iDDY
an Interactive, Capacitive & Non-Linear Instrument

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Master's Project

STUDENT REPORT
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Abstract:

This thesis presents iDDY, a novel digital musical instrument (DMI) that integrates nonlinear dynamics and capacitive touch sensing for expressive sound control. It combines a Duffing oscillator—a nonlinear system capable of generating complex and chaotic behaviors—with an 8-band filterbank for real-time spectral shaping. Capacitive sensors, including Trill Bar and Trill Hex, enable intuitive gestural control, allowing musicians to transition smoothly between stable and chaotic states. This versatile design supports intricate sound manipulation, making iDDY ideal for live performance, improvisation, and experimental sound creation. The research explores mapping strategies, evaluates playability using autobiographical design methods (ABD), and demonstrates how controlled chaotic behaviors can enhance musical expressivity. The findings contribute to DMI design by showing how chaotic systems can be effectively harnessed for dynamic, real-time sound manipulation.

Contents

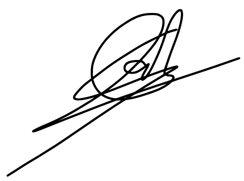
Preface

This thesis represents the culmination of my journey in creating iDDY, bridging my background in electroacoustic composition with new explorations in digital musical instrument design. The project, along with the master's program, has been a pivotal experience, combining technical development, DSP programming, and creative practice to transform an abstract concept into a fully functional instrument. I am deeply grateful to those who supported me throughout this journey.

Firstly, I would like to sincerely thank my supervisor, Dan Overholt, for his invaluable guidance and mentorship. His expertise and encouragement, both during this project and in the NIME class, were instrumental in navigating the intricacies of iDDY's design. My thanks also go to Jesper Greve and Peter Williams at AAU Manufakturet for their technical support and craftsmanship. I would also like to extend my gratitude to Giulio Moro for his invaluable assistance on Bela's forum, providing crucial insights that resolved hardware and software challenges. Lastly, I am deeply thankful to my friends and family for their unwavering support and belief in me, which kept me motivated throughout this process.

Creating iDDY has always been about building a complete instrument—one that resonates with my personal vision. It has been an enriching journey of learning, experimentation, and transformation. I am excited to see where iDDY will evolve and what new musical possibilities it may inspire in the future.

Aalborg University, October 5, 2024



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Chapter 1

Introduction

1.1 Context

The field of digital musical instrument (DMI) design has undergone significant evolution in recent decades, incorporating complex sensor technologies, advanced sound synthesis techniques, and sophisticated interaction paradigms to create expressive and dynamic systems for musical performance [22]. Unlike traditional acoustic instruments, which inherently offer musicians rich tactile and auditory feedback, DMIs rely on digital methods to simulate these interactions, requiring designers to develop intuitive interfaces that bridge the gap between performer input and sound output [14].

Achieving expressivity in DMIs often involves moving away from traditional *linear* synthesis models and exploring *nonlinear* dynamic systems, which are capable of generating richer and more complex sonic qualities. Linear synthesis models, such as sine or square wave oscillators, are characterized by predictable and stable behavior, where changes in control parameters (e.g., amplitude or frequency) lead to proportional and consistent alterations in the resulting sound [39]. This linearity is defined by the equation for a sine wave oscillator:

Example 1.1 (Linear Systems - Sine Wave Oscillator)

$$y(t) = A \cdot \sin(2\pi f t + \phi) \tag{1.1}$$

where: $y(t)$ represents the output waveform at time t, A is the amplitude, f is the frequency, and ϕ is the phase offset.

Because linear systems maintain a consistent relationship between input and output, they produce simple harmonic spectra, dominated by a fundamental frequency and its integer harmonics. While this predictability makes them ideal for generating static waveforms and repeating patterns, it often limits the expressive potential of the instrument, making them less suitable for dynamic musical contexts [32].

1.1.1 Nonlinear Dynamic Systems

In contrast, nonlinear dynamic systems introduce complex, often unpredictable behaviors that evolve dramatically in response to even minor variations in input. One of the most prominent examples is the **Duffing oscillator**, a second-order nonlinear differential system defined by:

> **Example 1.2 (Non-Linear Systems - Duffing Oscillator)**
>
> $$\ddot{x} + \delta \dot{x} + \alpha x + \beta x^3 = \gamma \cos(\omega t) \tag{1.2}$$
>
> where: $\ddot{x}$ is the acceleration, $\dot{x}$ is the velocity, δ is the damping coefficient, α, β are linear and nonlinear stiffness coefficients, γ is the amplitude of the driving force, ω is the driving frequency, and t is time [43].

The Duffing oscillator can transition between stable, quasi-periodic, and chaotic states depending on the parameter values, generating intricate harmonic structures with subharmonics, inharmonic overtones, and complex interactions between frequency components [10]. This dynamic behavior allows performers to explore a broad spectrum of sound textures, from smooth periodic oscillations to noisy, chaotic patterns, making nonlinear systems highly expressive and responsive to performer input [26].

1.1.2 Spectral Control through Filterbanks

Another powerful tool that complements the use of nonlinear dynamics in sound design is the *filterbank*, which segments an incoming audio signal into multiple frequency bands that can be processed independently. Filterbanks enable precise control over the spectral content of the sound, allowing musicians to emphasize, attenuate, or modulate specific frequency ranges in real-time [16]. When combined with nonlinear dynamics, filterbanks offer a broader palette for sound manipulation, as they allow the performer to isolate and sculpt different aspects of the complex spectra generated by chaotic systems like the Duffing oscillator.

The interaction between chaotic systems and structured spectral control has been explored in projects such as Tom Mudd's *Gutter Synthesis*, which combines a Duffing oscillator with a series of resonant filters to channel chaotic outputs into specific frequency bands [26]. This approach provides a continuum between chaotic, noise-like textures and more harmonic, resonant sounds, demonstrating how filtering can shape and constrain the output of a chaotic system into musically meaningful structures. Inspired by this methodology, iDDY—developed as part of this thesis—integrates a Duffing oscillator as its core sound source and a filterbank system to offer granular control over the spectral components of the audio.

1.1.3 Bridging the Gap: iDDY

iDDY leverages these principles, combining nonlinear dynamics with filterbank-based spectral manipulation to create a versatile and responsive DMI. By incorporating capacitive touch sensors for real-time interaction, iDDY allows performers to modulate the Duffing oscillator's state space, transitioning between stable and chaotic behaviors dynamically. This design introduces an element of unpredictability that enhances the expressive potential of the instrument, transforming it into a system that responds intuitively to the performer's gestures while maintaining a high degree of sonic complexity.

In essence, iDDY bridges the gap between the tactile, nuanced interactions offered by acoustic instruments and the computational power of digital systems, providing musicians with a platform for real-time exploration and creative expression. By integrating chaotic behaviors with structured spectral control, iDDY exemplifies how advanced synthesis techniques can be harnessed to achieve new levels of musicality and engagement [16, 43].

1.2 Problem Statement

Despite significant advancements in the field, many Digital Musical Instruments (DMIs) still struggle to offer musicians the same level of nuanced control and expressivity that traditional instruments provide. The challenge is further compounded when introducing *nonlinear dynamics*, which are known for their unpredictable and chaotic behavior. Although nonlinear systems, like the Duffing oscillator, can produce complex and evolving sound textures, making these systems 'musically' meaningful requires developing intuitive control interfaces that are sensitive to the performer's gestures. Similarly, while filterbanks are powerful tools for sound design, integrating them into a interactive or performance environment with intuitive, real-time manipulation capabilities has proven challenging.

The primary research problem addressed in this thesis is how to design a DMI that integrates nonlinear sound synthesis and filterbank processing in a way that allows for expressive, real-time control. This leads to several key questions:

1. How can nonlinear dynamic systems be effectively controlled in a live musical context?

2. What are the most effective mapping strategies for integrating capacitive sensors into a system that combines nonlinear and filterbank-based sound synthesis?
3. How can the element of unpredictability introduced by nonlinear dynamics and probabilistic triggers be harnessed to enhance, rather than hinder, musical expression?

1.3 Research Objectives

The goal of this thesis is to explore the design and development of **iDDY**, a digital musical instrument that integrates nonlinear dynamics and filterbank processing with an intuitive interaction framework. The specific objectives of this research are:

1. **To design and implement a DMI that uses the Duffing oscillator as its primary sound source**, incorporating the unpredictable and dynamic characteristics of nonlinear systems into musical performance.
2. **To develop a flexible filterbank that divides the audio spectrum into multiple frequency bands**, allowing for real-time manipulation of each band, providing musicians with sophisticated sound design capabilities.
3. **To investigate the use of capacitive touch sensors** as a means of controlling both the Duffing oscillator and the filterbank, with a focus on providing immediate, expressive feedback to the user.
4. **To prototype and iteratively test the iDDY instrument**, evaluating its usability and musical expressivity through user feedback and performance studies.

1.4 Overview of Chapters

This thesis is structured to provide a comprehensive exploration of iDDY's development, covering theoretical foundations, design, implementation, and evaluation. The chapters are organized as follows:

- **Chapter 2: Background and Related Work** This chapter reviews the theoretical foundations of digital musical instrument (DMI) design, focusing on human-computer interaction (HCI) principles, nonlinear dynamic systems, and advanced sound synthesis techniques. It discusses key research in the field, including previous work on nonlinear oscillators, probabilistic controls, and filterbanks. The chapter also examines influential frameworks and theories, such as Cook's interactive control, Overholt's Musical Interface Technology Design Space (MITDS), and Morrison McPherson's entanglement theory, establishing the foundation for iDDY's design.

- **Chapter 3: Nonlinear Dynamics and Sound Synthesis** This chapter delves into the role of nonlinear dynamic systems in sound synthesis, with a focus on the Duffing oscillator used in iDDY. It explores how nonlinear oscillators produce complex, evolving sound textures that are highly sensitive to performer input. The mathematical foundations of nonlinear dynamics are also introduced, contrasting these models with traditional linear synthesis in terms of spectral richness and unpredictability.

- **Chapter 4: Filterbanks and Spectral Manipulation** Filterbanks in iDDY segment the audio spectrum into multiple bands, providing real-time control over distinct frequency ranges. This chapter details the design and implementation of the custom filterbank system and explains how it is used to manipulate the complex harmonic content produced by the Duffing oscillator. The integration of filterbanks with nonlinear dynamics is analyzed, demonstrating the broader range of sound shaping possibilities.

- **Chapter 5: Interaction Design and Mapping Strategies** This chapter addresses the interaction design of iDDY, highlighting how capacitive sensors are used to control both the nonlinear and spectral components. Various mapping strategies, such as one-to-one, many-to-one, and probabilistic mappings, are discussed in relation to their impact on expressivity and playability. It also explores real-time control paradigms and the methods used to translate sensor data into meaningful musical gestures.

- **Chapter 6: Introducing Unpredictability and Probabilistic Control** This chapter investigates the role of unpredictability and randomness in DMIs, emphasizing probabilistic event triggers implemented in iDDY. It explores how controlled randomness enhances creative expression by adding surprise and complexity to the musical interaction. The chapter details probability-based algorithms used to generate evolving rhythmic and tonal patterns, enriching the feedback loop between performer and instrument.

- **Chapter 7: Implementation and Development** This chapter outlines the technical implementation of iDDY, including hardware and software components. It covers the use of the Bela platform for low-latency audio processing and Max/MSP and Pure Data for sound synthesis and sensor integration. The chapter provides a detailed overview of the technical setup, sensor integration, and software architecture, emphasizing real-time control of the nonlinear and filterbank elements.

- **Chapter 8: Evaluation and Testing** This chapter presents the evaluation framework used to assess iDDY's usability, expressivity, and overall performance. It includes results from heuristic evaluations and controlled testing sessions, focusing on how well the instrument supports intended musical interactions. The chapter concludes with a critical analysis of iDDY's strengths and areas for improvement.

- **Chapter 9: Results and Discussion** This chapter synthesizes the findings from the evaluation phase, discussing iDDY's performance in terms of sound quality, user interaction, and expressivity. It critically examines how well iDDY meets the research objectives and addresses the challenges of integrating nonlinear dynamics with real-time control. Key insights from the evaluation are used to refine the understanding of iDDY's capabilities.
- **Chapter 10: Conclusion and Future Work** This chapter reviews the contributions of the thesis, highlighting the successful integration of nonlinear dynamics and filterbank processing in iDDY. It discusses key achievements and limitations, and proposes potential areas for future development. Suggestions include making iDDY fully embedded on Bela, enhancing sync capabilities with external devices, and adding external audio input processing. Designing a custom PCB is recommended to improve hardware stability and portability. Future research could also refine the interaction design and expand sound synthesis techniques to further extend iDDY's expressive potential.

Chapter 2

Background and Related Work

2.1 Overview of Digital Musical Instrument Design

Contemporary digital musical instrument (DMI) design has moved far beyond the early attempts to replicate acoustic instruments, embracing novel interfaces, interactive paradigms, and complex sound synthesis techniques to explore new forms of musical expression. While the goal of traditional instruments is to provide consistent and reproducible sound quality, DMIs are often designed to offer a more flexible and dynamic platform for sonic exploration, using advanced computing and sensor technology to create rich, evolving soundscapes.

2.1.1 From Replication to Exploration: The Evolution of DMIs

The history of DMI design began with efforts to mimic the functionalities of acoustic instruments using electronic means. Moog's modular synthesizers, developed in the 1960s, focused on providing musicians with precise control over timbre and pitch using a familiar piano-style keyboard layout. This made Moog's instruments accessible to musicians accustomed to traditional Western music theory, which relies on a structured note-based system.

In contrast, Don Buchla —a contemporary of Moog—sought to create a fundamentally different paradigm for electronic instrument design. He eschewed the conventional keyboard interface, viewing it as an outdated structure that constrained the creative potential of new instruments. Instead, Buchla designed synthesizers that featured touch-sensitive surfaces, sliders, and intricate patching systems to allow for fluid, non-linear control over sound parameters. His designs, such as the Buchla 100 and 200 series, notably the Buchla 216 and 296, emphasized experimentation and improvisation, encouraging users to interact with the instrument as an evolving system rather than a fixed note-based structure.

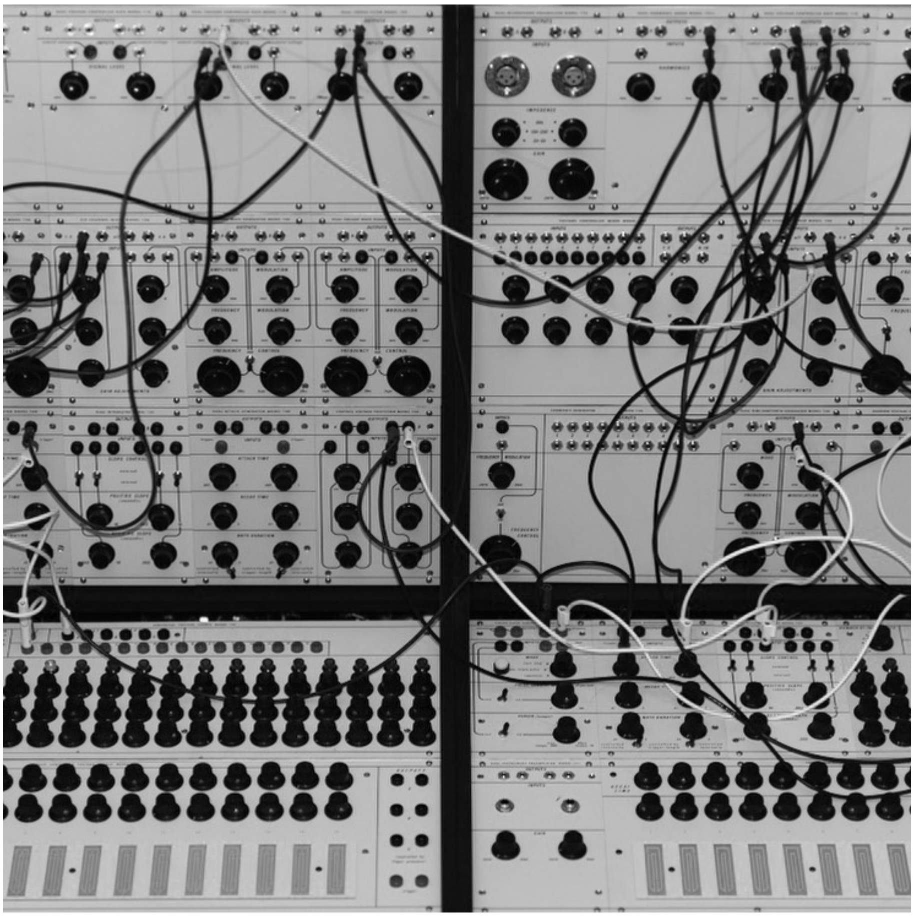


Figure 2.1: Buchla 100 Series

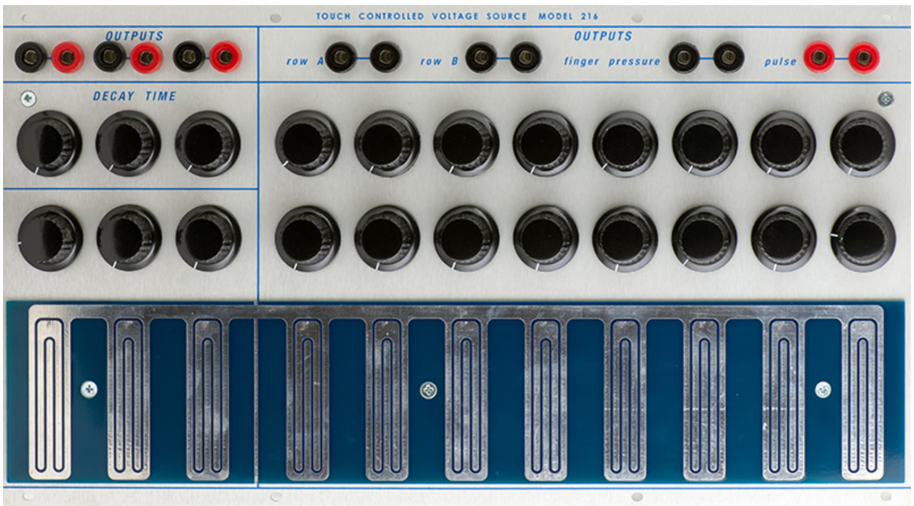


Figure 2.2: Buchla 216 - Touch Controlled Voltage Source Model

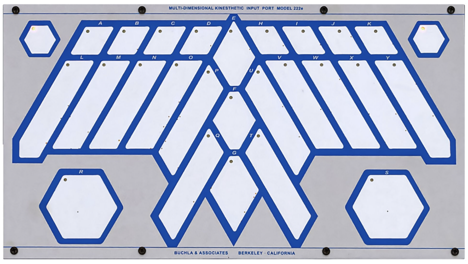


Figure 2.3: Buchla 222e - Multi-Dimensional Kinesthetic Input

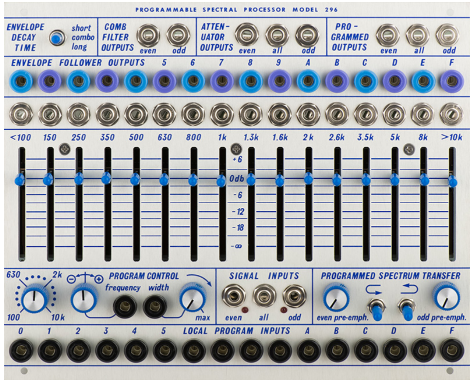


Figure 2.4: Buchla 296 - Programmable Spectral Processor Model

Buchla's philosophy of designing instruments that invite exploration and discovery is a key source of inspiration for the design of the iDDY instrument. His emphasis on moving away from fixed control mechanisms and introducing novel interfaces to shape sound has directly influenced iDDY's development process. The design of iDDY, like Buchla's instruments, avoids traditional pitch-based interaction and instead focuses on creating an environment where the performer can shape complex, evolving sound textures through real-time manipulation.

- **Alternative Interfaces and Non-Conventional Control Schemes**: Don Buchla's instruments employ a range of non-standard input methods, such as touch-sensitive plates, sliders, and unique control surfaces, which allow performers to manipulate multiple parameters simultaneously. This design approach enables a more nuanced gestural control, offering an interface that is sensitive to subtle variations in touch and movement. By avoiding traditional keyboard layouts, Buchla created instruments that encourage continuous exploration and improvisation, shifting the focus from precise note-based control to the modulation of complex sound parameters.

- **Dynamic Sound Sculpting**: Buchla's emphasis on open-ended sound exploration is central to his instrument designs. His modular synthesizers, such as the Buchla 200 series, were equipped with complex oscillators, random voltage generators, and patchable modulation paths that enabled performers to navigate between stable harmonic states and chaotic, noise-like textures. The flexibility of Buchla's systems allowed performers to sculpt the spectral content of sound in real-time, using dynamic interactions between oscillators, filters, and modulation sources to create evolving soundscapes that could range from smooth, tonal qualities to unpredictable noise patterns.

- **Focus on Interaction and User Experience**: Buchla viewed his instruments as interactive systems where sound was created through a continuous dialogue between the performer and the instrument. He designed his modules to be deeply interactive, with responsive touch surfaces and programmable controllers that reacted dynamically to the performer's input. His systems were intended to feel more like an extension of the performer's creative intent, making each performance a unique experience driven by the musician's physical gestures and decisions.

- **Encouraging the Performer's Discovery and Adaptation**: Buchla's design philosophy centered around creating instruments that require and reward exploration. His systems often introduced elements of randomness and unpredictability, ensuring that no two performances would be exactly the same. By integrating features like random signal generators and complex modulation matrices, Buchla's instruments offered surprises that made every performance an act of discovery. This approach encouraged performers to continuously adapt, listen, and respond, reinforcing the idea of the instrument as a co-creator in the musical process, rather than a passive tool.

The early focus on replicating the functionality of acoustic instruments gradually gave way to more experimental approaches that emphasized open-ended exploration and dynamic interaction. This shift was significantly influenced by the work of designers like Don Buchla, who deliberately moved away from traditional interfaces, such as the keyboard, and instead developed novel control surfaces that encouraged performers to engage in a process of discovery rather than just execution. Buchla's emphasis on unpredictability, user-driven exploration, and the interaction between the performer and the instrument laid the foundation for a new perspective in digital musical instrument design.

Building on these ideas, Perry Cook further expanded the understanding of what makes digital instruments expressive by integrating principles of interactive control and real-time responsiveness. Cook's focus was on creating digital instruments that felt "alive" [8] and were capable of nuanced responses to the performer's gestures, thereby bridging the gap between the experimental nature of Buchla's designs and the expressivity sought in traditional instruments. His theoretical contributions and practical frameworks became instrumental in guiding a new generation of DMI designers toward creating instruments that prioritize interaction, expressivity, and performer-instrument dialogue.

2.1.2 Perry Cook's Contributions to DMI Design

Perry Cook is widely regarded as a key figure in the field of digital musical instrument (DMI) design, with a body of work that has profoundly influenced the development of new interfaces and interaction paradigms for electronic music. His contributions extend beyond technical innovations; they encompass theoretical frameworks, design philosophies, and practical guidelines that have shaped how researchers and designers approach the creation of expressive and interactive digital instruments. Cook's work focuses on bridging the gap between the rich, responsive experience offered by traditional acoustic instruments and the flexibility and computational power of digital systems.

Remutualization and Interactive Control Theory

Cook argued that DMIs should aim to replicate this experience by incorporating multiple, rich control channels and feedback mechanisms that encourage a similar level of performer-instrument interaction. In his seminal paper, *"Principles for Designing Computer Music Controllers"* [8], Cook outlined a set of guidelines for creating instruments that feel "alive," emphasizing the importance of feedback, dynamic response, and intuitive control. His framework stresses that, for an instrument to be expressive, it must respond to the performer's actions in a way that is both predictable and surprising, mirroring the complex, dynamic interaction found in traditional instruments.

The idea of *remutualization* [8] is at the heart of Cook's approach to DMI design and is reflected in his advocacy for interactive control theory. This theory posits that the effectiveness of a musical instrument is determined not just by the sounds it produces, but by how it allows the performer to control and shape these sounds through a continuous, bidirectional feedback loop. Cook's research on interactive control has led to the development of instruments that prioritize sensitivity, immediacy, and nuance, enabling performers to expressively mold sound in real-time.

Multimodal Feedback and Embodied Interaction

A core element of Cook's design philosophy is the use of *multimodal feedback* to enhance the performative experience. Traditional instruments provide not just auditory feedback, but also tactile and even visual cues that guide the performer's interaction. For instance, the pressure of the strings on a guitar, the resistance of the bow on a violin, or the visual movement of a drumstick all contribute to the player's sense of engagement with the instrument.

In his work, Cook has explored various ways of replicating these feedback channels in DMIs using digital means. For example, he has investigated the use of haptic feedback systems to provide physical resistance and vibration in response to performer input, thus creating a more immersive and embodied interaction. By incorporating multimodal feedback, Cook's instruments aim to evoke a sense of physical presence and tactile response, even when the sound is being generated by purely digital means. This approach aligns closely with the concept of *embodied* *interaction*, where the performer's physical actions and the resulting sound form a coherent, unified whole.

Modeling Acoustic Instruments and Physical Models

Cook's work on *physical modeling synthesis* has been another major contribution to DMI design. Physical modeling involves simulating the physical properties of acoustic instruments—such as strings, membranes, or resonating bodies—using mathematical equations to generate sound. By creating models that emulate the behaviors of real-world materials, Cook was able to develop digital instruments that produce highly realistic and expressive tones.

Focus on Expressivity and Nuance in Control

The essence of a good musical instrument lies in its ability to capture and convey the performer's expressivity. Cook argued that expressivity is not merely a function of the instrument's ability to generate complex sounds, but rather of how well it translates subtle variations in the performer's gestures into meaningful auditory changes. In this respect, Cook's designs focus heavily on nuance in control—that is, ensuring that small changes in the performer's input (such as finger pressure, speed, or motion) result in perceptible, dynamic changes in the resulting sound.

One of Cook's notable achievements in this area is the development of the **STK (Synthesis ToolKit)**, a collection of C++ libraries designed to facilitate real-time synthesis and physical modeling. The STK has been widely adopted by researchers and developers for building both traditional instrument simulations and novel DMIs. Cook's physical models allow performers to explore a range of timbres and expressive possibilities that are closely tied to their gestural input, enhancing the sense of realism and responsiveness in digital instruments. Through his work on physical modeling, Cook has shown that it is possible to capture some of the inherent expressivity of acoustic instruments in digital form. However, his approach goes beyond simply replicating traditional instruments.

2.1.3 New Interfaces for Musical Expression (NIME)

The legacy of Moog and Buchla's divergent design philosophies is evident in the ongoing development of new musical interfaces presented at the annual *New Interfaces for Musical Expression (NIME)* conference. Founded in 2001, NIME has become a central platform for showcasing innovative digital musical instruments (DMIs) that incorporate cutting-edge technologies such as sensor arrays, biofeedback systems, and artificial intelligence to enable novel forms of musical interaction. According to Jordà [17], NIME has been instrumental in promoting a "digital lutherie" approach, where new musical interfaces are crafted to support not just traditional performance techniques but also the exploration of entirely new performance paradigms [17].

The roots of NIME can be traced back to the increasing interest in digital and experimental musical instruments during the late 20th century. The establishment of NIME formalized the study and creation of DMIs as a dedicated research field, highlighting a growing need to document and disseminate novel approaches in the design and implementation of interactive music systems. Over the years, NIME has evolved into a multidisciplinary platform where researchers from fields as diverse as computer science, human-computer interaction (HCI), and music performance come together to explore new ways to harness technology for musical expression.

2.2 Human-Computer Interaction (HCI) in Music Technology

The integration of **Human-Computer Interaction (HCI)** principles into music technology has transformed how digital musical instruments (DMIs) are designed and utilized. HCI in music focuses on creating systems that enable musicians to interact with digital devices in expressive, intuitive, and meaningful ways, emphasizing real-time feedback and complex gestural input [22]. The following core concepts define key focus areas of HCI in music technology:

- **Affordances and Perceived Mappings**: Affordances refer to the perceived properties of an object that indicate how it can be used, helping performers understand the relationship between their actions and the resulting sound [11]. For musical instruments, intuitive mappings between input gestures and sonic output reduce cognitive load and enhance expressivity, enabling performers to focus on creative expression [8].
- **Embodiment and Physical Interaction**: Embodied interaction considers the physical actions and gestures of the performer as integral to musical interaction. Interfaces that capture nuanced physical movements, such as pressure-sensitive surfaces and motion capture systems, provide a more natural and immediate connection between physical input and sound [36].
- **Expressivity and Nuance in Control**: Expressive control refers to the ability of an instrument to capture subtle variations in a performer's input, allowing fine-grained manipulation of sound parameters. Multidimensional control surfaces that capture attributes like touch pressure, speed, and angle enable nuanced sound shaping in real-time [22].
- **Real-Time Feedback and Adaptation**: Effective real-time feedback, whether visual, auditory, or haptic, creates a sense of "liveness," making the instrument feel more like a collaborative partner in performance [47]. Continuous

feedback allows performers to adjust their actions dynamically, maintaining a responsive interaction loop.

- **Multimodal Interaction**: Multimodal interaction combines multiple sensory channels—visual, auditory, and tactile—to create an immersive and intuitive experience. For example, combining haptic feedback with auditory and visual cues allows performers to "feel" the sound they are shaping, reinforcing the alignment between gesture and sonic output [22].

2.3 Nonlinear Dynamic Systems in Sound Synthesis

Nonlinear dynamic systems are fundamental to modern sound synthesis due to their capacity to generate complex, time-evolving sonic behaviors that are not achievable through traditional linear systems. Linear oscillators are characterized by stable, predictable harmonic structures, where variations in input parameters (e.g., amplitude or frequency) result in proportional and consistent changes in the output. By contrast, nonlinear systems exhibit sensitivity to initial conditions, which can lead to bifurcations, chaotic behaviors, and intricate spectral modulations that evolve over time [43]. This sensitivity allows for the production of rich, dynamic spectra that are highly responsive to even slight variations in control parameters, making them ideal for expressive and interactive sound synthesis.

A prominent example of a nonlinear system used in sound synthesis is the **Duffing oscillator**. The Duffing oscillator is a second-order nonlinear differential equation that is defined by the following form:

$$\ddot{x} + \delta\dot{x} + \alpha x + \beta x^3 = \gamma\cos(\omega t)$$

where $\ddot{x}$ is the acceleration, $\dot{x}$ is the velocity, and α, β, γ, and δ are system-specific coefficients that define the linear and nonlinear stiffness, external forcing, and damping, respectively [19]. The Duffing oscillator is renowned for its capacity to transition between periodic, quasi-periodic, and chaotic regimes depending on parameter values, allowing it to produce a wide range of sound behaviors, from stable harmonic oscillations to noise-like, chaotic textures. This sensitivity to control parameters introduces a multidimensional state space, where small changes in input can cause large, non-linear responses, resulting in dramatic alterations in the sound output. This makes it particularly suitable for real-time musical exploration, where the instrument's behavior can reflect the nuances of the performer's gestures, creating an interactive, expressive system.

Another well-known nonlinear system is the **Lorenz system**, governed by the equations:

$$\dot{x} = \sigma(y - x), \quad \dot{y} = x(r - z) - y, \quad \dot{z} = xy - bz$$

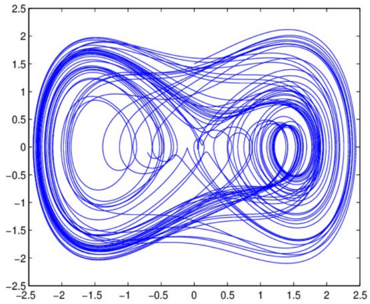


Figure 2.5: Phase space portrait of a single-well Duffing oscillator with parameters $\alpha = -0.5$, $\beta = 0.5$, $f = 1$, $b = 0.1$, and $\omega = 0.5$ [19].

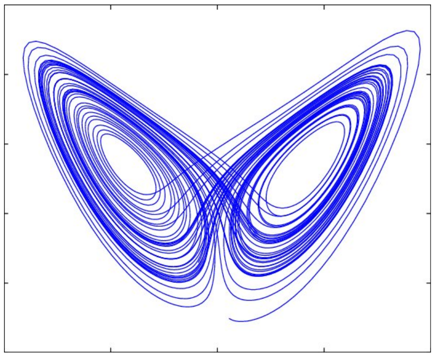


Figure 2.6: The butterfly effect as seen in the Lorenz system with parameters set to $\sigma = 10$, $r = 28$, and $b = \frac{8}{3}$ [43].

where σ, r, and b are system parameters that define the rate of change in each dimension [43]. The Lorenz system is most famously known for its *butterfly attractor*, a chaotic attractor that exhibits sensitive dependence on initial conditions—a hallmark of chaotic systems. This structure makes it a valuable tool in sound synthesis for generating evolving chaotic soundscapes and complex, non-repetitive patterns, which are highly sought after in experimental music and sound design contexts.

The **Van der Pol oscillator** is another nonlinear system that finds extensive use in sound synthesis. The Van der Pol oscillator is described by the equation:

$$\ddot{x} - \mu(1 - x^2)\dot{x} + x = 0$$

where μ is a parameter that dictates the system's nonlinearity and damping [10]. Unlike the Duffing oscillator, which is highly sensitive to external forcing, the Van der Pol oscillator exhibits self-sustained oscillations and limit cycles, making it ideal for creating rhythmic and pulsed patterns. Its capacity to produce stable, self-oscillating states allows for the generation of periodic signals with distinctive timbral qualities that can be further modulated to create a variety of complex rhythmic textures.

The use of nonlinear systems in sound synthesis significantly broadens the range of available sonic textures, moving beyond conventional harmonic spectra and tonal structures. By exploiting the unique behaviors of these systems, composers and sound designers can craft soundscapes that are rich in complexity and variation, making them feel more organic and "alive." This capacity to generate dynamic, evolving sonic patterns lends itself well to interactive digital musical instruments, where real-time modulation and control over these complex behaviors enable novel forms of musical expression [43].

2.4 Probabilistic Control and Unpredictability in DMIs

Incorporating probabilistic control mechanisms into digital musical instruments (DMIs) introduces stochastic behavior that enhances the system's responsiveness by generating dynamic and non-repetitive interactions. Unlike deterministic control schemes—where each performer gesture produces a predefined and predictable outcome—probabilistic control algorithms introduce elements of randomness, resulting in a non-deterministic mapping between performer input and system output [21]. This stochasticity necessitates real-time adaptation from the performer, transforming the instrument into a more autonomous system that behaves as an active agent in the musical process.

One commonly employed technique for probabilistic control in DMIs is the **Markov chain**, a mathematical model characterized by state-dependent transitions where the probability of each state transition is governed by a fixed set of transition probabilities [34]. In musical contexts, Markov chains are used to generate time-evolving rhythmic or melodic sequences based on probabilistic rules defined between discrete states (e.g., pitch classes, note durations, or dynamic levels). The use of Markov chains allows composers and performers to create generative sequences that maintain a coherent structural form while integrating stochastic variations.

For instance, a first-order Markov chain, defined by states corresponding to specific pitches, utilizes a transition matrix that determines the likelihood of moving from one pitch to another. The performer can modify the matrix values to influence the statistical properties of the sequence, such as its repetitiveness, harmonic density, or unpredictability [1]. This capability makes Markov chains highly effective for interactive performance scenarios, where performers require the system to generate musically relevant variations in response to real-time input, thereby blurring the line between compositional control and spontaneous generation.

Probabilistic control mechanisms can also modulate the parameters of nonlinear oscillators, resulting in dynamic and evolving soundscapes that respond sensitively to changes in performer input [45]. When applied to systems like the Duffing or Lorenz oscillators, probabilistic modulation of parameters such as amplitude, frequency, and damping introduces irregularities that expand the oscillator's state space, allowing for transitions between stable, periodic, and chaotic behaviors. This results in the generation of highly complex timbres and time-varying spectra, which are particularly effective for live performance applications where evolving and unpredictable sonic textures are desired.

The use of stochastic processes extends the expressive range of DMIs by allowing for probabilistic event triggers, noise-based modulations, and random walk algorithms that influence control parameters dynamically. This capability introduces a level of indeterminacy that is analogous to the subtle variabilities present in acoustic instruments, such as microvariations in pitch and timbre that arise from the physical properties of strings or reeds. Such variations contribute to the perception of "liveness" and organic behavior in digital instruments [8].

Overall, the implementation of probabilistic control strategies in DMIs supports the creation of interactive systems that operate in a complex, multi-dimensional state space, where performer actions and system responses are continuously entangled. This framework challenges traditional linear mappings and invites the performer to engage in an ongoing exploration of sound possibilities, reinforcing the notion of the instrument as a co-creator in the musical process.

2.5 Filterbanks in Sound Design and Live Performance

Filterbanks are integral components in sound design and live performance due to their ability to decompose complex audio signals into multiple, discrete frequency bands. Each band can be processed and modulated independently, allowing for precise spectral shaping, dynamic control, and the creation of complex, multi-layered sound textures. This approach provides significant flexibility for sound designers and performers, enabling the isolation, enhancement, or suppression of specific frequency ranges, thereby expanding the expressive capabilities of digital musical instruments (DMIs) [20].

In modular synthesis and live electronic setups, filterbanks offer powerful spectral manipulation capabilities by utilizing separate bandpass filters arranged in parallel. This configuration permits each frequency band to be modulated with different amplitude envelopes, routed through varying effect chains, or spatially positioned, allowing for highly differentiated and evolving timbral content [49]. This functionality makes filterbanks ideal for dynamic spectral transformations, time-based effects, and spatialization techniques in real-time performance contexts.

One of the most sophisticated hardware implementations of this concept is the **Buchla 296e Spectral Processor**, a 16-band voltage-controlled filterbank. Each band of the 296e can be addressed individually, either through external control voltages or manual faders, allowing performers to sculpt sound with a high degree of precision. The module features built-in spectral analysis and programmable control of each band's gain and amplitude modulation, making it capable of generating highly complex, real-time spectral morphing effects [2].

Figure 2.7: Buchla 296e - Spectral Processor

The 296e's architecture enables advanced applications such as formant synthesis, harmonic isolation, and spectral re-synthesis, which are critical for experimental sound designers [40].

Another prominent example is the **Moog MIDI MuRF (Multiple Resonance Filter)**. The MIDI MuRF is equipped with eight resonant filters, each tuned to a specific frequency band, and utilizes a built-in step sequencer for rhythmic control over the gain of each filter. This configuration combines the benefits of a traditional filterbank with the temporal modulation capabilities of step-sequenced control, allowing performers to create evolving rhythmic patterns by manipulating the envelope and gain structure of each band[35].

Figure 2.8: Moog MIDI MuRF Multiple Resonance Filter)

Additionally, the MuRF's MIDI integration enables precise synchronization with external devices, providing a high level of control and versatility for complex live setups [44].

Filterbanks are also employed extensively in software environments such as Max/MSP and Pure Data, where they can be customized and programmed for specific spectral processing tasks. These software-based filterbanks enable complex time-domain transformations, frequency-specific delay effects, and dynamic spectral convolution, making them highly adaptable for advanced sound design [37]. The use of digital filterbanks in software provides an extended range of possibilities, such as real-time spectral freeze, frequency-domain pitch shifting, and cross-synthesis, which are challenging to implement with traditional analog hardware.

Another notable hardware implementation is the **Serge Resonant Equalizer**, a 10-band resonant filterbank originally designed by Serge Tcherepnin. The Serge Resonant Equalizer emphasizes specific frequency ranges through resonant peaks, making it ideal for formant shaping and enhancing particular spectral components. Each band exhibits a distinct resonant behavior, enabling performers to introduce peaks and notches across the audio spectrum, which can be modulated to create dynamic, resonant effects [23]. This module's architecture is particularly suited for experimental synthesis and live performance where subtle variations in resonance and amplitude are used to create evolving, organic textures.

Figure 2.9: Serge Resonant Equalizer

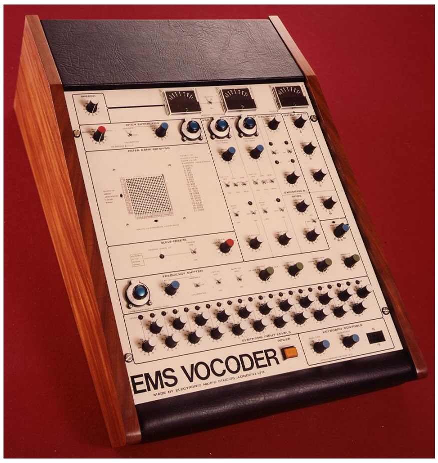


Figure 2.10: EMS Vocoder 5000

Furthermore, the **EMS Vocoder 5000** employs a 22-band filterbank for detailed spectral analysis and resynthesis of vocal signals. Each bandpass filter in the EMS Vocoder can be modulated separately, allowing for the fine-tuning of specific formants, making it a powerful tool for voice processing and spectral manipulation

[41]. The EMS Vocoder's implementation of a complex filterbank structure enables a detailed and natural-sounding synthesis of vocal characteristics, making it ideal for applications in both performance and studio environments [12].

Overall, filterbanks are indispensable tools for both analog and digital sound synthesis, providing intricate control over the spectral components of audio signals. Their use in both hardware and software configurations extends the boundaries of traditional sound manipulation, allowing for precise and dynamic spectral control, complex rhythmic modulation, and unique timbral shaping that are essential for contemporary sound design and performance.

2.6 Key Frameworks in DMI Design

Designing digital musical instruments (DMIs) involves navigating a complex interplay of technological, performative, and aesthetic factors. To address these complexities, researchers have developed theoretical frameworks that guide the design and evaluation of DMIs, helping to define the relationships between performer, instrument, and sound. Two influential frameworks in this field are Overholt's Musical Interface Technology Design Space (MITDS) and Morrison McPherson's Entanglement Theory. These frameworks provide conceptual models for understanding how DMIs function as interactive systems, shaping the experiences of musicians and audiences.

2.6.1 Overholt's MITDS Framework

The Musical Interface Technology Design Space (MITDS) is a theoretical framework proposed by Dan Overholt that aims to provide a comprehensive method for analyzing and designing digital musical instruments. The framework is structured around a multi-dimensional design space that categorizes the various aspects of musical interaction into distinct components, such as physical interface, sensor technology, and digital sound synthesis [30]. By isolating these components, the MITDS enables designers to systematically explore how changes in one dimension, such as sensor placement or sound synthesis algorithm, affect the overall interaction and expressivity of the instrument [29].

A key aspect of the MITDS framework is its emphasis on balancing the physical and digital affordances of a musical interface. Overholt argues that the most expressive DMIs are those that seamlessly integrate physical control elements (e.g., touch sensors, knobs, and sliders) with digital sound synthesis, allowing performers to intuitively manipulate complex sound parameters in real-time [31]. The MITDS framework encourages designers to consider how the physicality of an instrument impacts the performer's interaction and how digital elements can extend the instrument's capabilities beyond what is possible with traditional acoustic designs.

This framework has been applied to a range of novel musical interfaces, including *the Overtone Violin* and t*he CataRT controller*, to explore new forms of interaction that leverage both gestural control and real-time digital signal processing [31]. By offering a structured approach to instrument design, the MITDS framework helps bridge the gap between traditional acoustic instruments and contemporary digital systems.

2.6.2 Morrison & McPherson's Entanglement Theory

Entanglement Theory, proposed by Landon Morrison and Andrew McPherson, takes a different approach to DMI design by focusing on the relational and performative aspects of musical interaction. The theory suggests that DMIs should be understood not as isolated tools but as entangled entities that co-create musical experiences with the performer. This perspective views the instrument as an active participant in the creative process, capable of influencing the performer's actions and decisions through its unique affordances and behaviors [25].

A central concept in Entanglement Theory is the idea of *mutual influence*, where both the performer and the instrument shape each other's actions in a continuous feedback loop. Morrison and McPherson argue that this mutual influence is crucial for creating a sense of "liveness" and immediacy in digital musical instruments, making them feel more like traditional acoustic instruments that respond dynamically to the performer's gestures [25]. The entanglement framework emphasizes the importance of designing instruments that encourage exploration and adaptation, allowing performers to discover new musical possibilities through interaction.

Entanglement Theory has been applied to the design of several novel instruments, such as the *TouchKeys* and *Magnetic Resonator Piano*, which explore new forms of interaction that emphasize the co-evolution of performer and instrument [24]. These instruments incorporate dynamic mapping strategies and adaptive feedback mechanisms that respond to subtle variations in the performer's gestures, creating an environment where musical expression emerges through the interplay between human and machine.

Overall, Entanglement Theory provides a framework for understanding DMIs as complex systems that exist at the intersection of technology, performance, and artistic intent. By viewing instruments as entangled entities, designers can focus on creating interfaces that foster deep engagement and promote a sense of shared agency between performer and instrument.

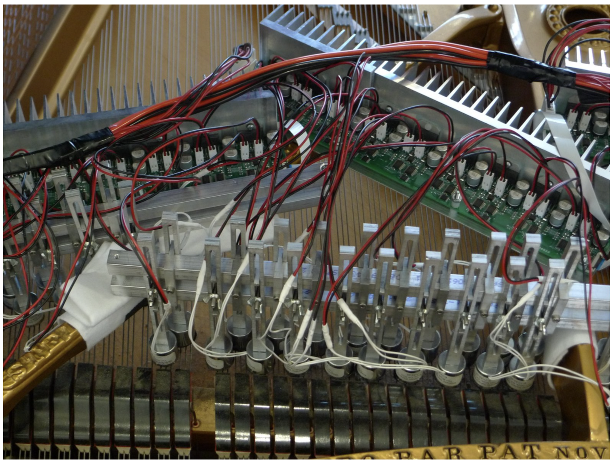


Figure 2.11: Magnetic Resonator Piano by Andrew McPherson

2.7 Summary and Theoretical Basis for iDDY

The design and development of iDDY draw heavily on the theoretical and practical insights offered by both Overholt's Musical Interface Technology Design Space (MITDS) framework and Morrison and McPherson's Entanglement Theory. These frameworks guide the design of iDDY by establishing a balance between the instrument's physical interaction elements and its complex sound synthesis capabilities. The integration of probabilistic controls, nonlinear dynamics, and filterbank-based sound design within iDDY aims to create a digital musical instrument that transcends conventional approaches, offering a platform for deep and sustained musical interaction.

The MITDS framework's structured approach to analyzing the components of digital musical instruments provides a blueprint for understanding how different technological choices impact the expressive potential of iDDY. For instance, Overholt's emphasis on the seamless integration of physical and digital elements directly informs iDDY's use of capacitive touch sensors to manipulate the parameters of the Duffing oscillator and filterbank in real-time. Each sensor in iDDY is mapped to specific control parameters—such as amplitude, frequency, and damping coefficients—allowing for highly nuanced gestural control over the evolving soundscape. This mapping structure ensures that physical actions on the capacitive touch surfaces are directly tied to digital sound outputs, creating a coherent and responsive interface that enhances performative expressivity [30].

Similarly, Entanglement Theory offers a conceptual framework for understanding iDDY's role as an active participant in the creative process. Morrison and

McPherson's emphasis on mutual influence and adaptive feedback is exemplified in iDDY's use of probabilistic triggers and chaotic modulation schemes, which introduce an element of unpredictability into the instrument's behavior [25]. For example, as the performer engages with iDDY, small variations in touch pressure or hand position may cause the Duffing oscillator to shift from a stable periodic state to a chaotic regime, resulting in sudden and dramatic changes in the sound output. This behavior mirrors the concept of a "lively" instrument that responds dynamically to the performer's gestures, making each interaction unique and non-repeatable.

The philosophical foundation of iDDY's design can be seen as a continuation of Don Buchla's approach to synthesizer development, where the instrument is not merely a tool for producing predefined sounds but an interactive system that shapes and is shaped by the performer's input. Buchla's philosophy of creating instruments that "invite exploration and discovery" is manifested in iDDY's architecture, which uses nonlinear oscillators and probabilistic controls to generate complex, evolving sonic textures that encourage performers to engage in a process of sonic exploration rather than execution. Much like Buchla's use of touch plates and non-conventional control surfaces to bypass traditional keyboard interfaces, iDDY's capacitive sensors and filterbank structure provide a multidimensional space for performers to experiment with sound modulation and control.

The MITDS framework and Entanglement Theory converge in iDDY's interaction design, which leverages probabilistic event triggers and chaotic modulation to introduce emergent behaviors. The combination of these design elements results in a system where performer input is not just translated into sound but becomes a catalyst for generating new and unexpected sonic patterns. This dynamic relationship between performer and instrument is akin to a conversation, where the performer's gestures prompt the instrument to respond in novel ways, much like a collaborative partner in the creative process. This interactive model transforms iDDY into a system that exhibits agency, blurring the boundaries between human intention and machine autonomy.

The design of iDDY can be likened to the concept of a "phase space," a mathematical construct used to represent the dynamic states of a complex system. In a phase space, each point corresponds to a unique configuration of the system's variables (e.g., amplitude, frequency, damping), and trajectories through this space represent the evolution of the system over time. iDDY's integration of nonlinear dynamics and probabilistic controls creates a high-dimensional phase space where performer input acts as a force that navigates the system through different states, ranging from stable periodic oscillations to chaotic patterns. In this analogy, the performer's gestures are not merely inputs but forces that shape the trajectory of the system, making iDDY a dynamic landscape for musical exploration.

The role of the filterbank in this analogy can be compared to a multi-dimensional lens that allows the performer to isolate and manipulate specific frequency bands within the overall sound texture. Each frequency band in iDDY's filterbank corresponds to a different "dimension" within the instrument's spectral space, and the performer's manipulation of these bands is akin to navigating through different layers of the phase space. By independently modulating each band, the performer can sculpt the spectral content in real-time, creating a highly dynamic interplay between the instrument's harmonic and inharmonic components. This level of control is essential for enabling performers to explore the full expressive potential of the system, transforming iDDY from a static instrument into a responsive and evolving environment.

Overall, the combination of Overholt's and Morrison and McPherson's frameworks provides a robust theoretical foundation for understanding iDDY's design as a complex interactive system. The MITDS framework's focus on the structural elements of DMI design complements Entanglement Theory's emphasis on performative interaction and mutual influence, resulting in a system where the boundaries between performer and instrument are fluid and constantly renegotiated. This approach not only enhances the performative capabilities of iDDY but also positions it as a platform for future research into the integration of chaotic systems and probabilistic controls in digital musical instrument design.

Chapter 3

Nonlinear Dynamics and Sound Synthesis

3.1 Overview of Nonlinear Dynamics - Example Systems

Nonlinear dynamic systems are characterized by complex, often chaotic behaviors that arise from nonlinear relationships between system variables. These systems exhibit phenomena such as bifurcation, sensitivity to initial conditions, and the presence of chaotic attractors [43]. Unlike linear systems, where outputs are proportional to inputs, nonlinear systems generate outputs that can be highly sensitive to small changes in parameters, making them ideal for creating rich, evolving sound textures in musical contexts [27]. This section introduces three example systems: the Logistic Equation, the Lorenz System, and the Duffing Oscillator, each of which demonstrates unique dynamic properties that can be applied to sound synthesis.

3.1.1 Logistic Equation

The Logistic Equation is a discrete-time nonlinear system that models population growth with limited resources. It is defined by the iterative formula:

$$x_{n+1} = rx_n(1 - x_n)$$

where x_n represents the state at iteration n, and r is the control parameter. As r increases, the Logistic Equation transitions through a series of bifurcations, moving from stable periodic behavior to chaotic, aperiodic behavior, illustrating the route to chaos [43]. This property makes the Logistic Equation an effective tool for generating unpredictable rhythmic patterns and modulating musical parameters in real-time [27].

3.1.2 Lorenz System

The Lorenz System is a set of three coupled differential equations:

$$\dot{x} = \sigma(y - x), \quad \dot{y} = x(r - z) - y, \quad \dot{z} = xy - bz$$

where σ, r, and b are constants that determine the system's behavior. The Lorenz system is best known for its "butterfly attractor," a chaotic attractor that demonstrates sensitivity to initial conditions, leading to complex, non-repetitive trajectories in phase space [43]. This makes it ideal for creating evolving soundscapes and dynamic modulations in musical contexts [27]. Because of its chaotic nature, the Lorenz System can produce a wide range of timbral variations, making it suitable for applications that require non-linear modulation of pitch, amplitude, or timbre.

3.1.3 Duffing Oscillator

The Duffing Oscillator is a second-order nonlinear differential equation:

$$\ddot{x} + \delta\dot{x} + \alpha x + \beta x^3 = \gamma\cos(\omega t)$$

where $\ddot{x}$ is the acceleration, $\dot{x}$ is the velocity, δ is the damping coefficient, α, β are linear and nonlinear stiffness coefficients, γ is the amplitude of external forcing, and ω is the driving frequency [19]. The Duffing Oscillator can transition between periodic, quasi-periodic, and chaotic states, making it highly suitable for musical contexts where dynamic, evolving timbres are desired. This sensitivity to input parameters allows performers to generate complex, time-varying sounds that can reflect subtle changes in performance gestures [27].

3.2 Properties of Nonlinear Dynamic Systems

Nonlinear systems exhibit several unique properties that distinguish them from linear systems. Some of the key properties include:

- **Bifurcation**: A phenomenon where a small change in a system parameter causes a sudden qualitative change in its behavior. In sound synthesis, this can manifest as abrupt shifts in pitch, rhythm, or timbre, adding to the expressive potential of the instrument [43].
- **Multi-Stability**: The presence of multiple stable states for a given set of parameters. This allows for a variety of possible behaviors, making the system highly sensitive to initial conditions and performer input [27].

- **Sensitive Dependence on Initial Conditions**: Often referred to as the "butterfly effect," small changes in initial conditions can lead to vastly different outcomes over time, providing a source of variation and unpredictability in musical applications.
- **Chaotic Attractors**: Complex, fractal-like structures in phase space that represent the long-term behavior of chaotic systems. Chaotic attractors provide a rich source of dynamic variation in sound synthesis, allowing for the creation of evolving soundscapes that are highly engaging in real-time performance contexts [27].

3.3 Nonlinear Sound Synthesis in Musical Contexts

The use of nonlinear systems in sound synthesis opens up new possibilities for creating dynamic, evolving sound textures that go beyond the capabilities of traditional linear models. According to Tom Mudd [27], nonlinear systems can introduce a level of expressivity that is difficult to achieve with standard linear oscillators. For example, the Duffing oscillator's sensitivity to initial conditions allows for nuanced control over sound parameters, making it an ideal candidate for real-time interaction in digital musical instruments (DMIs).

Nonlinear dynamics also enable the creation of chaotic sound patterns that can be tamed and shaped using external control inputs. For instance, Mudd's *Gutter Synthesis* project combines a Duffing oscillator with a filterbank to channel chaotic outputs into specific frequency bands, thereby transforming chaotic behaviors into musically meaningful structures [27]. This approach allows performers to navigate a continuum between stable harmonic sounds and noisy, chaotic textures, providing a rich palette of timbral variations that can be explored in live performance.

Furthermore, nonlinear systems can be used to modulate other sound synthesis parameters, such as amplitude, frequency, or phase, resulting in complex, evolving behaviors that respond to the performer's gestures. This capability is particularly valuable in DMI design, where the goal is to create instruments that feel responsive, intuitive, and capable of producing a wide range of expressive soundscapes [8]. By incorporating nonlinear dynamics into sound synthesis, composers and performers can achieve a new level of sonic complexity and variation, making nonlinear systems a powerful tool in contemporary music technology.

3.4 Implementing the Duffing Oscillator in iDDY

The implementation of the Duffing oscillator in iDDY involved a multi-stage process, beginning with initial prototyping in Max/MSP's `gen` environment and then migrating to the `rnbo` environment for enhanced flexibility and integration into hardware systems. The Duffing oscillator is a second-order nonlinear system defined by the following differential equation:

$$\ddot{x} + \delta\dot{x} + \alpha x + \beta x^3 = \gamma\cos(\omega t)$$

where $\ddot{x}$ represents acceleration, $\dot{x}$ is velocity, and x is displacement. The parameters δ, α, β, γ, and ω define the damping, stiffness coefficients, external forcing, and driving frequency, respectively. The Duffing oscillator is known for its ability to transition between periodic, quasi-periodic, and chaotic states depending on the values of these parameters, making it a versatile tool for dynamic sound synthesis in digital musical instruments (DMIs) [43].

3.4.1 Development in Max/MSP's `gen~` Environment

The initial implementation of the Duffing oscillator was developed using Max/MSP's `gen~` environment. The `gen~` object provides a low-level Digital Signal Processing (DSP) patching interface for creating custom algorithms using a combination of visual elements and code-based components. This implementation accurately models the chaotic dynamics defined by the Duffing equation, a second-order nonlinear differential system that exhibits a range of complex behaviors, including stable, periodic oscillations and chaotic states. The patch was built upon a reference design from the Cycling '74 community, which provided a basic framework for simulating the Duffing system [7].

Duffing Oscillator Equations

The Duffing equation is expressed as a second-order nonlinear differential equation:

$$\ddot{x} + \delta\dot{x} + \alpha x + \beta x^3 = \gamma\cos(\omega t)$$

where:

- x is the displacement,
- $\ddot{x}$ is the acceleration,
- $\dot{x}$ is the velocity,
- δ is the damping coefficient,

- α, β are stiffness coefficients,
- γ is the driving amplitude,
- ω is the driving frequency, and
- t is the time variable.

In digital systems, the equation is typically separated into two first-order equations:

$$\dot{v} = \gamma \cos(\omega t) - \delta v - \alpha x - \beta x^3$$

$$\dot{x} = v$$

where:

- $v = \dot{x}$ represents the velocity, and
- x represents the displacement.

Implementation in gen∼

To implement the Duffing oscillator in gen∼, the patch utilizes the following components to map each mathematical operation to real-time DSP processing (see Figure 3.1 for the visual layout):

1. **Numerical Integration**:
   - The differential equations are discretized using a combination of `history` and `integrate` objects.
   - The velocity equation ($\dot{v}$) is computed first by accumulating the changes over each time step.
   - This updated velocity value is then used to update the displacement (x) using another `integrate` block.
2. **Driving Oscillator**:
   - The driving force $\gamma \cos(\omega t)$ is computed using an oscillator block (`cos`) multiplied by a gain parameter (γ), allowing real-time modulation of the driving amplitude.
3. **Nonlinear and Linear Terms**:
   - The linear and nonlinear stiffness terms (αx and βx^3) are generated using basic multiplication and power operations.

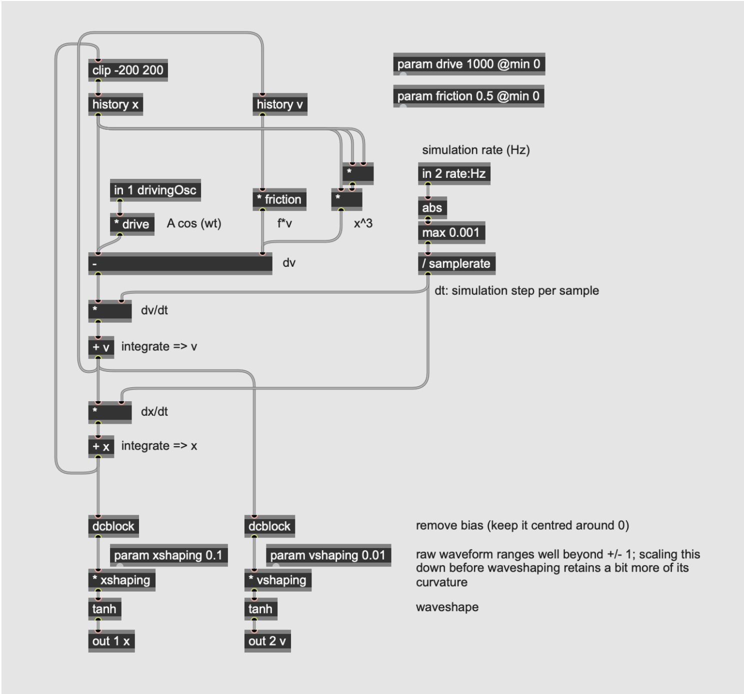


Figure 3.1: Duffing oscillator implementation in Max/MSP's `gen` environment [7]. The patch uses `history` operators for real-time integration of the system's differential equations.

- The damping term (δv) is computed with a separate coefficient that can be dynamically adjusted during performance.

4. **Wave Shaping and Output Scaling**:

   - The raw output of the Duffing oscillator often exceeds the normal audio range (± 1), making it necessary to apply a hyperbolic tangent (`tanh`) wave shaper to compress the output and retain the curvature of the waveform.
   - The `dcblock` object is applied to remove any DC bias, ensuring that the waveform is centered around zero.

5. **Parameter Control and Stability**:

   - The parameters for drive, friction, and the sampling interval (dt) are defined as interactive controls, allowing for real-time adjustment.
   - The patch also includes a `clip` block to prevent the system from becoming unstable during chaotic states by bounding the values of x and v.

Patch Analysis and Stability Management

One of the critical challenges in implementing the Duffing oscillator in a digital environment is maintaining numerical stability, especially when transitioning between regular and chaotic behaviors. This was managed by:

- Fine-tuning the damping coefficient (δ) and integration step size (dt) to prevent the system from becoming unbounded.
- Adding clipping limits on the values of x and v to constrain the state variables within a predefined range.
- Utilizing `param friction` and `param drive` controls, which dynamically adjust the damping and driving force during performance.

The final implementation in `gen~` offers a flexible and responsive interface for exploring the complex dynamics of the Duffing oscillator, enabling musicians and researchers to interact with a chaotic system in real-time.

3.4.2 Migration to RNBO Environment

After the initial prototyping phase in `gen~`, the Duffing oscillator was migrated to Max/MSP's `rnbo` environment. RNBO (Real-time Neural Bytecode Orchestrator) is designed for generating highly optimized C++ code from Max patches, making it suitable for deployment on a variety of hardware platforms, such as microcontrollers and embedded systems. This step was crucial for enabling the Duffing oscillator to function as part of a standalone instrument rather than being confined to a computer-based Max environment.

The translation involved converting the gen~ operators (e.g., `accum` and `history`) into RNBO-compatible components. Special care was taken to preserve the numerical integration method and ensure that RNBO's handling of control and sample rate signals matched that of the gen~ patch. RNBO's ability to export patches as standalone code allowed the Duffing oscillator to be integrated into the iDDY hardware prototype, providing real-time control over chaotic behaviors.

3.4.3 Parameter Control with Capacitive Sensors

Capacitive touch sensors were employed in iDDY to provide precise and responsive real-time control over critical parameters of the Duffing oscillator, such as α, β, δ, γ, and ω. These sensors were selected due to their high sensitivity and minimal latency, which are essential for the fine-grained control required to navigate between the Duffing oscillator's stable, periodic oscillations and chaotic, noise-like behaviors. By adjusting these parameters dynamically, the performer is able to

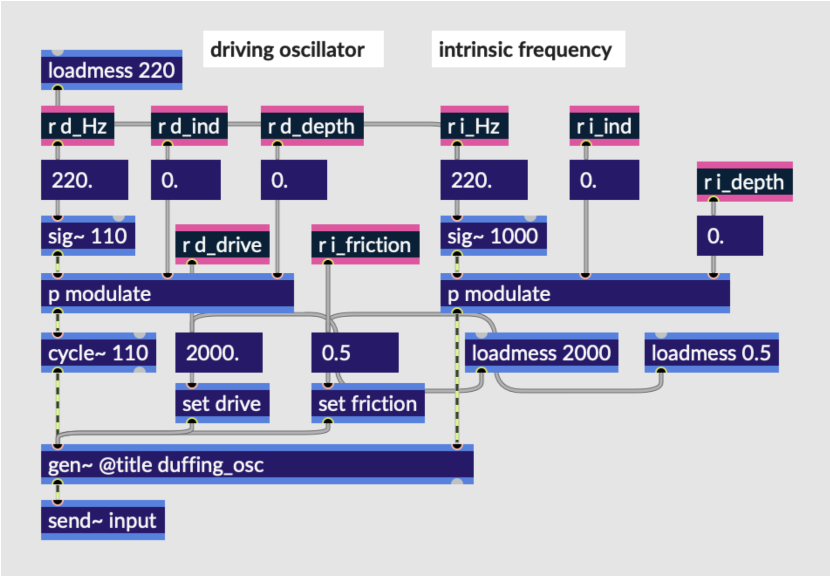


Figure 3.2: Duffing oscillator re-implemented in RNBO, showing parameter modulation for real-time interaction. The architecture was adapted from the original Gen patch for hardware deployment.

transition fluidly across different states of the oscillator, significantly expanding the expressive potential of the instrument [27].

The sensor data is captured using analog-to-digital converters (ADC) and processed in real-time within the `rnbo` environment. This architecture ensures that parameter changes are reflected instantaneously in the resulting sound, enabling a highly responsive interaction. This responsiveness mirrors the chaotic and evolving characteristics found in acoustic instruments, where subtle changes in the performer's gestures lead to complex variations in sound output [8].

Further technical details regarding the mapping strategies, sensor calibration, and parameter control methodologies are elaborated in Chapter 7, where the implementation specifics and design considerations are discussed.

Chapter 4

Filterbanks and Spectral Manipulation

4.1 Introduction to Filterbanks

Filterbanks are essential tools in sound design and audio processing, enabling the decomposition of an audio signal into multiple frequency bands for independent analysis and manipulation. Each band is typically represented by a bandpass filter with a defined frequency range, allowing for precise control over the spectral components of the sound. This capability makes filterbanks highly versatile for a range of applications, including equalization, noise reduction, spectral morphing, and formant shaping [38]. The ability to isolate and manipulate distinct spectral bands is particularly useful for digital musical instruments (DMIs), where performers may want to emphasize or suppress specific frequency regions in real-time.

4.2 Theory of Spectral Segmentation

The theory of spectral segmentation is grounded in the mathematical representation of signals in the frequency domain. A filterbank splits the input signal $x(t)$ into N subbands, each corresponding to a specific frequency range, using a set of bandpass filters $H_n(\omega)$ defined as:

$$X_n(\omega) = H_n(\omega) \cdot X(\omega)$$

where $X(\omega)$ is the Fourier transform of $x(t)$, and $X_n(\omega)$ is the spectral component in the n-th band. By independently adjusting the gain, phase, or modulation characteristics of each band, it is possible to achieve complex spectral transformations [28]. This decomposition process provides a granular level of control over the audio spectrum, enabling dynamic timbral shaping that can evolve over time.

4.3 Real-Time Control of Filterbanks

Real-time control over filterbank parameters, such as frequency, gain, and bandwidth, is crucial for interactive music systems. In iDDY, this control is facilitated through capacitive sensors that map performer gestures to different filterbank parameters. This mapping allows the performer to seamlessly transition between various spectral configurations, providing an intuitive interface for shaping sound textures in real-time. The real-time control is achieved using a low-latency processing pipeline, ensuring that adjustments made by the performer are immediately reflected in the sound output [33].

4.4 Designing the Filterbank System in iDDY

The filterbank system in iDDY was implemented using Max/MSP's `gen~` environment with the `codebox` operator, which allows for low-level DSP programming. This approach provided the flexibility needed to define custom band shapes and create non-standard filter responses. The `codebox` in `gen~` is a textual code editor that allows the definition of custom DSP algorithms using GenExpr, a language specifically designed for audio and video processing. By utilizing the `codebox`, it was possible to create a complex filterbank architecture that supports dynamic modulation of multiple parameters in real-time.

The implementation of the filterbank uses a modular approach, where each band is defined by a second-order resonant filter. The `reson()` function in the `codebox` is designed to calculate the coefficients for a bandpass filter based on its frequency and bandwidth parameters. This allows each band to be independently tuned, with control over the center frequency, bandwidth, and resonance (Q-factor) of each filter.

The resonant filter is implemented using the following difference equation:

$$y[n] = a \cdot x[n] + b \cdot y[n-1] + c \cdot y[n-2]$$

where $y[n]$ is the current output, $y[n-1]$ and $y[n-2]$ are the previous outputs, $x[n]$ is the current input, and a, b, c are the coefficients calculated based on the filter's center frequency and bandwidth. This equation is derived from the general form of a second-order Infinite Impulse Response (IIR) filter, which allows for efficient implementation of resonant bandpass filters. The coefficients are calculated as follows:

- $a = 1 - (c + b)$

- $b = 2 \cdot \cos(\omega_0) \cdot e^{-b_w/2}$
- $c = -e^{-b_w}$

where ω_0 is the center frequency in radians, and b_w is the bandwidth.

```
reson(x_1, freq, bandwidth1) {
  History y2(0); // Delay buffer for y[n-2]
  History y1(0); // Delay buffer for y[n-1]

  // Convert parameters to radians per sample:
  freq_rps = freq * twopi/samplerate;
  bw_rps = abs(bandwidth1) * twopi/samplerate;

  // Calculate coefficients:
  b = 2 * cos(freq_rps) * exp(bw_rps * -0.5);
  c = -exp(-bw_rps);
  a = 1 - ((c + b));

  // Compute next output sample:
  y_1 = a * x_1 + b * y1 + c * y2;

  // Store results in histories:
  y2 = y1;
  y1 = y_1;

  return y_1;
}
```

Listing 4.1: Code snippet of a resonant bandpass filter implemented in GenExpr.

The code snippet defines a resonant filter function called `reson()` that takes in an input signal, a center frequency, and a bandwidth as parameters. The use of `History` objects allows for storing the previous output samples, which are required to compute the current output using the difference equation. This modular design enables each band of the filterbank to be controlled independently in real-time, with the ability to adjust parameters such as frequency, bandwidth, and resonance.

4.5 Integrating Filterbanks with Nonlinear Dynamics

The integration of filterbanks with nonlinear dynamic systems, such as the Duffing oscillator, introduces a powerful means of shaping chaotic behaviors into musically meaningful structures. When the chaotic output of a Duffing oscillator is fed through a filterbank, the resulting sound can be tamed and sculpted by emphasizing or attenuating specific frequency bands. This setup enables performers to highlight harmonic components within a chaotic texture or to isolate noise elements, creating a wide range of timbral variations [27]. The combination of chaotic dynamics and filterbank segmentation allows for a continuum between structured, tonal sounds and more abstract, noisy textures.

4.6 Spectral Shaping Possibilities in iDDY

The filterbank in iDDY provides a broad spectrum of spectral shaping possibilities, from smooth, harmonic sculpting to aggressive, inharmonic filtering. Each band can be independently modulated in frequency and amplitude, enabling complex rhythmic patterns and dynamic spectral effects. Additionally, by using nonlinear mapping strategies, it is possible to introduce probabilistic variations into the filterbank's behavior, resulting in evolving spectral patterns that reflect the performer's gestures [14].

4.7 Practical Applications in Live Performance

Filterbanks are particularly effective in live performance scenarios, where they allow for on-the-fly modifications of the instrument's spectral characteristics. In iDDY, the performer can use the filterbank to dynamically emphasize certain frequencies, creating contrasts between different sonic textures during a performance. For example, isolating higher frequencies can bring out sharp, metallic timbres, while boosting lower bands can add weight and depth to the sound. This real-time flexibility makes filterbanks indispensable for performers seeking to craft unique soundscapes in response to the acoustic environment or the musical context [20].

Chapter 5

Interaction Design and Mapping Strategies

5.1 Interaction Design Principles in DMIs

The interaction design of Digital Musical Instruments (DMIs) involves a structured approach to creating responsive systems that maximize expressivity and control. Unlike traditional acoustic instruments, where interaction is inherently constrained by the physical properties of the instrument, DMIs are highly flexible and allow for the implementation of diverse interaction paradigms. The design of interaction for DMIs, therefore, revolves around defining effective mapping strategies, selecting appropriate sensor technologies, and ensuring that real-time feedback mechanisms are in place [14]. These design choices directly influence the instrument's usability, expressivity, and overall playability [22].

5.2 Mapping Strategies: Direct vs. Indirect Control

In DMI design, mapping strategies define the relationship between performer inputs (e.g., gestures, touch, or motion) and the resulting sonic output. The two main categories of mapping strategies are direct and indirect mapping. Direct mapping establishes a one-to-one relationship between a control input and a sound parameter, ensuring predictable behavior. Indirect mapping, by contrast, transforms the control inputs through intermediary processes, such as mathematical functions or probability-based algorithms, before affecting the sound output [14].

5.2.1 Direct Mapping Strategies

Direct mapping strategies are implemented in iDDY through the use of eight 10k linear slide potentiometers, each corresponding to an individual frequency band of the filterbank system. This one-to-one mapping enables fine-tuned control over various parameters associated with each band, such as envelope shape, bandwidth, delay time, and frequency shift amount. Additionally, a set of 10k knob potentiometers is used for panning control, allowing the performer to adjust the spatial position of each band within the stereo field. Such a configuration provides a high degree of granularity in spectral shaping and spatial manipulation, making it ideal for real-time sound design, where performers require instantaneous feedback and intuitive control [46].

5.2.2 Indirect and Many-to-One Mapping Strategies

In contrast to direct mappings, indirect mapping strategies are used in iDDY for controlling complex, interdependent parameters through a single input source. This is realized using the Bela *Trill Hex* sensor, which supports multidimensional control. The x and y-axis indexes of the Trill Hex sensor provide a continuous control space, allowing the performer to modulate parameters such as index, depth, drive, friction index, and frequency of the Duffing oscillator's driving and intrinsic oscillators. This configuration supports simultaneous control of multiple parameters, enabling performers to navigate between stable and chaotic states of the oscillator using a single gesture [22].

Additionally, the Trill Hex sensor is employed to control a rotating clock divider, which modulates the probability of amplitude triggers for all bands of the filterbank. By integrating a probability-based algorithm, the system introduces controlled randomness, enhancing the complexity and unpredictability of the generated patterns. Furthermore, parameters of a plate reverb algorithm, including decay time, size, diffusion, and high-frequency damping, are mapped to the same sensor, allowing the performer to control spatial attributes of the sound in real-time [21].

5.3 Designing Expressive Control with Capacitive Sensors

The implementation of capacitive sensors in iDDY provides the basis for designing nuanced, expressive controls. Capacitive touch sensors are highly sensitive to variations in touch pressure, contact area, and movement, making them ideal for capturing complex gestural input. Two Bela *Trill Bar* sensors are employed to control the first four bands (1–4) and the remaining four bands (5–8) of the filterbank system, respectively. This setup allows for independent control of different spectral regions using separate hands, offering performers a multidimensional interaction space.

The multitouch capabilities of the Trill Bar sensors enable a range of interactions, including triggering individual bands like a keyboard, crossfading between bands, or dynamically modulating multiple parameters through sliding gestures. By leveraging the high-resolution data provided by the Trill sensors, the iDDY system supports complex gestural input that directly translates to rich spectral modulations in real-time, making the instrument highly responsive to performer intent [18].

5.4 Real-Time Sensor Data Translation

Real-time data translation is a critical component of the iDDY instrument, as it ensures that the performer's gestures are accurately captured and processed with minimal latency. Sensor data from the potentiometers and Trill sensors is routed through an Analog-to-Digital Converter (ADC) and then processed within the RNBO environment. To interface the Trill sensors with the Bela platform, iDDY utilizes the Inter-Integrated Circuit (I2C) protocol, which allows for efficient data transmission with minimal latency and low overhead. The use of I2C for the Trill sensors enables smooth, high-resolution control, ensuring that the performer's gestures are captured with high fidelity and accuracy [8].

Additionally, a multiplexer IC is used to expand the number of available analog inputs for the Bela system, allowing for the integration of the eight 10k linear slide potentiometers and a set of 10k knob potentiometers dedicated to panning control for each of the frequency bands in the filterbank system (as discussed in the *One-to-One Mapping Strategies* section). By implementing adaptive filtering and scaling algorithms, the system ensures that sensor data is interpreted correctly, providing a smooth and intuitive interaction experience [8].

5.5 Evaluating Playability and Expressivity

The evaluation of playability and expressivity in a DMI involves both qualitative and quantitative analysis. Playability is assessed based on the instrument's responsiveness, ease of use, and ability to support a range of playing techniques. Expressivity is evaluated by analyzing how well the instrument captures subtle variations in performer input and translates them into meaningful sonic output. In iDDY, these factors are evaluated through performance studies that focus on the interaction between the performer and the complex nonlinear behaviors of the Duffing oscillator and filterbank system [18]. Such evaluations provide insights into the strengths and limitations of the instrument and inform future design iterations.

Chapter 6

Introducing Unpredictability and Probabilistic Control

6.1 Unpredictability in Musical Interaction

In digital musical instrument (DMI) design, unpredictability is often employed as a tool to enhance the dynamic interplay between the performer and the instrument. By introducing elements of randomness and indeterminacy, DMIs can generate responses that are not entirely predetermined, encouraging the performer to engage more actively and creatively with the instrument [21]. This unpredictability transforms the instrument into a more autonomous entity that can surprise the performer, creating a unique interaction each time the instrument is played. The theoretical basis for employing unpredictability in musical interaction is grounded in Husserl's Model of Time-Consciousness, which explores how temporal structures influence the perception of time and rhythm [15]. In a musical context, randomness and unpredictability can disrupt expected rhythmic or tonal patterns, compelling the performer to adapt in real-time, thereby deepening the sense of engagement and interaction.

6.2 Controlled Randomness in DMI Design

The concept of controlled randomness is central to achieving a balance between predictability and unpredictability in DMI design. Unlike complete randomness, controlled randomness allows the designer to specify boundaries or probabilities for certain outcomes, creating a nuanced interaction space where the instrument can behave autonomously within defined limits. This approach provides a richer interactive framework where the performer can anticipate general patterns but not specific details, enhancing the feeling of "liveness" and emergent behaviors [45].

Implementing probabilistic control mechanisms such as Markov chains, random walks, or probabilistic event triggers allows DMIs to produce complex and evolving sonic outputs that remain coherent and musically meaningful.

6.3 Designing Probabilistic Event Triggers in iDDY

In iDDY, probabilistic control is implemented through the use of a *rotating clock divider*, similar to the architecture of the 4ms Rotating Clock Divider module. The rotating clock divider modulates the frequency of trigger events across multiple rhythmic layers, creating patterns that are continuously evolving. This was implemented using Pure Data (Pd), where a custom `pd_rotating_clock_euclid` subpatch was developed to manage the clock rotation and probability settings.

The main logic of the patch revolves around two independent rotating clock divider subpatches—one for the left side (`r_rot_l`) and one for the right (`r_rot_r`). Each subpatch receives a master clock signal from the `r_m_clock` object and then divides this clock into separate rhythmic subdivisions (e.g., 1/2, 1/3, 1/4), generated using modulo operations. The modulo operation determines the rhythmic subdivisions by taking the master clock and performing a division modulo N, where N is an integer value sent dynamically from `r_rot_l` and `r_rot_r`. These rotation inputs send integer values from 1 to 8, which control the clock division by determining the base subdivision value used in the modulo calculations.

This configuration allows for dynamic rotation of each clock divider, where changes in the rotation values shift the alignment of the rhythmic subdivisions in real-time. For example, if `r_rot_l` is set to 2, it will modify the division base to generate a sequence aligned with a 1/2 subdivision, whereas setting it to 3 will generate a 1/3 sequence. This dynamic modulation capability enables the performer to reconfigure the rhythmic structure of each clock division in real-time, creating a continuously evolving temporal pattern.

Each output division is then routed to a probability control mechanism, where a random number is generated (using the `random` object) and compared against a set probability threshold to decide whether a trigger event occurs. The probability thresholds are stored and updated via the `r_prob_l` and `r_prob_r` values, corresponding to the left and right clock dividers respectively. This allows for independent control over the probability of each clock division, resulting in a complex, evolving rhythmic texture.

By dynamically adjusting the probability from 0 to 100%, the performer can influence the density and rhythmic complexity of the generated patterns, ranging from sparse, unpredictable sequences to highly dense, repetitive motifs. This setup allows for real-time manipulation of rhythmic structures, where the performer can navigate between predictable and chaotic states, depending on the desired musical outcome [15].

6.4 Using Probability for Rhythmic Complexity

The use of probabilistic event triggers in rhythmic pattern generation offers significant advantages in creating complex and evolving rhythmic textures. Traditional rhythmic sequencing relies on fixed, grid-based structures where timing and duration are strictly defined. In contrast, probabilistic approaches allow for variable timing and dynamic changes in rhythmic density, producing patterns that evolve naturally over time [1]. By controlling the probability of individual triggers, iDDY introduces an element of stochasticity into the rhythmic structure, making the patterns less predictable and more responsive to the performer's gestures.

For example, a low probability setting can generate sparse rhythmic sequences with occasional, unexpected hits, while a high probability setting produces dense, almost continuous rhythms. These changes can be adjusted dynamically through the Trill Hex sensors, providing the performer with a direct, tactile interface for controlling rhythmic complexity in real-time. This capability makes iDDY highly suitable for live performance contexts where adaptability and on-the-fly variation are crucial.

6.5 Generating Evolving Rhythmic and Tonal Patterns

By using probabilistic control mechanisms, iDDY is capable of generating rhythmic and tonal patterns that evolve over time, providing a continuous flow of variation and surprise. This approach is influenced by concepts from algorithmic composition, where probabilistic rules are used to guide the generation of musical material in a structured yet non-deterministic manner [34]. In iDDY, the evolving nature of these patterns is achieved through a combination of probability-controlled triggers, rotating clock divisions, and modulation of the Duffing oscillator's parameters.

The Trill Hex sensors, in conjunction with the rotating clock divider, allow the performer to influence not only the rhythm but also the tonal characteristics of the generated patterns. For instance, changes in the x and y coordinates of the Trill Hex can modulate the frequency and amplitude of the Duffing oscillator, creating a feedback loop between rhythmic and tonal elements. As a result, the rhythmic patterns are not only evolving in terms of timing but also in terms of spectral content and timbral variation, producing a rich, multi-layered sound texture.

6.6 Enhancing Performer-Instrument Interaction

The introduction of controlled randomness in iDDY enhances performer-instrument interaction by making the instrument behave more like a co-creator in the musical process. Rather than simply responding to fixed inputs, iDDY generates outputs that can surprise and inspire the performer, prompting new ideas and directions. This dynamic interplay aligns with Husserl's phenomenology of rhythm, where the perception of time and rhythm is shaped by a continuous process of expectation, fulfillment, and disruption [15]. By incorporating probabilistic controls, iDDY encourages the performer to engage more deeply with the instrument, creating a dialogue where both the performer and the instrument contribute to the evolving musical texture.

6.7 Practical Implementation and Future Directions

The implementation of probabilistic control in iDDY is realized through a combination of hardware and software components, including the Bela platform for real-time processing, Trill sensors for multidimensional control, and the RNBO environment for signal routing and modulation. Future work could explore the integration of machine learning algorithms to dynamically adapt the probability distributions based on performer input, allowing for even more sophisticated interaction paradigms.

Figure 6.1: 4ms Rotating Clock Divider Module

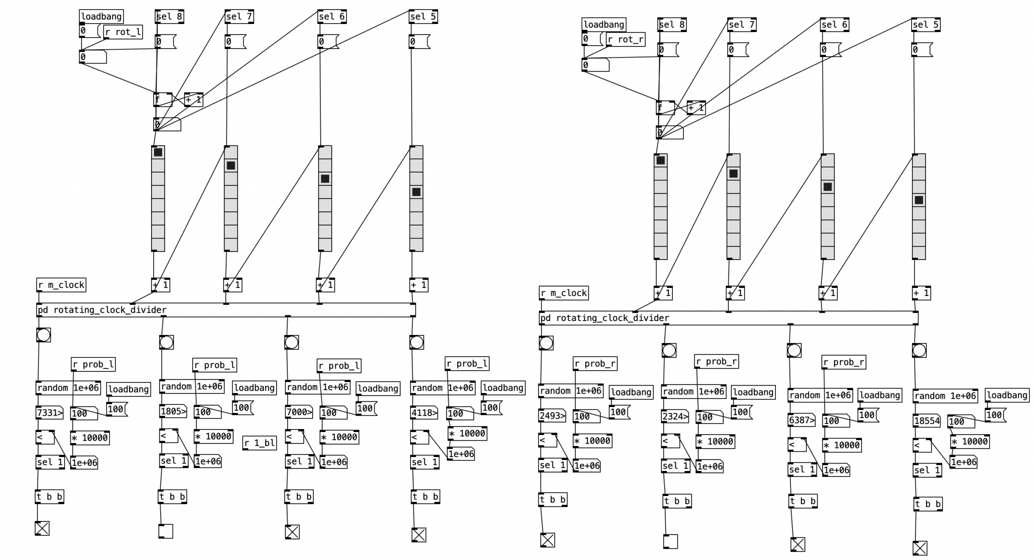


Figure 6.2: Rotating clock divider patch in Pure Data

Chapter 7

Implementation and Development

7.1 Hardware Platform: Bela for Low-Latency Processing

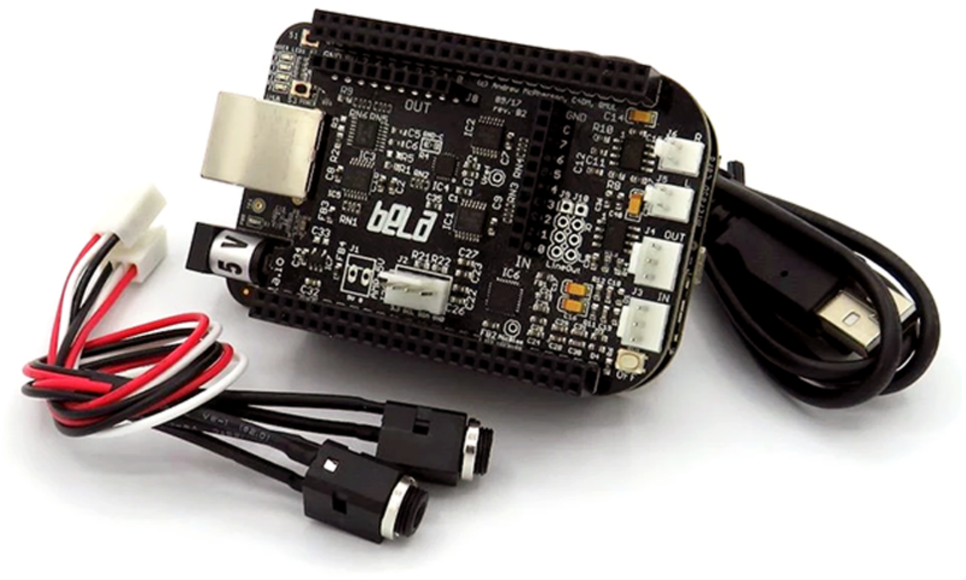


Figure 7.1: Bela

The core hardware platform for the iDDY system is the Bela, a low-latency embedded platform designed specifically for real-time audio and sensor processing. Bela is built around the BeagleBone Black (BBB), a single-board computer that integrates a 1GHz ARM Cortex-A8 processor, 512MB of RAM, and a dedicated Programmable Real-Time Unit (PRU) subsystem. Bela's high-resolution 16-bit analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), running at a sample rate of up to 44.1kHz with a latency of less than 1ms, make it particularly suitable for digital musical instruments (DMIs) that require real-time responsiveness [4].

7.1.1 Technical Specifications of Bela

The following specifications highlight the key features of the Bela platform that make it an ideal choice for implementing complex sensor-based interactions in digital musical instruments:

- **Processor:** ARM Cortex-A8 1GHz processor on the BeagleBone Black, providing enough computational power for complex audio processing and sensor data acquisition [4].
- **RAM:** 512MB DDR3 RAM, supporting multiple concurrent processes and allowing for real-time audio and control data handling [3].
- **Latency:** Sub-millisecond round-trip latency (<1ms), crucial for maintaining tight synchronization between performer gestures and sonic output [5].
- **ADC/DAC Resolution:** 16-bit resolution on all ADC and DAC channels, ensuring high-fidelity signal processing [4].
- **Sampling Rate:** 44.1kHz (default), with an optional high-sample-rate mode of 88.2kHz for more demanding applications.
- **Analog Inputs/Outputs:** 8 high-resolution analog inputs (16-bit), 8 analog outputs (16-bit), and 16 digital GPIO pins that can be used for triggers, push-buttons, and LEDs.
- **Programmable Real-Time Unit (PRU):** Dual 200MHz programmable PRUs, providing deterministic real-time processing capabilities for handling high-speed I/O operations [5].
- **I2C Communication:** Integrated I2C bus, supporting the connection of multiple external sensors such as Trill capacitive touch sensors [**bela_i2c**].
- **Multiplexing Capabilities:** Support for connecting multiplexers to expand the number of analog and digital inputs, enabling the integration of complex sensor arrays.
- **Operating System:** Runs a customized Debian-based operating system, allowing for the use of Pure Data (Pd) and other real-time DSP environments [3].

7.2 Sensor Integration and Control Mapping

The iDDY instrument utilizes a comprehensive sensor setup consisting of linear potentiometers, capacitive touch sensors, and push-button controls. Each sensor type is mapped to specific parameters in the synthesis engine, enabling the performer to interact intuitively with the nonlinear dynamic systems and filterbank structures.

7.2.1 Detailed Sensor and Control Layout

7.3 Sensor Integration and Control Mapping

The iDDY instrument utilizes a comprehensive sensor setup consisting of linear potentiometers, capacitive touch sensors, and push-button controls. Each sensor type is mapped to specific parameters in the synthesis engine, enabling the performer to interact intuitively with the nonlinear dynamic systems and filterbank structures.

7.3.1 Detailed Sensor and Control Layout

- **8 x 10k Linear Slide Potentiometers:** These potentiometers are used for one-to-one mappings to control parameters of each of the 8 bands in the filterbank, including envelope shape, bandwidth, delay time, and frequency shift amount. This allows for precise control over the spectral shaping of each band, providing high-resolution adjustments during live performance.

- **8 x 10k Rotary Potentiometers for Individual Panning of Bands:** These potentiometers are dedicated to controlling the panning of each of the 8 bands, allowing the performer to create dynamic stereo images by adjusting the spatial position of each frequency band.

- **2 x 10k Rotary Potentiometers for Dry/Wet of Effect Sections:** One potentiometer is mapped to control the dry/wet mix of the delay and frequency shift unit, while the other is used for the dry/wet mix of the plate reverb algorithm. This setup allows the performer to seamlessly blend in time-based effects with the primary audio signal.

- **1 x 10k Rotary Potentiometer for Master Volume:** The master volume control potentiometer allows for global adjustments to the output level, ensuring consistent loudness management during performance.

- **1 x 10k Rotary Potentiometer for Base Frequency:** This potentiometer offsets the base frequency of the filterbank, effectively shifting all 8 bands simultaneously. This parameter provides a global control over the spectral content of the sound, enabling rapid tonal changes.

- **1 x 10k Rotary Potentiometer for Master Clock Tempo:** Controls the master clock tempo, which affects all time-based processes, such as the rotating clock divider and probability event triggers. This allows for synchronized rhythmic modulations and time-based control.

- **2 x Trill Bar Sensors:** The Trill Bar is a high-resolution capacitive touch sensor capable of detecting multitouch gestures along a linear surface. The left and right Trill Bars are placed on either side of the panel, providing gestural control over various aspects of the filterbank system. Each Trill Bar has a length of 15 cm and supports up to five simultaneous touch points, enabling a range of interaction styles from triggering individual bands to controlling crossfader effects and feedback levels. In iDDY, they are mapped to control specific bands based on the performer's hand position, providing tactile, responsive input for real-time modulation.

- **2 x Trill Hex Sensors:** The Trill Hex sensors are multidimensional capacitive touch surfaces with a hexagonal grid structure, allowing for sophisticated gestural input in two dimensions (x and y axes). Each Trill Hex sensor can detect multiple touch points, making it ideal for navigating complex parameter mappings. In iDDY, the left Trill Hex controls the rotating clock divider and probability-based event triggers for bands 1-4, while the right Trill Hex modulates the same parameters for bands 5-8. Additionally, these sensors are used to manipulate Duffing oscillator parameters and reverb settings, providing an expressive control interface for dynamic sound shaping. The Trill Hex sensors communicate via the I2C protocol, offering high-resolution data with minimal latency.

- **4 x SPST Push-Buttons:**

  - **Button 1:** Toggles the parameter being controlled for the Trill Hex sensor, allowing for dynamic remapping of the sensor to control different sets of parameters.
  - **Button 2:** Switches the parameter group being controlled by the slide potentiometers, enabling the performer to quickly shift between different control configurations.
  - **Button 3:** Changes the parameter group associated with the Trill Bar, facilitating multiple levels of control without requiring physical rewiring.
  - **Button 4:** Start/Stop button for the master clock, enabling live control over the timing and synchronization of rhythmic elements.

All analog inputs from the potentiometers are routed through a multiplexer to the Bela's ADC channels, significantly expanding the number of control signals that can be processed simultaneously. This setup allows for smooth integration of complex control mappings, enabling iDDY to respond dynamically to real-time performer gestures.

7.3.2 Trill Sensor Specifications

The Trill sensors, developed by Bela, are designed for high-resolution capacitive touch sensing. They offer a precise and responsive interface, ideal for gestural input in musical contexts:

- **Trill Bar:** A 112mm-long capacitive touch strip supporting up to five simultaneous touch points. It communicates with the Bela board using the I2C protocol, offering low-latency performance. Each Trill Bar can be configured to detect touch position, pressure, and multitouch gestures, making it highly versatile for dynamic control scenarios.
- **Trill Hex:** A hexagonal, multidimensional touch surface that can track touch positions in both x and y axes. With support for multiple touch points, it is particularly suited for controlling complex parameter mappings. The Trill Hex sensor communicates using I2C, offering fast response times and high-resolution tracking for expressive performance interactions.

(a) Trill Bar

(b) Trill Hex

Figure 7.2: Bela Trill sensors

The Trill sensors are integrated seamlessly into the iDDY system, providing a robust interface for nuanced control over a wide range of synthesis and processing parameters.

7.4 Communication Protocols: I2C and UDP Integration

The iDDY instrument relies on two primary communication protocols: the I2C (Inter-Integrated Circuit) protocol for local sensor data acquisition and the UDP (User Datagram Protocol) for remote data transmission between Bela and the RNBO patch. Both protocols are essential for the system's performance and functionality, ensuring that data is accurately and efficiently routed to control multiple aspects of the instrument in real-time.

7.4.1 I2C Communication Protocol

The I2C protocol is a synchronous, multi-master, multi-slave, packet-switched communication protocol widely used in embedded systems for interfacing sensors and microcontrollers [48]. In the iDDY instrument, I2C is used to connect multiple Trill sensors to the Bela platform. Each Trill sensor communicates through a shared two-wire bus consisting of a data line (SDA) and a clock line (SCL). The master device, Bela in this case, initiates communication with each Trill sensor by sending a unique address, allowing multiple sensors to share the same communication bus.

Key characteristics of I2C that make it suitable for iDDY's sensor network include:

- **Addressing:** Each sensor is assigned a unique 7-bit address, which enables Bela to communicate with up to 127 different devices on the same bus.
- **Speed:** I2C can operate at standard mode (100 kbps), fast mode (400 kbps), or high-speed mode (3.4 Mbps), making it responsive enough for real-time data acquisition.
- **Scalability:** I2C's support for multiple slave devices simplifies the integration of additional sensors, such as Trill Bar and Trill Hex sensors, without complex wiring.

In the iDDY implementation, the I2C protocol is used to transmit touch data from the Trill Bar and Trill Hex sensors to Bela, where it is processed and mapped to various synthesis parameters. The high-speed, low-latency nature of I2C ensures that touch gestures are immediately reflected in the instrument's sound output, maintaining the expressive potential of the device [13].

7.4.2 UDP Communication Protocol

The User Datagram Protocol (UDP) is a transport layer communication protocol used for low-latency, connectionless data transmission [42]. Unlike TCP, which prioritizes reliable data delivery, UDP is optimized for scenarios where speed and efficiency are more critical than reliability. This makes UDP ideal for transmitting control data in real-time audio systems, where even minor delays can disrupt the performer's interaction with the instrument.

In the iDDY system, UDP is used to transmit sensor data and control messages from the Pure Data patch running on Bela to the RNBO patch on the desktop computer. Each sensor reading, including clock signals and parameter changes, is encoded as a UDP packet and sent to the RNBO patch, where it is used to control the Duffing oscillator, filterbank parameters, and reverb settings.

The advantages of using UDP in this context include:

- **Low Latency:** UDP has minimal overhead, allowing for faster transmission times compared to TCP. This ensures that control data is delivered to the RNBO patch with minimal delay, preserving the instrument's responsiveness.
- **Efficiency:** Since UDP does not require acknowledgment packets, the communication overhead is reduced, making it suitable for applications where real-time performance is a priority.
- **Multicasting Support:** UDP supports multicasting, enabling the same control data to be sent to multiple receivers simultaneously if required.

In the iDDY setup, UDP packets are transmitted at a high frequency to ensure that every touch gesture and clock update is accurately reflected in the sound generation process. The use of UDP also allows for flexible routing of control data, making it easy to adapt the system for different hardware configurations and network setups.

7.5 Developing Real-Time Audio Processing

The initial development phase of iDDY began with a standalone Max/MSP patch using a Korg nanoKONTROL 2 MIDI controller and virtual sliders to mimic the final hardware setup. This allowed for rapid prototyping and testing of control mappings and synthesis algorithms. After finalizing the control strategy, the Max/MSP patch was translated into RNBO and compiled onto a Raspberry Pi, but the computational load proved too demanding for stable operation. The project was then migrated to Bela, which provided the necessary low-latency environment but still experienced high CPU usage.

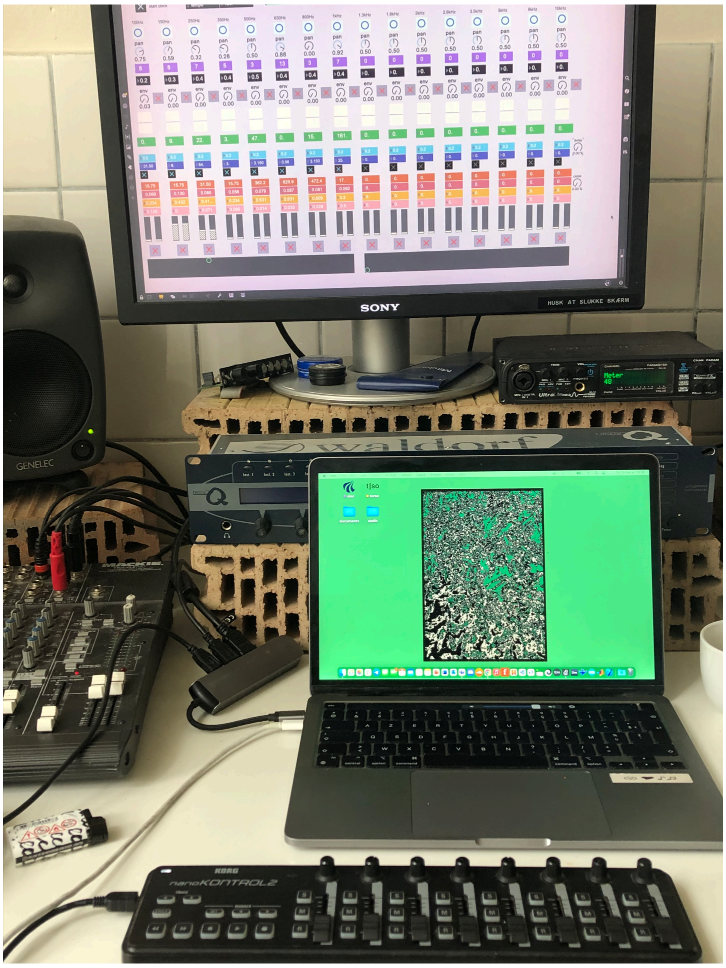


Figure 7.3: iDDY standalone Max/MSP patch setup with a Korg nanoKONTROL 2

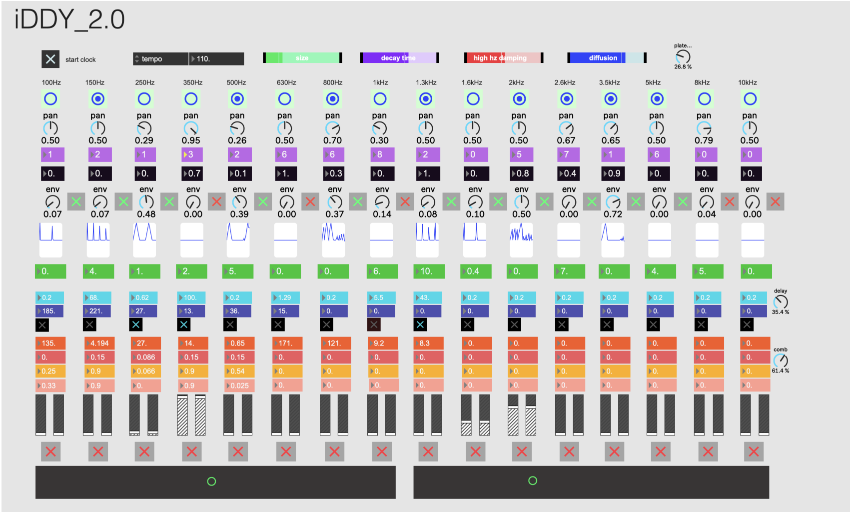


Figure 7.4: Screenshot of the initial iDDY standalone Max/MSP patch

The final implementation utilizes a hybrid system, where the RNBO patch runs on a desktop computer for primary sound generation and processing, while a Pure Data patch on the Bela handles sensor data acquisition, LED animations, and time-based processes like the rotating clock divider. All real-time data, including sensor readings and clock information, is transmitted over UDP from Bela to the RNBO patch, ensuring that the entire system remains synchronized.

7.6 Integrating Nonlinear Dynamics with Filterbanks

The Duffing oscillator's chaotic behavior is controlled using the Trill Hex sensor's x and y axes, while the filterbank's parameters are adjusted through the slide potentiometers and Trill Bar sensors. The filterbank consists of 8 parallel bandpass filters implemented in RNBO's `codebox`, allowing for fine-grained spectral shaping of the chaotic oscillator output. Each band can be independently modulated, with additional delay lines and frequency shifters in the feedback loop to create complex, evolving textures.

7.7 Implementation of a Griesinger-Style Plate Reverb

The reverb algorithm implemented in iDDY is based on the Griesinger-style plate reverb design, as detailed by Dattorro [9]. The core of the implementation consists of a combination of `comb~` and `allpass~` filters arranged in parallel and series configurations, emulating the dense and diffuse reflections of a traditional plate reverb.

7.7.1 Comb Filters

The primary structure involves a series of parallel comb~ filters, each having unique delay lengths and feedback parameters. In the Max patch, the delay lengths are set using the comb~ objects, which take four arguments:

- comb~ <delay-time> <feedback> <delay-buffer> <wet-level>

These delay lengths are typically chosen based on prime numbers to reduce resonance buildup at specific frequencies. For example, delay lengths might range from 25 to 160 samples, creating a complex set of reflections that diffuse over time.

7.7.2 Nested All-Pass Filters

The output of the parallel comb~ filters is further diffused using nested allpass~ filters. Each allpass~ object takes three arguments:

- allpass~ <delay-time> <feedback> <wet-level>

The feedback parameter controls how much of the delayed signal is fed back into the filter, creating the desired echo density. Multiple allpass~ filters are arranged in a serial configuration, effectively smearing the reflections and creating a smooth reverb tail.

7.7.3 Feedback Matrix

To add complexity and richness to the reverb tail, the outputs of the nested allpass~ filters are routed back into the input of the comb~ filters using a feedback matrix. This matrix is created using tapin~ and tapout~ objects in Max, allowing for precise control over the routing paths and decay characteristics of the reverb. The tapin~ and tapout~ objects are used as variable delay lines, ensuring that the feedback signal is properly aligned with the input signal.

7.7.4 Low-Pass Filtering in the Feedback Path

A low-pass filter (lores~) is placed in the feedback path to simulate the frequency-dependent absorption of high frequencies found in physical plate reverbs. This is achieved by setting the cutoff frequency of the lores~ object dynamically based on a damping parameter. This parameter can be adjusted in real-time to control the brightness and decay characteristics of the reverb tail.

7.7.5 Integration in RNBO

The entire Griesinger-style plate reverb is implemented using Max/MSP objects within the RNBO environment, ensuring that the processing is optimized for real-time performance. This implementation ensures that the reverb can run at low latencies (<1ms) even with complex parameter configurations, making it suitable for live performance scenarios in iDDY.

7.8 Parallel Delay Lines with Frequency Shifting Feedback

To add a layer of spectral complexity, each bandpass output of the 8-band filterbank is routed through a parallel delay line structure, each with its own frequency shifter in the feedback path. The delay time and frequency shift amount are independently controlled for each band, allowing for a wide range of modulation effects, including chorusing, flanging, and spectral smearing.

The implementation of the parallel delay lines with frequency shifting in iDDY is designed to introduce subtle pitch changes and create evolving textures across the feedback loops of each delay. This section consists of 8 independent delay lines, one for each band of the filterbank, with each line incorporating a frequency shifter in the feedback path. This setup allows for spectral manipulation that maintains clarity while producing rich and varied timbral transformations.

The Max/MSP implementation uses a combination of key objects to achieve this effect:

- `tapin~` and `tapout~`: These objects form the core of each delay line. The `tapin~` object receives the input signal and sets the maximum delay time (in this case, 2000ms), while the `tapout~` object outputs the delayed signal based on the specified delay time. The delay time can be dynamically adjusted to create a wide range of rhythmic and temporal effects.

- `freqshift~`: This object performs frequency shifting, a modulation effect that shifts all frequency components of the input signal by a constant amount. In the feedback path of each delay line, the `freqshift~` object is used to add a small frequency offset, which prevents phase buildup and adds evolving pitch variations to the delayed signal. The `freqshift~` amount is controlled by the `zmap` object, which maps an external control input to a usable frequency shift range, allowing precise manipulation of the shift amount.

- Gain Control with `*~` and `limi~`: Each delayed signal is multiplied by a gain factor (`*~ 0.5`) to prevent excessive feedback buildup and distortion. This gain control is further stabilized using the `limi~` object, which acts as a limiter to ensure that the output does not exceed a safe amplitude range.

- `line~` and `pack`: These objects provide smooth interpolation between delay times and frequency shift values. The `pack 0 10.` and `line~` combination sets up a ramp signal that gradually adjusts the frequency shift value over a defined period, thus avoiding abrupt changes that could cause unwanted artifacts in the audio output.

The overall configuration is structured so that each delay line feeds back into itself through the frequency shifter. This setup creates a self-modulating feedback loop, where slight frequency shifts accumulate over time, producing continuously evolving textures. By adjusting the frequency shift amount and the delay times dynamically, performers can sculpt a wide range of soundscapes, from subtle detuning effects to chaotic, inharmonic textures.

7.9 Software Architecture Overview

The software architecture of iDDY consists of three main components:

1. **RNBO Patch:** Handles core sound synthesis, including Duffing oscillator, 8-band filterbank, and stereo plate reverb algorithm.
2. **Pure Data Patch on Bela:** Manages sensor input processing, time-based control signals, and LED feedback.
3. **UDP Communication Protocol:** Ensures low-latency transmission of control data between Bela and the RNBO patch.

7.10 Hardware and Technical Setup for iDDY

The hardware setup includes a Bela connected to a multiplexer for analog input expansion, 8 slide potentiometers for direct filterbank parameter control, 8 rotary potentiometers for band panning, and 2 potentiometers for delay/reverb dry-wet mix. A set of push-buttons is used for switching parameter groups and master clock control, while Trill sensors are employed for multidimensional gestural input. This combination of sensors and controls provides a rich interaction space, enabling complex sound manipulation in real-time.

7.11 Physical Enclosure and Front Panel Design

The physical design and layout of iDDY were carefully planned to facilitate intuitive interaction and to ensure that the electronic components are securely housed within a robust enclosure. The front panel design was created using Inkscape, a

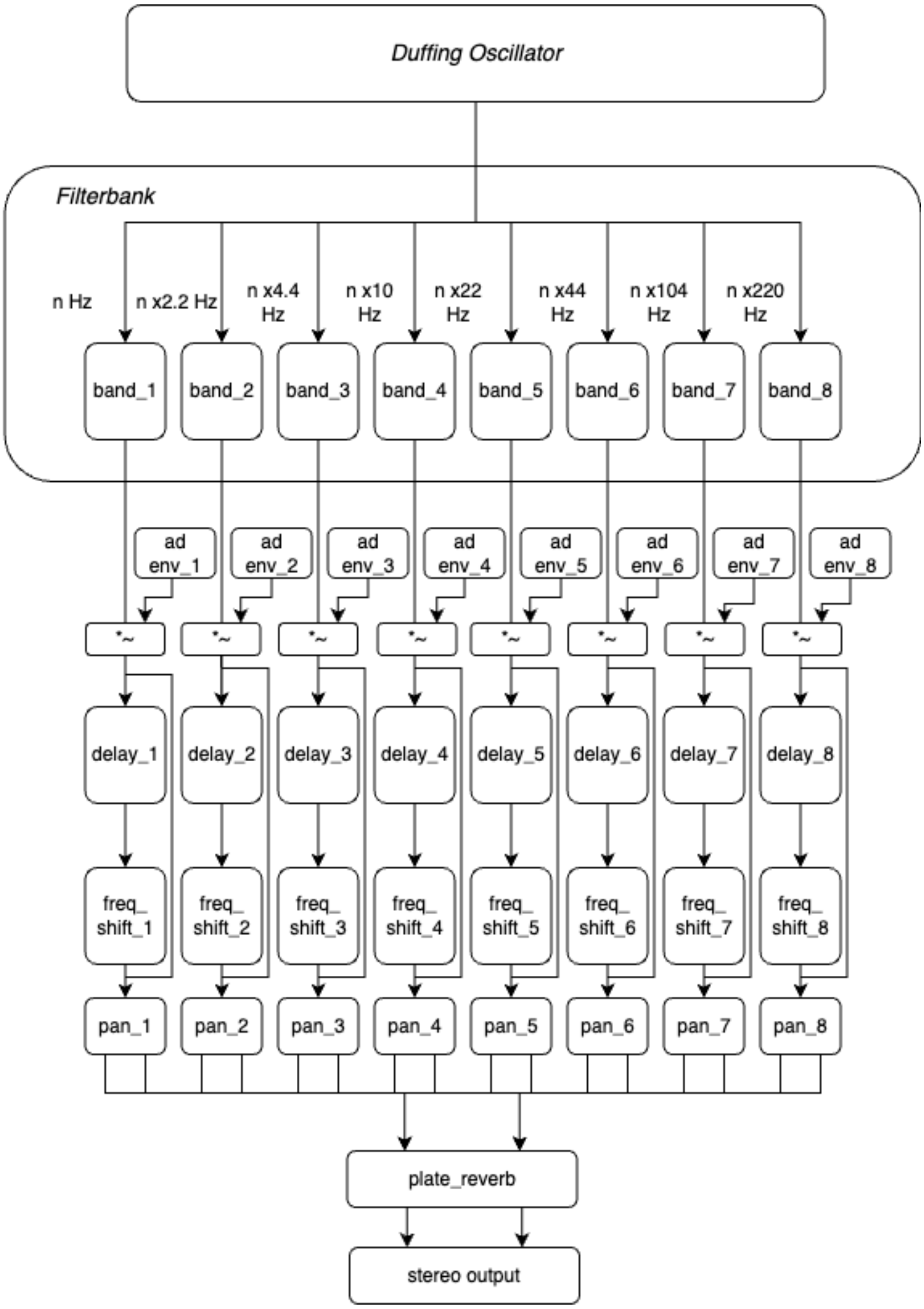


Figure 7.5: iDDY's signal path, without Trill sensors

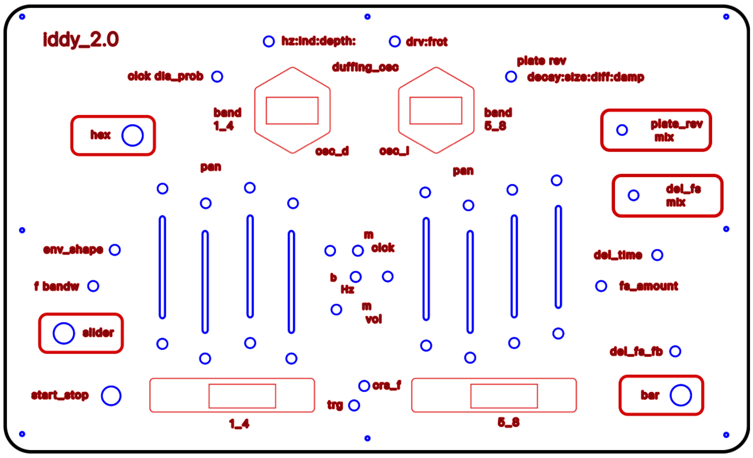


Figure 7.6: SVG file of iDDY designed on Inkscape

popular vector graphics software, which allowed for precise positioning of all control elements, including potentiometers, buttons, and Trill sensors. Once the design was finalized, it was exported as a vector file for laser cutting and engraving. The laser-cut front panel provides clear labels and visual guides for each control parameter, ensuring that performers can quickly access and manipulate the desired parameters in live performance contexts.

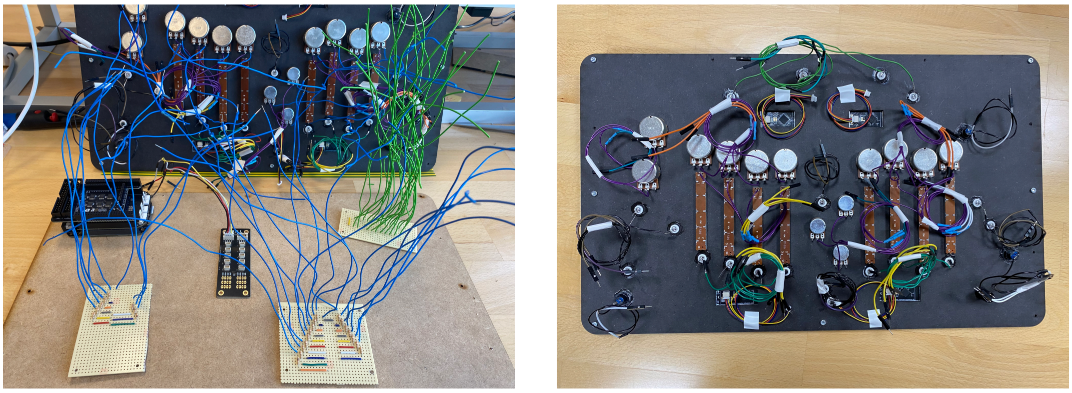
7.11.1 Enclosure Design and Dimensions

The entire enclosure is constructed using 3mm acrylic sheets for both the top and bottom panels, each measuring 470mm x 250mm. The panels are separated by three stacks of 20mm M2.5 metric male-female threaded hex brass spacers. Each stack consists of three spacers, providing a total separation of 60mm between the top and bottom panels. This spacing was chosen to accommodate the height of the potentiometers and other control elements, as well as to provide sufficient clearance for the internal circuit wiring.

- **Top Panel:** The top panel is engraved with labels for each of the control elements, such as potentiometers, buttons, and Trill sensors, to provide clear visual feedback on the function of each component. The laser engraving process ensures high-contrast markings that remain legible even under low lighting conditions, which is essential for live performance.

- **Bottom Panel:** The bottom panel is a solid acrylic sheet that supports the main PCB, multiplexers, and other electronic components, providing a stable base for the entire instrument. The bottom panel also includes cutouts for power cables, USB connections, and other I/O ports.

7.11.2 Internal Circuitry and Mounting



(a) the Bela, the Bela Trill Hub and VCC and Ground Prototype Breadboards

(b) iDDY's electronic components at the back of the panel

Figure 7.7: iDDY's Internal Circuitry

All electronic components, including the Bela board, multiplexer, and potentiometers, are mounted on the bottom panel. The internal circuit wiring is organized between the top and bottom panels, ensuring a clean layout that minimizes interference and allows for easy maintenance. The potentiometers and buttons are mounted through the top panel using hex nuts, which secure them firmly in place and prevent any lateral movement during intense performance. The stacked spacers provide mechanical stability and ensure that the top panel does not flex or bend under pressure, maintaining a consistent feel across all control surfaces.

7.11.3 Design Considerations for User Interaction

7.11.4 Trill Hex Control Area

The Trill Hex control area is designed for multidimensional modulation and mapping of several key parameters across the iDDY system. The left and right sides of the Trill Hex sensor are independently mapped to control two distinct sets of parameters, providing comprehensive gestural input for real-time control:

- **Rotating Clock Divider for Bands 1-4 and 5-8:** The left half of the Trill Hex sensor is mapped to control the rotation and probability of event triggers for bands 1 to 4, while the right half controls the same parameters for bands 5 to 8. This setup allows the performer to dynamically alter the rhythmic pattern and complexity of each subset of the filterbank, creating evolving rhythmic textures.
- **Duffing Oscillator Parameters:** The Trill Hex sensor is also mapped to manipulate core Duffing oscillator parameters, such as driving frequency, fric-

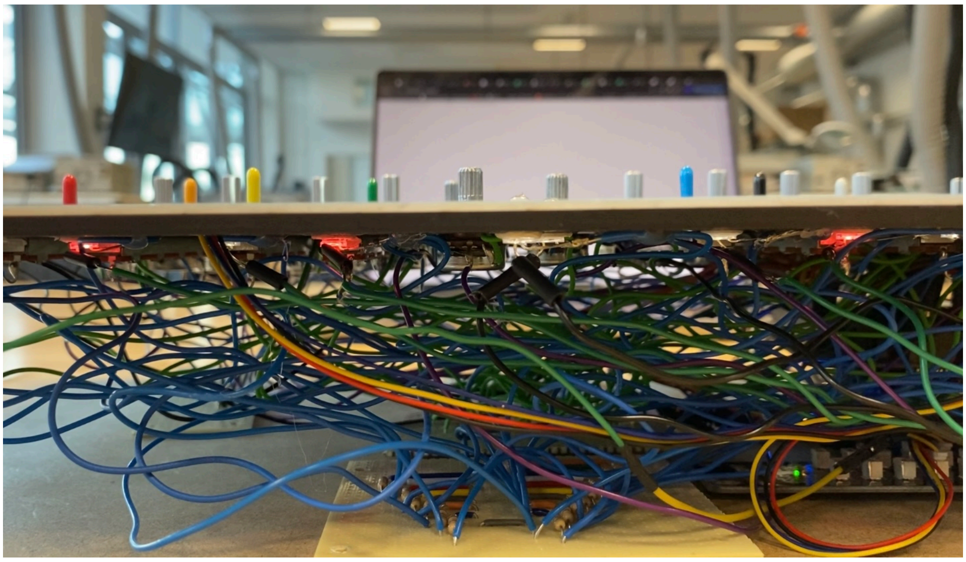


Figure 7.8: Eye-level view of iDDY from AAU's Manufakturet in Sydhavn, Copenhagen

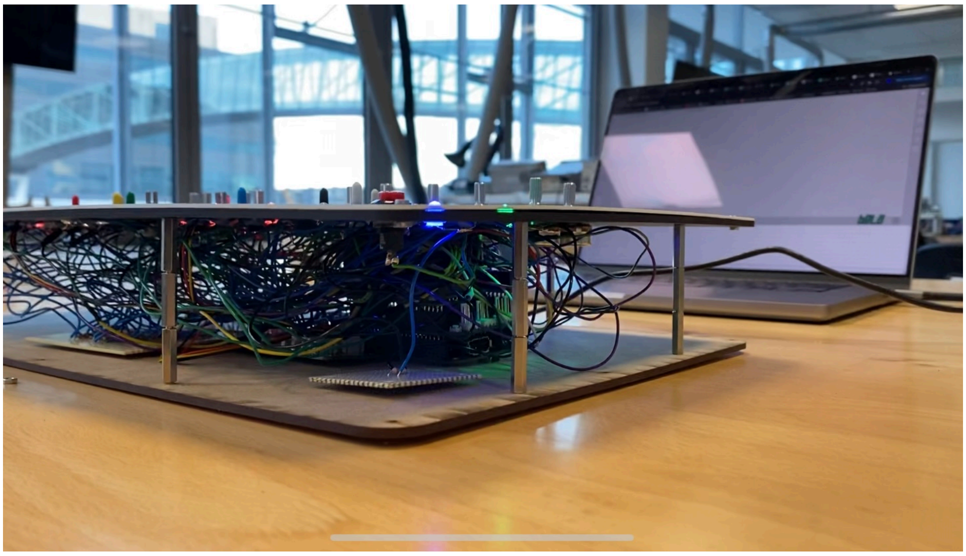


Figure 7.9: Side view of iDDY from AAU's Manufakturet in Sydhavn, Copenhagen

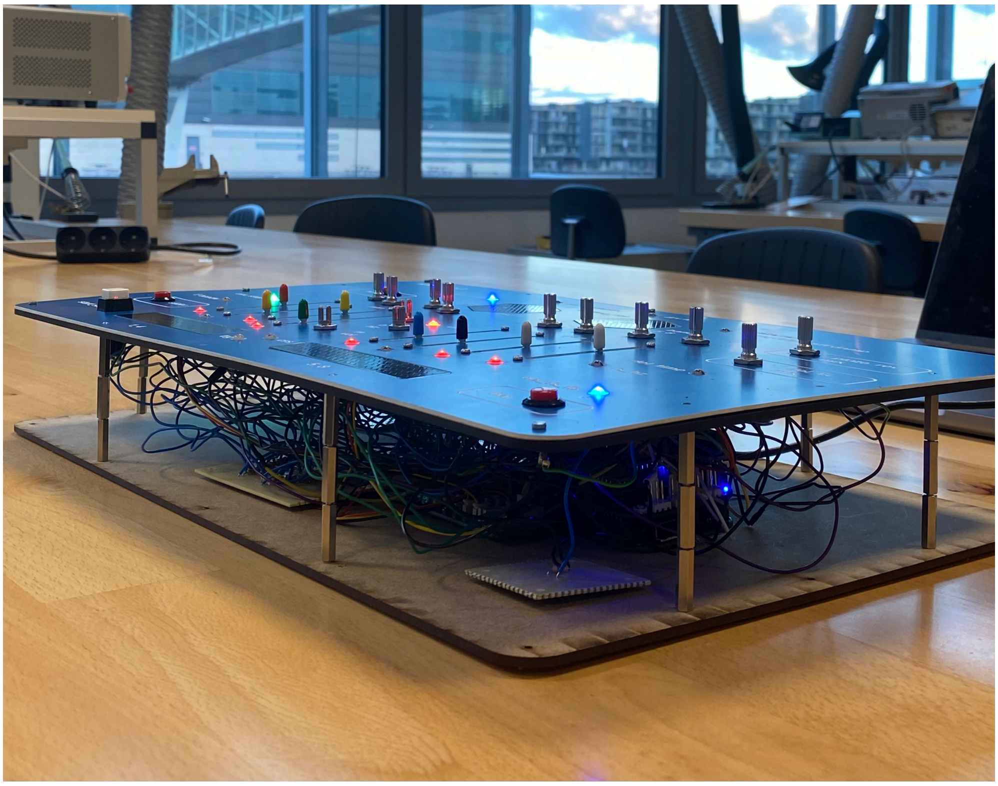


Figure 7.10: A different view of iDDY from AAU's Manufakturet in Sydhavn, Copenhagen

tion, and index, allowing the performer to modulate between stable, periodic oscillations and chaotic behaviors with simple hand gestures.

- **Plate Reverb Parameters:** Additionally, the Trill Hex can control key reverb parameters such as decay time, diffusion, and high-frequency damping. This configuration enables the performer to shape the spatial characteristics of the sound, adding subtle or dramatic reverb effects to the output.

The push buttons located adjacent to the Trill Hex sensor allow for quick switching between these parameter groups, enabling a seamless transition during performance. This layout is optimized for immediate access and intuitive control over the rhythmic and textural attributes of iDDY's sound output.

7.11.5 Slider Control Area

The central slider control area features 8 linear slide potentiometers, each corresponding to a unique frequency band within the filterbank. These sliders provide direct control over several critical spectral parameters for real-time sound shaping:

- **Frequency and Bandwidth Control:** The primary role of each slider is to adjust the frequency and bandwidth of its respective band, allowing for precise spectral sculpting. This enables the performer to emphasize or attenuate specific frequency regions to suit the desired sound texture.
- **Envelope Shape and Dynamics:** The slider controls also affect the envelope shape of each band, modifying attack, decay, and sustain characteristics. This feature provides an additional layer of control for dynamic shaping of the spectral output.
- **Delay and Frequency Shift:** Each band's output can be routed through a dedicated delay line with a frequency shifter in the feedback loop. The delay time and frequency shift amount are independently controlled by the sliders, offering unique modulation effects such as chorusing, flanging, and spectral smearing.

The rotary potentiometers located above each slider correspond to the spatial panning of each band, allowing the performer to create complex stereo images. This cohesive layout facilitates simultaneous manipulation of spectral and spatial properties using both hands, ensuring fluid control over the instrument's sound.

7.11.6 Trill Bar Control Area

The Trill Bar control area is positioned on either side of the front panel, providing a flexible interface for gestural interaction. The Trill Bars can operate in three distinct interaction modes, each tailored to a specific performance context:

- **Manual Trigger Mode:** In this mode, the performer can use the multitouch capabilities of the Trill Bars to manually trigger individual bands. Each touch on the sensor corresponds to a specific band, allowing for precise, percussive articulation of the filterbank's output.
- **Crossfader Mode:** This mode allows the performer to gate the incoming clock distribution across all bands. By using multitouch gestures, the performer can crossfade between different rhythmic distributions, enabling smooth transitions between sparse and dense textures.
- **Self-Running Mode:** In self-running mode, the Trill Bars autonomously trigger each band in sequence. This can be combined with the **del_fs_fb** parameter to activate feedback in the delay lines, creating accentuated effects and evolving textures for sound design. This mode is ideal for generating complex rhythmic and melodic patterns that evolve independently.

Each of these modes can be toggled via dedicated push buttons, providing the performer with quick access to different interaction paradigms during a performance. The Trill Bar control area thus serves as a versatile interface for exploring novel rhythmic and gestural expressions in the iDDY system.

Design Enhancements for Live Performance

The panel features laser-engraved labels with high-contrast text, ensuring visibility even under low-light stage conditions. Each section is distinctly marked, and the use of different button shapes and colors (e.g., the red and white push buttons) helps differentiate between functions. The use of robust materials and precise spacing between controls enhances durability, while the combination of slide and rotary potentiometers offers tactile feedback suited to rapid adjustments.

This well-organized layout, combined with the sturdy build and clear visual feedback, makes the iDDY instrument highly suitable for live performance contexts where precision and speed of interaction are paramount.

This design philosophy ensures that performers can intuitively access and control a wide array of sound parameters, enhancing the expressivity and playability of the instrument while maintaining a streamlined interaction flow.

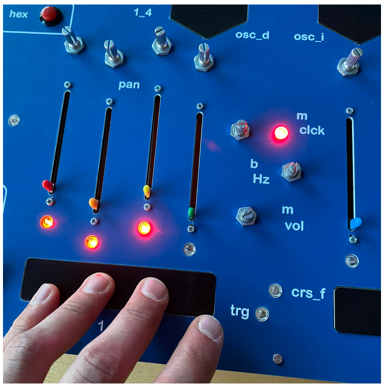


Figure 7.11: iDDY's LEDs for position feedback and band trigger

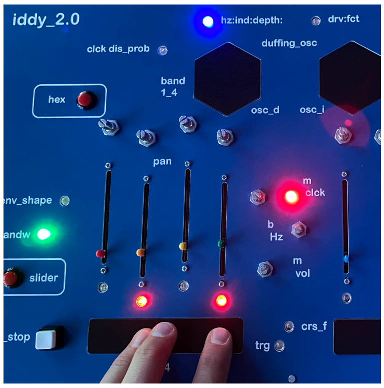


Figure 7.12: iDDY's LEDs for position feedback and band trigger

Figure 7.13: iDDY's LEDs for position feedback and band trigger

Chapter 8

Evaluation and Testing

8.1 Evaluation Framework for DMIs

The evaluation of Digital Musical Instruments (DMIs) is inherently complex and multifaceted, as it involves both quantitative and qualitative dimensions of user experience. For the iDDY instrument, a tailored evaluation framework was established, which combines traditional usability metrics with the principles of Autobiographical Design Methods (ABD). ABD is a research methodology where the designer uses their own experience as a basis for evaluating the system, thus allowing for deeper insights into the interactive and expressive qualities of the instrument [6]. The framework includes three primary criteria:

1. **Usability:** Measured by how effectively the instrument's interface and controls support learning and performance. Aspects such as intuitiveness, ergonomics, and the clarity of mappings are evaluated based on the designer's own experience and observations.

2. **Expressivity:** Determined by the instrument's responsiveness to nuanced performer inputs, enabling a broad range of dynamic and timbral variations. The designer's autobiographical reflections are used to identify how subtle gestural variations influence the instrument's sonic output.

3. **Playability:** Assessed based on the overall experience of playing the instrument, including how engaging and satisfying it is to perform with the instrument over extended periods. Personal experiences and subjective reflections are used to understand how well the instrument supports spontaneous, creative expression.

This framework integrates the unique insights provided by ABD with traditional evaluation approaches such as heuristic analysis, controlled testing sessions, and comparative studies.

8.2 Autobiographical Design and Heuristic Evaluation

The heuristic evaluation of iDDY was conducted using the designer's own experiences as a performer and DMI developer. This approach, aligned with ABD principles, allowed for a highly detailed and contextually informed analysis. The heuristics included:

- **Gestural Mapping Transparency:** The relationship between performer gestures and the resulting sound should be clear and intuitive. The linear slide potentiometers and capacitive touch sensors were evaluated based on their ability to provide predictable control over synthesis parameters, using the designer's firsthand interactions.
- **Responsiveness:** The instrument's response to input gestures was measured by evaluating the latency between control inputs and sonic output. The Bela platform's sub-millisecond latency was confirmed through extensive self-testing and analysis [4].
- **Consistency:** Consistency in the control mappings was assessed by repeatedly performing similar gestures and evaluating the stability of the resulting sound parameters. The designer's direct engagement helped identify areas where control mappings needed refinement.

Each heuristic was rated using a five-point scale (1 = Poor, 5 = Excellent), with the designer's subjective experiences providing a nuanced understanding of how the instrument performs under varying conditions.

8.3 Controlled Testing Sessions

Using the principles of Autobiographical Design Methods (ABD), the designer conducted a series of controlled testing sessions to systematically explore and validate the instrument's features. These self-directed sessions allowed the designer to delve deeply into specific performance scenarios and document the experiences and challenges encountered. The testing sessions focused on the following core aspects:

- **Real-Time Control:** The designer adjusted filterbank parameters, oscillator dynamics, and reverb settings while performing, observing the precision and responsiveness of each control. This process highlighted strengths and potential bottlenecks in the interface's design.
- **Chaotic State Transitions:** The ability to transition between stable and chaotic states in the Duffing oscillator was tested extensively, with attention paid to

how intuitively these transitions could be managed. The designer used various parameter configurations to assess the predictability and expressivity of these shifts.

- **Rhythmic and Timbral Variation:** The rotating clock divider and probabilistic event triggers were explored to generate complex rhythmic and timbral patterns. The goal was to evaluate how effectively these features could be used to sculpt evolving textures and how well the system responded to rapid adjustments.

Through repeated testing, the designer was able to refine the instrument's control mappings and interface layout, ensuring that the instrument could support a wide range of musical gestures and performance styles.

8.4 User Feedback on Expressivity and Playability

As part of the ABD approach, user feedback was substituted with introspective self-reflection, where the designer critically evaluated the instrument's expressivity and playability. Key evaluation criteria were defined and revisited throughout the iterative design process:

1. **Range of Expressive Control:** The designer evaluated how well the instrument captured and translated nuanced variations in gesture and touch.
2. **Ease of Use:** The interface was assessed for its intuitiveness and whether the control layout supported quick and accurate parameter adjustments without causing confusion or fatigue.
3. **Physical Ergonomics:** The designer reviewed the instrument's physical setup, focusing on comfort during extended use and the arrangement of controls to enable fluid and dynamic performances.

This self-reflective process provided continuous feedback, allowing for real-time adjustments and refinements in both the physical and software components of the instrument.

8.5 Evaluating Expressivity and Playability Using ABD

Autobiographical Design Methods (ABD) provided the foundation for evaluating expressivity and playability in a systematic yet subjective manner. By taking the role of both the designer and performer, the evaluation process could focus on the nuanced interplay between the instrument's affordances and the designer's own creative practices. This approach aligns with existing research in HCI and interaction design, where autobiographical methods are used to uncover insights that may be difficult to capture through traditional user testing [6].

8.6 Identifying Strengths and Limitations

The evaluation of iDDY using ABD revealed several key strengths and limitations:

8.6.1 Strengths

- **Expressive Control:** The combination of capacitive touch sensors and linear potentiometers enabled a high degree of control over the instrument's sound parameters, facilitating smooth transitions between different sonic states.
- **Dynamic Sound Shaping:** The integration of nonlinear dynamics with a custom filterbank structure provided a rich palette of sonic possibilities, ranging from chaotic textures to structured harmonic patterns.
- **Interface Intuitiveness:** The physical layout and grouping of controls were designed to be intuitive, making it easy for the designer to navigate complex mappings and maintain flow during performance.

8.6.2 Limitations

- **CPU Load:** The hybrid implementation (RNBO for synthesis and Pure Data for control) occasionally led to high CPU usage, which affected the system's stability in certain configurations.
- **Parameter Mapping Complexity:** The flexibility of the Trill sensors for multi-dimensional control could sometimes be overwhelming, making it challenging to achieve precise control during complex performance scenarios.

These findings will guide future development efforts, focusing on optimizing the system's performance and simplifying the control mappings for enhanced playability.

Chapter 9

Results and Discussion

9.1 Analysis of User Feedback

The analysis of user feedback for iDDY was conducted using Autobiographical Design Methods (ABD) as the primary evaluation strategy. ABD provided a unique perspective by allowing the designer to act as both the performer and the evaluator. This approach replaced traditional user testing with introspective reflections, enabling a detailed, context-sensitive evaluation of the instrument's usability, expressivity, and playability [6]. Key observations were made on the instrument's responsiveness to gestural inputs, its ability to support dynamic sound sculpting, and its overall ease of use. The use of ABD offered deep insights into how iDDY facilitated spontaneous creative expression, a core objective for the instrument's design.

9.2 Evaluation of Sound Quality

The sound quality of iDDY was evaluated by examining the output of its nonlinear synthesis and filterbank processing modules. Through iterative testing, the designer identified the unique sonic characteristics produced by the Duffing oscillator, ranging from smooth, harmonic tones to complex chaotic textures. The filterbank's ability to isolate and emphasize specific spectral regions added further richness to the sound, providing a broad range of timbral possibilities. By engaging in detailed auditory analysis, the designer fine-tuned the parameters to achieve a balance between stability and unpredictability, ensuring that the instrument could produce both traditional musical sounds and more experimental sonic textures.

9.3 Interaction Dynamics and Musical Expressivity

The integration of nonlinear dynamics with responsive gestural control allowed iDDY to capture a high degree of musical expressivity. The designer's experience revealed that even subtle variations in finger pressure or slider movements resulted in noticeable changes in the instrument's output. This sensitivity enabled a diverse range of interactions, from controlled, rhythmic modulation to abrupt shifts in timbre and dynamics. The use of capacitive sensors and slide potentiometers, combined with complex mapping strategies, supported continuous control over the instrument's state space, providing an engaging and versatile platform for real-time performance.

9.4 Meeting the Research Objectives

The research objectives for iDDY centered around creating a DMI that could seamlessly integrate nonlinear dynamics and real-time gestural control to enable complex sound manipulation. Through ABD and iterative design cycles, the instrument successfully met these objectives by:

1. Developing a robust hardware and software architecture capable of real-time audio processing and sensor integration.
2. Implementing a hybrid system with RNBO and Pure Data, allowing for advanced synthesis and sensor data handling.
3. Achieving a high degree of responsiveness and expressivity through carefully designed control mappings and interaction strategies.

The findings from the evaluation indicate that iDDY achieved a balance between complexity and playability, offering a rich interaction space for both novice and expert users.

9.5 Addressing Challenges in Real-Time Control

One of the primary challenges encountered during the development of iDDY was managing the real-time control of multiple parameters. The use of capacitive touch sensors (Trill) and slide potentiometers presented challenges related to parameter jumps when switching between different control modes. This issue was mitigated by implementing a "catch-up" mechanism, where the system only updated the parameter value once the slider position matched the stored parameter value within a specified threshold. Additionally, low-pass filtering was applied to smooth out noisy input signals from the analog sensors, ensuring that the real-time control remained stable and predictable.

9.6 Insights on Integrating Nonlinear Dynamics in DMIs

The integration of nonlinear dynamics in digital musical instruments presents unique opportunities and challenges. The use of the Duffing oscillator in iDDY provided a dynamic, evolving sound source that responded sensitively to even minor changes in input parameters. However, controlling such a system required careful attention to the mapping strategies to avoid overwhelming the performer. The evaluation showed that using multidimensional controllers like the Trill Hex sensor made it possible to navigate the complex parameter space of the Duffing oscillator effectively. This approach highlighted the importance of designing intuitive, direct mappings when working with chaotic systems to ensure that the performer maintains control and expressivity.

9.7 Refining the Design of iDDY

Based on the results of the ABD evaluation, several refinements were proposed to enhance the playability and stability of iDDY:

- **Parameter Mapping Refinement:** Simplifying the control mappings for the Trill sensors to reduce cognitive load during performance. Implementing visual feedback (e.g., LEDs) to indicate active parameter mappings and states.
- **CPU Optimization:** Optimizing the RNBO patch to reduce CPU load and improve stability during complex performance scenarios. Offloading some processes to the Pure Data patch on Bela for better resource management.
- **Physical Layout Adjustments:** Repositioning the slide potentiometers for easier access and more comfortable hand placement, ensuring that the instrument supports longer performance durations without fatigue.

These refinements aim to improve the overall playability and usability of iDDY, making it more accessible to a wider range of performers.

Chapter 10

Conclusion and Future Work

10.1 Summary of Contributions

The development of iDDY represents a significant contribution to the field of Digital Musical Instruments (DMIs) by integrating nonlinear dynamics, sophisticated filterbank processing, and real-time control strategies into a cohesive and highly interactive instrument. This thesis explored the potential of using chaotic systems, such as the Duffing oscillator, within a performance context, enabling new forms of expressive control. The use of autobiographical design methods (ABD) throughout the evaluation phase provided a deep understanding of the instrument's strengths and limitations, resulting in a refined design that offers both technical and artistic innovation.

10.2 Key Achievements and Limitations

Key Achievements

- **Nonlinear Dynamics in DMIs:** Successfully integrated a Duffing oscillator into a DMI, demonstrating how chaotic systems can provide a broad range of expressive possibilities.
- **Advanced Control Mapping:** Implemented complex parameter mappings using capacitive touch sensors and potentiometers, enabling multidimensional control over synthesis and processing parameters.
- **Real-Time Feedback and Interaction:** Developed a real-time feedback system using LEDs and visual indicators to enhance performer interaction, facilitating intuitive control.

- **Embedded System Implementation:** Transitioned the instrument to a fully embedded system using the Bela platform, improving stability and reducing setup complexity.

Limitations

- **CPU Constraints:** The complex nature of the synthesis algorithms and real-time control mappings led to high CPU usage, impacting system stability during intensive performance scenarios.
- **Parameter Mapping Complexity:** The flexibility of the Trill sensors for controlling multiple parameters could sometimes overwhelm the performer, complicating real-time control during high-intensity performances.
- **Lack of External Synchronization:** The current version of iDDY does not support synchronization with external devices, limiting its integration into larger musical setups.

10.3 Making iDDY Syncable with External Devices

One of the major areas for future development is enabling iDDY to sync with external devices such as MIDI controllers, DAWs, and other digital instruments. This could be achieved by implementing a MIDI clock input/output system on the Bela platform, allowing iDDY to be integrated into a broader ensemble or live performance context. By supporting standard communication protocols such as MIDI and OSC (Open Sound Control), iDDY can become part of a larger networked system, enabling more complex musical interactions and collaborations.

10.4 Adding External Audio Processing Capabilities

To further expand iDDY's sonic palette, external audio processing capabilities could be introduced. This would involve adding audio inputs and reconfiguring the filterbank and synthesis algorithms to allow for external signals to be processed in real-time. By integrating external audio, iDDY could function as both a standalone instrument and a dynamic effects processor, providing performers with even greater flexibility. This enhancement would transform iDDY into a versatile tool that can reshape and modulate external sound sources, opening new possibilities for creative exploration.

10.5 Designing a Custom PCB for Hardware Stability

The current hardware setup relies on a breadboard-based circuit, which, while functional, is prone to mechanical instability and signal interference. Designing a custom PCB for iDDY would ensure more robust connections, reducing the likelihood of hardware failures during live performances. The custom PCB would integrate the Bela board, multiplexer, and sensor interface circuits into a single, compact unit, significantly enhancing the instrument's durability and portability.

10.6 Enhancing Portability for Live Performances

Portability is a critical factor for live performance instruments. To enhance iDDY's portability, future iterations could focus on minimizing the instrument's size and weight. This could involve reducing the physical footprint of the control elements, optimizing the layout, and utilizing lightweight materials for the enclosure. Additionally, integrating a battery power option would allow for untethered performances, making iDDY a more versatile instrument for both stage and outdoor environments.

10.7 Future Work

This thesis documented the initial development phase of research around a new DMI concept. A second prototype of iDDY will hopefully make its way, incorporating the findings from the present evaluation phase and implementing new hardware features to simplify its setup. Future iterations will focus on creating a fully embedded system using Bela and RNBO, reducing dependency on external computing resources and enhancing portability for live performances.

Additionally, future research will aim to refine the analytic and adaptive capabilities of the instrument. Once these technical aspects are solidified, the focus could shift to artistic production, using iDDY to create new experimental works, collaborations with other musicians in the contemporary music scene, and a foundational live instrument to the designers improvisational setup.

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Appendix A

Appendix