

# The JD-1: an Implementation of a Hybrid Keyboard/Sequencer Controller for Analog Synthesizers

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## ABSTRACT

This paper presents the JD-1, a digital controller for analog modular synthesizers. The JD-1 features a capacitive touch-sensing keyboard that responds to continuous variations in finger contact, high-accuracy polyphonic control-voltage outputs, a built-in sequencer, and digital interfaces for connection to MIDI and OSC devices. Design goals include interoperability with a wide range of synthesizers, very high-resolution pitch control, and intuitive control of the sequencer from the keyboard.

## Keywords

keyboard, sequencer, analog synthesizer, capacitive touch sensing

## 1. INTRODUCTION

Despite advances in digital synthesis, many musicians still prefer the sound and interface of classic analog synthesizers developed from the mid-1960s to the early 1980s. Current trends in commercial electronic music reflect this preference, from analog modeling in software synthesizers, to the recent releases of new hybrid analog/digital synthesizers by Buchla and Associates<sup>1</sup> and Moog Music Inc.<sup>2</sup>, to a growing market for modern analog modular synthesizers that are modeled off of the extensible systems of the 1960s and 1970s, including manufacturers such as Doepfer, MOTM, and Wiard.

Advantages of analog modular synthesizers include near-zero latency, complete lack of aliasing effects, and a user interface that gives each user parameter a dedicated physical control.

Disadvantages of analog modular synthesizers include tuning instability, high cost when compared with software-based systems, lack of repeatability and preset storage, and difficulty communicating with modern digital systems.

This paper presents the JD-1, a digital controller for analog synthesizers that combines a touch keyboard with a built-in sequencer. Details of the hardware and implementation are discussed, along with our motivations behind the design, and our approach to the challenges of building a controller that is compatible with several different standards. Our design retains the advantages of analog modular synthesizers while alleviating some of their disadvantages, while also allowing interoperability with modern digital systems.

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## 2. EXISTING INSTRUMENTS

The primary historical precedent for our work is to be found in touch controllers and sequencers from the 1960s and 1970s, which have either become scarce or have no capability for digital communication, and our aim is to emulate and extend this technology. The primary model for the JD-1 keyboard/sequencer is the TKB, designed by Serge Tcherepnin in the 1970s, and still commercially available today from Sound Transform Systems<sup>3</sup>. The innovation of the TKB lies in its combination of the touch keyboard and analog sequencer paradigms. When used as a keyboard, the voltages associated with knobs above each key are selected by touching the capacitive sensing keys.

Though there had been precedents for both capacitive touch sensing and sequential voltage control, Don Buchla<sup>4</sup> pioneered the application of both the touch keyboard and the analog sequencer to modular synthesizers. The model 112 touch interface introduced the concept of arbitrary voltages, set by knobs, which could be selected by capacitive touch plates, and also allowed for the touch plates to send a varying voltage derived from the added capacitance of the musician's finger as it covers more surface area on the touch-plate. At around the same time, Buchla developed the first analog sequencer, in which voltages set by knobs could be stepped through via a clock pulse. Moog followed soon thereafter with his own version of the analog sequencer, and the design paradigm is still present in vestigial form in modern drum machine software. Serge Tcherepnin made an important contribution to the controller genre in the mid-1970s with the introduction of the TKB, which combined the capacitive touch-sensing keyboard idea with the analog sequencer. The TKB allowed for more control possibilities in a smaller space, since the knobs could now serve as both sequencer stage voltages (voltages that are output when a sequencer clock steps to them) and key-associated voltages (voltages that are output when the user touches a particular key).

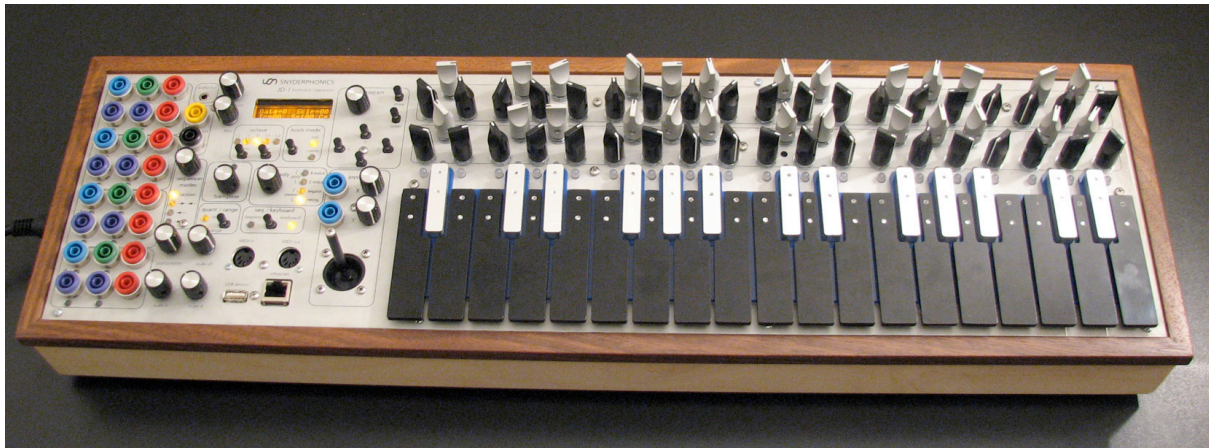
More recently, research has continued into capacitive touch sensing as a viable technology for extending the keyboard or keyboard-like controllers. The Manta, by Jeff Snyder [1], uses capacitive touch sensing to achieve continuous control data related to surface area covered by a finger on discrete sensors laid out in a hexagonal grid. The Touchkeys [2], by Andrew McPherson, applies capacitive sensing technology to traditional piano keys to achieve additional control information from finger position and centroid mass. Other recent inventions that extend the touch keyboard concept include the Hakken Continuum by Lippold Haken, who has developed a successful touch keyboard that senses both finger position and finger depth, using a design involving Hall effect sensors [3].

<sup>1</sup> <http://www.buchla.com/>

<sup>2</sup> <http://www.moogmusic.com/>

<sup>3</sup> <http://www.serge-fans.com/>

<sup>4</sup> <http://www.synthmuseum.com/buchla/buc10001.html>

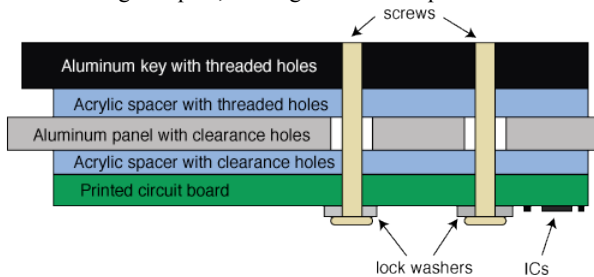


**Figure 1: The JD-1 keyboard/sequencer controller.**

### 3. DESIGN

#### 3.1 Overview

The JD-1 (Figure 1) is a controller that integrates traditional touch keyboard functionality with analog sequencer functionality, and extends these paradigms with sophisticated digital control and modern interfacing technology. The right side of the JD-1 presents the touch keyboard and knob banks, and the left side of the controller presents an analog joystick, a user interface for operational modes and settings, analog control voltage outputs, and digital interface ports.



**Figure 2: Side view of JD-1 key construction.**

#### 3.2 The Keyboard

The keyboard of the JD-1 (Figure 2) is made up of 32 CNC-milled aluminum keys, arranged in a traditional diatonic piano/organ layout. The keys are fixed in place and do not move; they act as capacitive touch sensors, and each sensor outputs a value proportional to the surface area covered by the musician's finger on a key. Our early prototypes of the JD-1 keyboard followed more traditional capacitive sensor design, in which the sensors are etched into a PCB as a flat, undifferentiated surface. While this works well for generalized, tile-like layouts like the Manta or Buchla 112 controller, a flat layout was found to be unsuitable for the traditional diatonic layout, since it loses the ergonomic advantages afforded by the raised flats and sharps on a standard musical keyboard. After experimentation, it was found that 3mm of height difference between the accidentals and naturals was enough for musicians to more accurately play scales with many flats or sharps. Another advantage of the JD-1 key design over a flat PCB capacitive sensing interface is the tactile distinction between all of the keys. The physical gaps between the keys make the keyboard easier to play without visual feedback.

Each key is mechanically and electrically connected by two screws, which screw through the circuit board from below and into threaded holes in the keys. The keyboards have been anodized for scratch resistance, aesthetic appeal, and color coding, so the threaded holes are plugged before the anodization process to maintain electrical conductivity. The keys are anodized in a color scheme commonly called

“reverse”, in which the naturals are black and the accidentals are lighter, clear anodized aluminum in the case of the JD-1. This is done as a visual reference to the harpsichords and organs of the 16<sup>th</sup> and 17<sup>th</sup> centuries, to give an attractive styling to the instrument.

The span size of the keyboard is 158 mm for the octave, slightly smaller than a modern piano (which is usually 165 mm), and more in line with what is often called the French keyboard span, in reference to the key size of 18<sup>th</sup> century French harpsichords [4]. This was done to conserve panel space, and also as another playful reference to keyboard history.

#### 3.3 Analog Synthesizer Outputs

The JD-1 has both continuous voltage outputs and gate outputs, both of which are necessary to control analog synthesizers.

##### 3.3.1 Continuous Voltage Outputs

A primary goal of the JD-1 is to allow highly accurate control of pitch, ideally within one cent (1/100<sup>th</sup> of a semitone) precision. The JD-1 has 16 continuous analog control voltage (CV) outputs, including four with 16-bit resolution and twelve with 12-bit resolution. The 16-bit outputs are intended as pitch control voltages, and the 12-bit outputs are intended for other parameters where accuracy is not as critical.

Since the JD-1 was designed to allow the control of various synthesizer brands, the CV outputs can be scaled to support various synthesizer standards. The most prevalent analog CV standards for pitch control are 1V/oct, 1.2V/oct and Hz/V. 1V/oct, in which a change in the input voltage by one volt causes a change in frequency of one octave, is the standard adopted by Robert Moog, and followed by many synthesizer builders in the 1970s and almost all modern modular synthesizer manufacturers<sup>5</sup>. 1.2V per octave is the standard set by Don Buchla, chosen so that 100mv is equal to 100 cents. The third standard is what is often called Hz/V. In this standard, followed by Korg and Yamaha, the linear-to-exponential scaling is not done inside the oscillator, and therefore the control voltage sent to the oscillator has to implement an exponential curve to produce a perceptually linear rise in pitch.

In terms of the 1V/oct standard, 16-bit resolution for a standard 10V range would theoretically provide 0.183 cents resolution over 10 octaves. For 1.2V/oct, 16-bit resolution theoretically provides an even better 0.153-cent resolution range. By contrast, a 12-bit resolution DAC would theoretically provide 2.92 cents resolution for 1V/oct scaling. If applied to the Hz/V standard, resolution would vary over the range of the oscillator, with the lowest resolution falling in the lower frequencies. Most synthesizers expect pitch control voltages from 0V to 10V, but some, including Serge Modular, use -5V to 5V, and others use 0V to 5V for many non-pitch parameters.

<sup>5</sup> <http://en.wikipedia.org/wiki/CV/Gate>

Whether the analog oscillator receiving the voltage is capable of a high level of pitch accuracy is beyond the control of the JD-1, or any analog synthesizer controller, but our design goal was to be at least as accurate as the best analog oscillator designs. As for commercial manufacturers, both Buchla and Wiard state tuning resolution within +/-5 cents over 8 octaves, the extremes of which would be noticeable in a just intonation setting; other manufacturers do not state a tuning resolution for their oscillator modules. Any inaccuracy or non-linearity in the JD-1 would cause even more error in VCO tuning, so our design works to minimize these errors. The most critical specifications for the DAC IC are offset voltage and nonlinearity; frequency domain performance is not important. The circuit that follows the DAC output adds a low pass filter sufficient to remove high-frequency noise and zipper noise without causing perceptible slew, which would be heard as portamento, and also scales the voltage with a gain of two, using precision resistors to avoid gain error.

Our results have been promising. When the JD-1 controls VCOs built from Ian Fritz's sawtooth-core circuit<sup>6</sup>, which is specifically designed for tuning accuracy and low temperature drift, just intonation intervals that sound very accurate to the ear are possible over the range from approximately C1 to C7. Tests with oscillators following Ray Wilson's design<sup>7</sup> (which is based on the same Terry Mikulic Electronotes VCO design [5] as the Ian Fritz) show acceptable but less precise tuning results.

### 3.3.2 Gate and Trigger Outputs

Gate Controls are another type of voltage control used by analog synthesizers, usually to trigger envelopes or switch signals. As with continuous voltage control, there are several competing standards. Most manufacturers use a two-state gate control, in which there is an off state and an on state. In the standard used by Moog, often called "S-Triggered", a "high" voltage (nominally 5V) represents the off state, and a "low" voltage (nominally 0V) represents the on state. The inverse of this, in which 0V is off and 5V is on, is standard on many synthesizers made by other brands, and is often called "V-Triggered". Buchla synthesizers follow an alternate standard with three states, called "Gate+Trigger", where a 12V pulse signals an event, after which the gate voltage quickly drops to 7V until a release action occurs to drop the voltage down to 0V. The JD-1 has eight gate outputs, all of which are capable of conforming to all three of these gate standards, depending on the mode settings chosen by the user.

## 3.4 User Modes and Controls

There are several user modes and controls that are accessible via buttons, potentiometers, and rotary encoders on the left side of the panel. LED indicators and a 3x16 LCD display provide user feedback. Descriptions of the user controls follow.

### 3.4.1 Keyboard Mode

A button labeled keyboard/sequencer allows the user to switch between a keyboard-style mode and a sequencer-style mode.

When Keyboard Mode is active, the JD-1 only outputs analog voltages when keys are touched on the keyboard. Polyphonic handling is chosen with a rotary encoder that allows for 5 modes: monophonic retrigger, monophonic legato, dual-voice polyphony, four-voice polyphony, and no polyphony handling (equivalent to full 32-note polyphony). The polyphonic restrictions are useful for interfacing with analog synthesizers

where the number of voices is limited, and the mode without polyphony handling is useful when the JD-1 is used as a MIDI or OSC controller for software and therefore polyphony handling is not necessary. Tri-color LEDs above the keyboard light red to indicate which pitches are currently assigned to polyphony voices. For each active polyphony voice, there are four continuous analog voltage outputs, and two gate outputs.

One of the 16-bit DAC channels outputs the "pitch" data, which relates to the chromatic pitch selected on the keyboard. This voltage is in twelve-tone equal temperament by default, but can be further adjusted to other scales stored in memory. These alternate scales are selectable by navigating the LCD.

One of the 12-bit DAC channels outputs a voltage proportional to the amount of surface area covered by a finger on the touch key; this voltage is continuously updated every four milliseconds while the key is touched. This output can be scaled down from full range with a dedicated potentiometer.

Two more 12-bit DAC channel outputs the voltages set by the two knobs above the touched key. The outputs are labeled A and B, corresponding with labels on the knob banks—the upper bank is A, the lower is B. These voltages are also continually updated every four milliseconds, so they respond to changes that occur while the key is touched, and each output has a dedicated knob for proportional scaling. Like all other analog outputs on the JD-1, these can be used to control any parameter of an analog synth, including pitch, filter cutoff, or amplitude.

One of the gate channels outputs a gate-on event when the key is touched, and a gate-off event when the key is released. Another gate channel outputs a short gate-on event when the key is touched, which is quickly followed by a gate-off event—traditionally called a "trigger" voltage. The actual voltages of these events are controlled by internal modes that can be changed by the user between S-Trigger, V-Trigger, and Buchla-style Gate+Trigger.

### 3.4.2 Sequencer Mode

When the JD-1 is switched to Sequencer Mode, touching a key no longer triggers an output. Instead, output is triggered by a clock pulse, either from the internal clock in the microcontroller, or from an external trigger voltage. At each clock pulse, a new sequencer stage is selected and the associated pair of potentiometers determines the voltages at the A and B analog outputs. The tri-color LED associated with the currently selected sequencer stage lights up for performer feedback, though the color of the LED depends on the current sequencer mode. The voltage for the pitch associated with the currently selected sequencer stage is also output from the 16-bit DAC channel. The maximum continuous sensor reading for surface area on the keys (including all touched keys) is output as a voltage on the surface area voltage output.

In sequencer mode, there are two sub-modes, which determine how the touch keyboard interacts with the sequencer functionality. In the first sub-mode, called Range Mode, touching two keys on the keyboard will restrict the sequencer to only step between the two stages associated with the touched keys, which light green for performer feedback. This range restriction remains in place after the musician's fingers leave the keys. In the second sub-mode, called Quantize Mode, the sequencer does not clock unless at least one key is touched. When at least one key is touched, the sequencer will only step to stages that are currently touched by the musician, and the LEDs above the touched keys light red for performer feedback. When used in conjunction with the "pitch" control voltage output, the functionality of Quantize Mode is very similar to a classic keyboard arpeggiator.

<sup>6</sup> [http://home.comcast.net/~ijfritz/sy\\_cir2](http://home.comcast.net/~ijfritz/sy_cir2)

<sup>7</sup> [http://www.musicfromouterspace.com/analogsynth\\_new/VCO20090724REV0/VCO20090724REV0.html](http://www.musicfromouterspace.com/analogsynth_new/VCO20090724REV0/VCO20090724REV0.html)

The choice of the next step is determined by a rotary encoder. This control chooses between the following modes: left-to-right, right-to-left, back-and-forth, and random.

There several additional features that give further control over the sequencer functionality. A skip-step value allows the user to adjust the percentage of clock pulses that result in a sequencer step – allowing for an adjustable proportion of randomly skipped steps. When the internal clock is used, user parameters accessible from knobs on the panel include a speed control and a randomness control, which allows for varying levels of randomness in the duration between clock pulses.

### 3.4.3 The Joystick

An spring-return analog joystick reports its X and Y location as analog voltages between 0V and 5V, and is also sensed by the main microcontroller and converted for MIDI and OSC output. Each analog output for the joystick can be scaled down from full scale by a potentiometer.

### 3.4.4 Additional Controls

Octave Up and Octave Down buttons allow the user to immediately transpose the pitch up or down by one octave, and the current octave is indicated by nearby LEDs.

A Transpose rotary encoder allows for transposition up and down by up to twelve semitones. When a tuning system other than equal temperament is used, the size of the semitones is adjusted according to the pitch class in the current tuning system. The current transposition is indicated on the LCD screen, and any transposition other than zero causes a “transpose on” LED to light above the rotary encoder.

There are two buttons that set the functionality of the A and B knob banks, called Independent and Combined. When the Independent button is pressed, the A and B knob banks are treated separately, and output independent voltages. When the Combined button is pressed, the B knob bank acts as a set of fine tune knobs for the A knob bank, allowing for higher resolution if the user wishes to use these knobs for pitch.

The LCD menu allows the user to select between 1V/Oct control voltages and 1.2V/Oct control voltages, as well as allowing the choice of gate style to adapt to different synthesizer standards. It also affords the ability to fine tune the pitch control voltage scaling, so that synthesizers that don't achieve a linear response can be accommodated. While storage of knob settings is currently not implemented in the firmware, it is completely possible with the current hardware design, and will eventually be navigable via the LCD menu.

## 3.5 Digital Interfaces

In addition to the analog control voltage outputs, there are three digital communication protocols implemented on the JD-1: MIDI, USB, and Ethernet.

MIDI connectivity is provided via two standard 5-pin DIN jacks, one for MIDI In and one for MIDI Out. The MIDI In port allows for direct MIDI control of the analog outputs, making the JD-1 also function as a MIDI-to-CV converter. The MIDI In port also allows for clocking of the sequencer using MIDI note-on messages. The MIDI Out port sends data that matches the behavior of the analog control voltage outputs, with MIDI notes that reflect note-on and note-off events, and MIDI continuous controller values that represent the continuous surface area outputs and the state of the A and B knob banks. When polyphony handling is set to two-voice or four-voice, the MIDI Out port sends the data for the polyphony voices on separate MIDI channels. When polyphony handling is turned off, the MIDI Out port sends individual data on 16 different MIDI channels, with up to 16-note polyphony.

USB connectivity is limited to embedded host mode, meaning that the JD-1 cannot be used as a USB device sending data to a computer. Currently, the USB port is only used for firmware updates using a USB flash drive, but it could also allow for the JD-1 to understand other USB devices, such as a Manta controller, HID joystick, or USB MIDI-keyboard.

The Ethernet port is to allow the JD-1 to send and receive Open Sound Control (OSC) messages when connected to a computer or a network [6]. Each of the analog control voltage outputs can be independently controlled from a network to their full resolution, and the JD-1 keyboard and sequencer information is sent out as OSC messages as well. When polyphony mode is turned off, the JD-1 sends fully polyphonic data over OSC, allowing for a computer to get continuously updated information about the state of all the keys and knobs.

## 4. FUTURE WORK

While the hardware is built and functional, there are several features that the hardware design makes possible that have not yet been implemented in the firmware.

The design could benefit from the type of velocity detection algorithm employed on the Manta controller, which estimates attack velocity on an immobile capacitive touch sensor by applying a trained machine learning algorithm to successive sensor readings. In fact, the data collected is more suited to the task, since the scan rate is 4ms rather than 6-8ms, as on the Manta, and the large surface area of the metal keys allows the JD-1 to sense a finger approaching the key at a distance of a quarter inch, information that could be used in the velocity detection algorithm to speed up response and accuracy.

User programmability of the JD-1 could be significantly improved. One particularly useful feature that the hardware makes possible is the ability to save and recall the states of the A and B knob bank. An EEPROM IC was included in the hardware design to enable a large amount of saved knob settings, but the firmware doesn't yet support this feature. Also, while the JD-1 currently implements six preset tuning system options, the instrument would ideally be programmable over OSC, enabling the user to enter their own tuning tables, or load them in using Scala format files<sup>8</sup>.

## 5. ACKNOWLEDGMENTS

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<sup>8</sup> [http://www.huygens-fokker.org/scala/scl\\_format.html](http://www.huygens-fokker.org/scala/scl_format.html)