Umbilical: A Hybrid System for Creating Custom Modular MIDI Controllers - A Eurorack/VCV Rack Case Study

Celeste Betancur Gutiérrez
celeste@ccrma.stanford.edu
CCRMA, Stanford University
Stanford, California

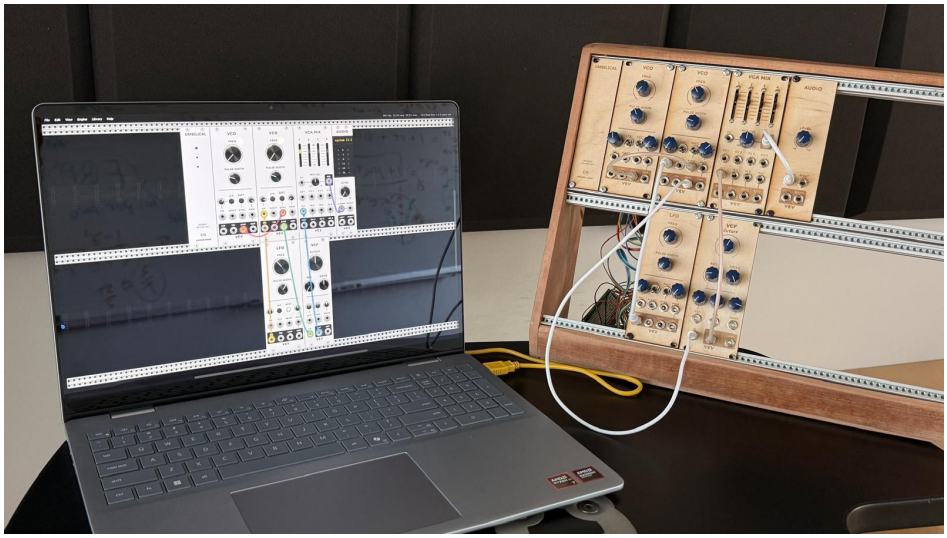

Figure 1: The Umbilical interface synchronizes a custom physical modular controller with the VCV Rack environment, establishing a precise one-to-one mapping of all knobs, switches, and more importantly, the patch cables.

Abstract

This paper introduces Umbilical, a hybrid system for creating custom modular MIDI controllers that prioritizes tactile embodiment through strict one-to-one mapping. Focusing on a VCV Rack case study, Umbilical utilizes a dual architecture: a digital symbiont module that exposes the software API, and a physical interface that mirrors digital modules, including the physical patching of cables essential to Eurorack performance. By requiring performers to craft specialized interfaces, Umbilical bypasses the abstractions of universal controllers. The system leverages the high-density I/O of the Umbilical Monster Board to restore the bespoke "small gestures" vital to performance practice. I argue that this approach establishes an intuitive connection between the artist and their digital instrument without the prohibitive cost of a traditional hardware setup.

Keywords

hybrid, interfaces, tangible interaction, modular, mapping, custom

1 Introduction

In the evolution of digital music production, the transition to software and screens has often sacrificed tactile immediacy. Performers are frequently forced to navigate diverse and contradictory musical tasks using generic, universal interfaces. Drawing on theories of embodied interaction, which emphasize that our tools are not merely passive transmitters but active participants in cognition [1], Umbilical bridges this gap by restoring the physicality of specialized, bespoke mappings. While modern digital platforms offer unparalleled flexibility, universal MIDI controllers introduce layers of abstraction that provide limited pedagogical or creative benefit. Umbilical argues that "small gestures" such as the precise turn of a dedicated knob or the physical routing of a signal are epistemically essential to musical expression.

Driven by the increasing accessibility of low-cost microcontrollers, Umbilical advocates for hardware setups that precisely mirror their digital counterparts. While this paper details a custom modular controller replicating VCV Rack modules, emphasizing physical patch cable detection and direct hand-eye correspondence, the underlying framework is extensible to other platforms.

2 Related Work

The push to merge the flexibility of software with the physicality of hardware has driven significant innovation in digital instrument design. Embedded DSP platforms like Bela, Axoloti, and Daisy have successfully brought software patches into standalone physical objects. In the modular synthesizer realm, interfaces like

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the Expert Sleepers ES-8 and ES-9 act as audio-rate bridges, allowing physical Eurorack control voltages to interact with software environments.

Furthermore, researchers have explored tangibility in modular systems. Projects like Patchwerk [4] demonstrated large-scale, multi-user physical control over modular setups, while Fasciani and Rahman's Tangible Virtual Patch Cords [2] explored physical routing for digital engines. McPherson and Zappi [5] have also highlighted the importance of exposing the "scaffolding" of digital instruments to the performer.

Umbilical builds upon this foundation but occupies a distinct niche. Rather than focusing on audio-rate CV transmission (like the ES-8) or generic standalone DSP (like Bela), Umbilical focuses strictly on the 1:1 physical replication of the interface itself, in this case, specifically the act of patching cables as an educational and performance interface for VCV Rack. It aims to democratize the Eurorack experience by decoupling the physical interface cost from the DSP engine.

3 Umbilical

Umbilical is a hybrid system that "ghosts", in the sense of the Greek Imago, digital plugins within the physical world. Rather than acting as a generic controller, it serves as a physical manifestation of a digital essence. The system architecture is bifurcated into two primary components:

The Digital Symbiont: A specialized plugin implanted within the host environment (in this case a VCV Rack module). This component functions as a communication hub, intercepting the host's internal API and exposing it via MIDI, serial and OSC protocols. By acting as a "symbiont" it leverages the host's processing power and signal routing while managing the bidirectional flow of data between the software and the outside world.

The Physical Mirror: A custom hardware interface designed to mirror the digital UI with precision. This extends beyond standard parameters like knobs, sliders, and switches to include the physical patching of cables. The hardware detects physical connections between modules and communicates these states back to the software in real-time.

The core philosophy of Umbilical is the deliberate limitation of the system to a one-to-one mapping. By enforcing this strict correspondence, the system removes the cognitive load of "remapping" and menu-diving. However, this rigidity is balanced by the modularity of the design, which allows the physical interface to expand and evolve alongside the user's digital library. In essence, Umbilical provides the tactile soul of a hardware synthesizer with the infinite flexibility of a digital engine.

Umbilical emerges as a functional bridge for the concepts of hybrid interfacing discussed in the concluding chapters of *Developing Virtual Synthesizers with VCV Rack*[3]. It occupies a critical middle ground in the synthesizer ecosystem. While prototyping within a digital platform like VCV Rack is inherently accessible, cost-effective, and flexible, the transition from a virtual prototype to a physical Eurorack system often presents a prohibitive barrier in terms of cost and complexity.

Umbilical offers a solution to this disparity. it allows the user to develop a performance practice that mirrors the one-to-one tactile logic of Eurorack. In this sense, the system does not merely control a plugin; it facilitates the acquisition of hardware-based muscle memory and gestural expression within a digital framework.

3.1 Eurorack / VCV Rack

The Eurorack standard represents a unique paradigm in instrument design; it is a decentralized ecosystem that allows a multitude of developers, companies, and artists to create individual modules that can be effortlessly put into "conversation" with one another. This generates a dense network of connections living not only within the circuitry of the synthesizer itself but also within a global community of creators. This level of interoperability and collective innovation is rarely replicated in other musical ecosystems. Eurorack has been described as a mycelium "as the modular network of patch cords evolves."[7]

VCV Rack is an open-source virtual environment that replicates the functionality of the Eurorack standard in a digital format. It provides an expansive library of virtual modules that communicate using the same voltage-control paradigms as their physical counterparts. For years, VCV Rack has been celebrated for its educational accessibility and its power as a hybrid performance tool [6], allowing users to map the software to any commercially available MIDI controller or just the mouse.

However, VCV Rack was chosen as the first workbench for Umbilical due to its specific architectural approach to audio: the cable as a widget. In VCV Rack, every module is connected via virtual cables that represent the routing of signals. While traditional commercial MIDI interfaces can easily replicate buttons, switches, and potentiometers, they fail to address the most essential element of the modular experience: the patching process. A process that used to be the standard but now is not commonly found in commercially available controllers. The physical act of patching is one of the gestures that makes Eurorack a versatile and expressive tool. By focusing on VCV Rack, Umbilical aims to solve the hurdle of digital modular synthesis, bringing the tactile, spatial logic of the patch cable out of the screen and into the performer's hands.

4 Architecture and Implementation

Umbilical "ghosts" digital modules within the physical world. The architecture is bifurcated into a digital VCV Rack module and a custom physical hardware board.

4.1 Digital dimension

The digital component is implemented as a standard, installable VCV Rack module called Umbilical. It will be released under the Celestial Sounds brand, which also includes Chrysalis, a customizable module that runs the ChucK programming language. Rather than generating audio, Umbilical interfaces with the VCV Rack API, translating software states into accessible serial, midi and OSC protocols. It manages:

Dynamic Widget Management: Monitoring the creation and destruction of virtual modules to maintain hardware-software synchronization.

Signal Conditioning: Raw analog sensor data inevitably contains jitter. The module implements a slew limiter (a single-pole low-pass filter) to smooth control data. This prevents "staircasing" or "zipper noise" that occurs when discrete digital values step abruptly during parameter sweeps.

Memory and Mapping: Handling low-level memory routing to map hardware addresses to virtual parameters with minimal computational overhead.

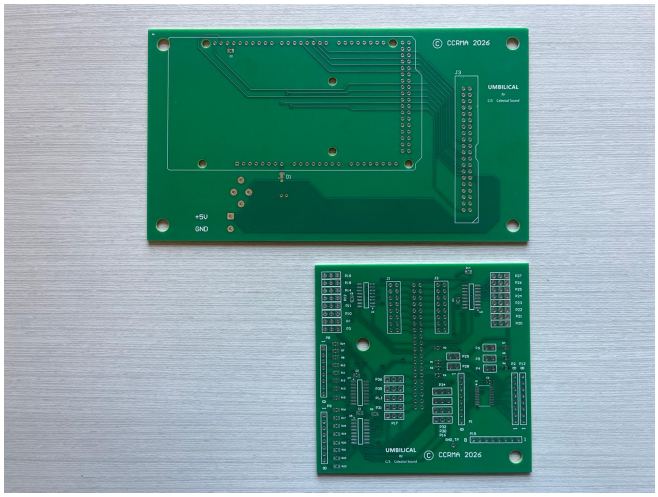

Figure 2: Naked PCBs for both motherboard and modules

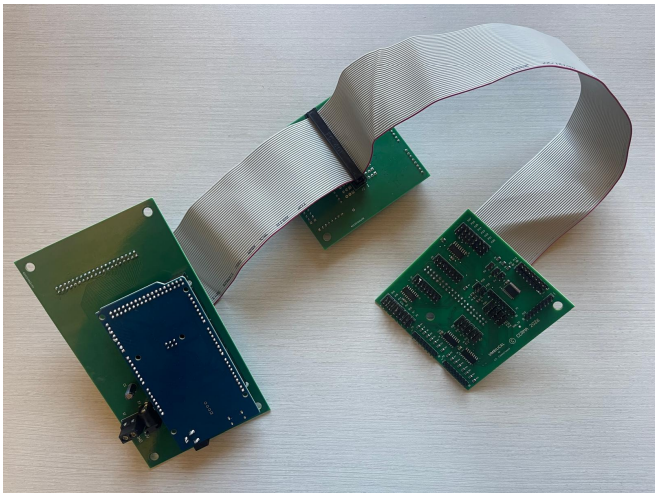

Figure 3: The Monster board connected. One motherboard and two modules

4.2 Physical dimension

The hardware replicates the Eurorack chassis philosophy, built around the "Umbilical Monster Board" which is a high-density I/O system driven by an ATmega2560 architecture expanded via multiplexer arrays.

To manage the massive data requirements, the hardware provides:

- 128 Analog Inputs: High-resolution reading for potentiometers.
- 512 Digital Inputs: For switches, gates, and encoders.
- 512 Digital Outputs: For LED feedback.
- 1024 "Patching" Duplex Pins: A specialized I/O matrix for patch cables.

The Patching Matrix: The core innovation is the patch cable detection. The 1024-pin duplex matrix uses a row-column scanning technique driven by cascaded shift registers and multiplexers. The microcontroller pulses a digital HIGH signal sequentially across output rows; if a physical cable bridges an output to an input column, the connection is read and registered. The matrix incorporates standard diode protection at each node to prevent "ghosting" when multiple cables form complex, concurrent routing webs.

Performance Characteristics: Matrix scanning runs iteratively at roughly 60 Hz, yielding a worst-case physical-to-software latency of approximately 4.6 ms. This falls well within the acceptable boundaries for non-audio-rate control gestures and structural patching.

Workflow for Expansion: Adding a new physical module requires three steps:

- Hardware: Wiring the new potentiometers/jacks to the next available headers on the multiplexer bus.
- Fabrication: Crafting and engraving a physical faceplate to match the VCV interface.
- Software: Updating a localized JSON configuration file on the host machine, which tells the Umbilical module which hardware pins map to which specific VCV parameters.

5 Evaluation and Future Work

At present, evaluation has consisted primarily of iterative performance testing by the author, informal feedback sessions within the Center for Computer Research in Music and Acoustics (CCRMA), and testing during the course Music 222B: Modular Synthesis for Composers and Performers. While this approach succeeds in establishing strong tactile immediacy and proving its pedagogical value, several limitations remain including other evaluations.

Currently, the primary bottleneck is the serial communication bandwidth required to transmit states for a massive 1024-pin matrix alongside high-resolution analog reads, which limits the upper bound of the system's scanning frequency. Furthermore, a transition module is currently in development to allow direct control voltage (CV) signal exchange between physical Eurorack systems and VCV Rack (conceptually similar to the ES-8).

6 Conclusion

Through the use of high-density I/O and low-cost microcontrollers, Umbilical proves that specialized, bespoke hardware is no longer a luxury, but a viable path for performers and educators seeking to eliminate unnecessary layers of abstraction. Ultimately, this system "redeems" the importance of the small gesture, ensuring that even in a virtual world, the connection between the performer and the instrument remains tangible, intuitive, and deeply expressive.

The project's source code, PCB schematics, and firmware are currently under embargo pending the resolution of grant and intellectual property agreements.

7 Ethical Statement

This research adheres to the ethical guidelines established by the NIME community. The instrument's design incorporates biodegradable materials to promote sustainability to the extent of possibilities, specifically through the use of wood-based composites in the chassis and panel construction. No human participants were involved in the evaluation of this system; the study relies on technical performance data and the researcher's auto-ethnographic performance practice.

References

[1] Paul Dourish. 2001. *Where the action is: the foundations of embodied interaction.* MIT press, Cambridge, MA.
[2] Stefano Fasciani and Habibur Rahman. 2018. Tangible virtual patch cords. (2018).

[3] Leonardo Gabrielli. 2020. *Developing Virtual Synthesizers with VCV Rack*. Focal Press.
[4] Brian Mayton, Gershon Dublon, Nicholas Joliat, and Joseph A Paradiso. 2012. Patchwork: Multi-user network control of a massive modular synthesizer. In *Proceedings of the International Conference on New Interfaces for Musical Expression*.
[5] Andrew McPherson and Victor Zappi. 2015. Exposing the scaffolding of digital instruments with hardware-software feedback loops. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. 162–167.
[6] J Oliver and B García-Zapirain. 2022. A LEARNING PATH FOR MODULAR SYNTHESIS. In *INTED2022 Proceedings*. IATED, 232–238.
[7] Justin Randell and Hillegonda C Rietveld. 2024. Eurorack to VCV Rack: Modular synthesis as compositional performance. In *Modular Synthesis*. Focal Press, 172–184.