mounted on the end of the shaft, which passes between the emitter and detector of a photosensor module. The closed loop servo motor system guarantees that the pickwheel assembly can be quickly and accurately rotated so that a note can be struck and the next pick brought into position to await the next trigger. Additionally, the pickwheel can be rotated at various speeds to produce humanly impossible feats of tremolo.

A "clapper" solenoid is used as a damper which, when activated, closes on the string and stops vibration. This allows the instrument to respond to note-off requests and also permits a playing technique in which the string is picked while dampened, producing a muted "thumping" and more percussive sound without sustain.

An electromagnetic pickup of our own design is affixed to a flexible metal arm which clamps to the base. The design of the arm permits the pickup to be positioned at various places along the length of the string to take advantage of variations in tone. We used a 1/4" diameter rare earth magnet as the base of our hand wound single coil pickup which, when complete, proved to have excellent gain and noise rejection characteristics when compared to off the shelf systems with which we initially experimented.

2.2 Electronics

Each GuitarBot module has onboard circuitry to handle all actuators, motor control and feedback locally. Custom control boards were designed around a Microchip PIC16F87x-series microcontroller and contain two DC servo amps, MIDI I/O circuitry and power supply and microprocessor support components. The board additionally features assorted diagnostic and status LEDs and in-circuit serial programming connections.

Inputs to the microcontroller include opto-isolated MIDI-format serial, analog values from the slide position potentiometer and digital input from the pickwheel encoder. The slide position pot values are sampled at 10-bit resolution, which, as we are using approximately 95% of the pot range, results in an effective resolution of almost 1000 linear positioning steps over the 2 octave range of the instrument.

Outputs from the microcontroller include MIDI-format serial, PWM motor control, and digital control of the damper solenoid.

2.3 Software and Control

The GuitarBot embedded software system can be broken into three components: Input, Configuration and Control. The Input component is responsible for receiving, filtering and dispatching MIDI messages to the other components. The Configuration component is used to save, restore and implement control routing presets and the system tuning table. The Control component is responsible for driving the bridge and pickwheel motor and managing the damper state.

The bridge positioning subsystem is the most complex piece of the Control component. The primary objective of this subsystem is to position the bridge smoothly and accurately at a user definable speed. The following is a summary of the structure and operation of the bridge subsystem.

The inputs to the bridge positioning subsystem:

1. The current position of the bridge as measured from the idler pulley rotary potentiometer and converted to a digital value via the microcontroller's on-board analog-to-digital converter (ADC).
2. A user defined target position and travel velocity. The travel velocity determines how fast the bridge should travel to the target position.

The outputs calculated by the bridge positioning subsystem:

1. The bridge motor voltage. This output directly determines the speed of rotation of the motor and therefore the speed of motion of the bridge.
2. The bridge positioning motor direction. This output determines whether the bridge moves toward higher or lower pitched notes.

The bridge positioning subsystem periodically generates a new set of output signals by running the following algorithm:

1. Determine the current bridge position by reading the rotary pot ADC.
2. If the bridge target position is not the same as its current position generate the best motor voltage and direction for moving the bridge towards the target position at the user defined travel velocity.
3. Wait until the next read time occurs then go to 1.

The obstacles to achieving smooth and accurate control of the bridge can be demonstrated by considering how the physical bridge system responds to repositioning requests at very high and very low speeds. For example at high speeds the bridge will tend to overshoot the target position. The overshoot is a result of the momentum the bridge may have gained during travel and the inevitable delay between when the rotary pot ADC is read, when the next motor voltage is computed, and how quickly the motor is able to respond to that new voltage. At low speeds the physical system has a different set of characteristics. For example it will tend to move sporadically as it overcomes static friction or encounters changing forces due to the slight twisting produced by the side mounted drive belt.

After trying several ad-hoc motion control schemes we arrived at a satisfactory software solution to the bridge positioning problem by implementing a Proportional-Integral-Derivative (PID) based algorithm. The PID algorithm accepts as input an error value and three user definable coefficients referred to as P,I and D. In this case the error value is the difference between the current bridge position and the target bridge position. The algorithm directly computes the bridge motor voltage by scaling the error, the time derivative of the error, and the time integral of the error by P,I, and D respectively and then summing the three scaled values. We arrived at values for the P,I, and D coefficients through interactive experimentation.

The Control component also implements two pickwheel operational modes. In the first mode the user can set when the pickwheel is triggered and how many times the the string is plucked per trigger. In the second mode the pickwheel spins continuously and the user can control the speed of rotaion.

The Control components damper control subsystem manages a set of user selectable trigger/release algorithms. These include a mode which allows applying the damper directly, a mode which keeps the damper on the string for a predetermined amount of time after each damper trigger and

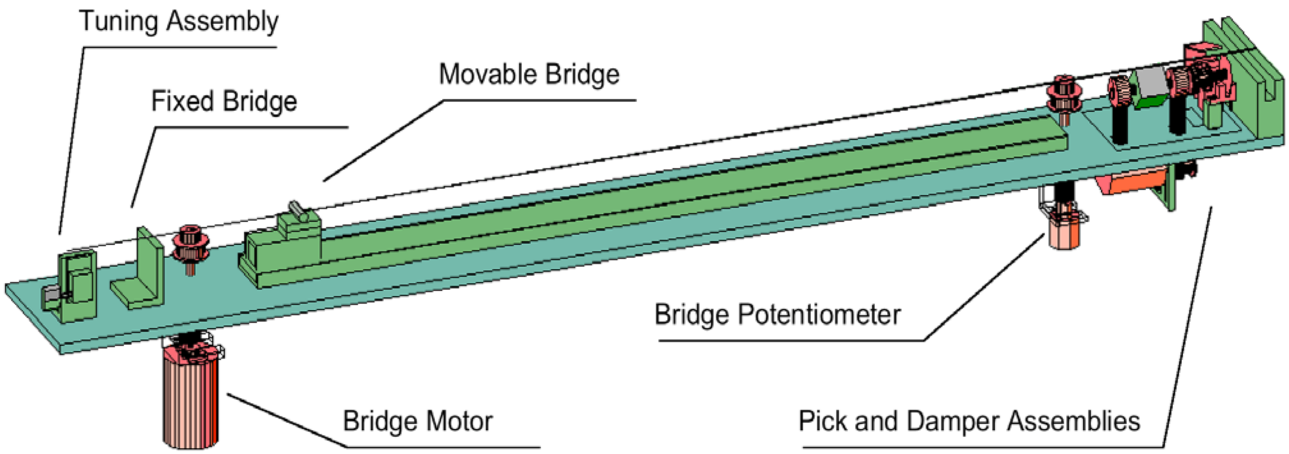

Figure 2. CAD model of current version

then automatically lifts it, and a mode where the damper is lifted just prior to the pick wheel pluck and then put down manually or automatically after an elapsed time.

All of the control component variables used to determine the bridge position, pickwheel triggering and damper state are user programmable via MIDI. The Configuration component is responsible for deciding which MIDI messages are routed to each of the control component variables. This logical distinction between control and configuration allows for maximum flexibility in defining user interface modes. By default Note-on pitch values determine the center pitch, pitch bend messages determine pitch offset above and below the center pitch, and note-on velocity messages control bridge velocity. This setup allows a MIDI keyboard to easily control the instrument in the expected way. However the routing configuration can be easily changed to more unusual schemes. For example if the MIDI pitch wheel is routed to the center pitch, the MIDI modulation wheel to the pick wheel velocity, and the note-on/off gate to the damper trigger, the pitch and the pluck rate can be controlled quickly and continuously for interesting sonic results.

The Configuration component also manages the storing and recalling of configuration presets and the system tuning table to non-volatile memory. The default tuning table supports the traditional Western twelve notes per octave equal-tempered system however it can be changed by the user to contain any arbitrary values.

3. FUTURE

Future aesthetic and functional improvements are planned. The picking system is designed to be interchangeable, and different actuation systems can easily be swapped in and out. Other mechanisms under consideration for playing the string include bouncing action, bow-like action, rubber and glass wheels and electromagnetics (i.e. EBow).

Software improvements will include the addition of a load balancing and dynamic allocation algorithm, allowing a designated master unit to distribute monophonic and polyphonic note data to the best available unit or units.

By making the units of the instrument modular, we are able to place them into different sculptural and aesthetic contexts. Future designs concepts in which to incorporate the guitar units include a pyramidal structure with integrated speakers and amplification and an anthropomorphic humanoid "Guitar God" robot. Also, on-unit MIDI-controllable lighting effects will be implemented.

4. ABOUT LEMUR

LEMUR – League of Electronic Musical Urban Robots – is a New York City based group of musicians, artists, engineers and technologists dedicated to producing robotic musical instruments (http://ericsinger.com/LEMUR). Founded by Eric Singer in 2000, LEMUR received a $30,000 Rockefeller Foundation grant awarded in 2001 to create an orchestra of musical robots. Under this development grant, LEMUR completed four instruments in 2002: the string-based *GuitarBot*, and three percussion-based instruments, *ShivaBot*, *!rBot* and *TibetBot*.

LEMUR is affiliated with Harvestworks Digital Media Arts Center, a non-for-profit organization founded in 1977 to cultivate artistic talent using electronic technologies (http://harvestworks.org).

LEMUR research and development is headquartered at the Madagascar Institute, a Brooklyn-based collective of art stars, geeks, pyromaniacs, insurgents and other misfits dedicated to keeping NYC art spontaneous, hazardous and exciting by means of guerilla street performance, techno-art, carnival rides, kinetic sculptures and a whole lot of stuff blowing up. (http://madagascarinstitute.com).

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Figure 3: Completed GuitarBot in its native urban environment

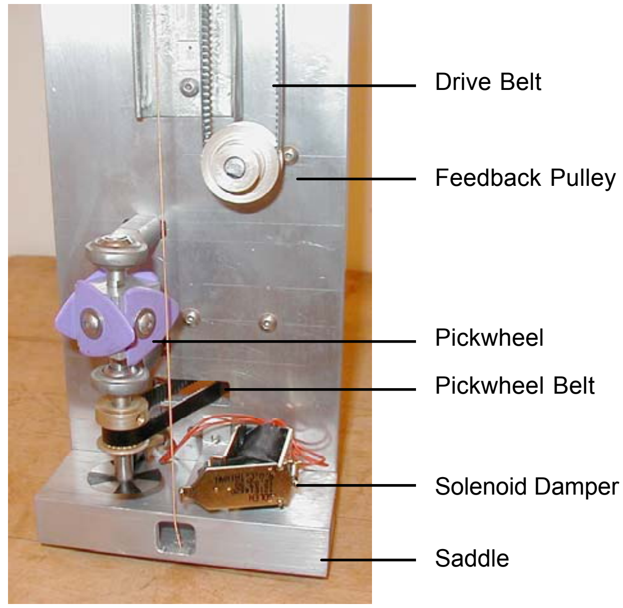

Figure 4: Detail of Pickwheel and Damper assemblies