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ABSTRACT

We present an interactive modular system built in Cycling '74 Max and interfaced with Grame's FAUST for the purpose of analyzing, processing and mapping electrophysiological signals to sound. The system architecture combines an understanding of domain-specific (biophysiological) signal processing techniques with a flexible, modular and user-friendly interface. We explain our design process and decisions towards artistic usability, while maintaining a clear electrophysiological data flow. The system allows users to customize and experiment with different configurations of sensors, signal processing and sound synthesis algorithms, and has been tested in a range of different musical settings from user studies to concerts with a diverse range of musicians.

CCS CONCEPTS

• Human-centered computing → User studies; **• Applied computing → Sound and music computing**; **Performing arts**.

KEYWORDS

Electroencephalogram (EEG), Electromyogram (EMG), Digital Musical Instruments (DMIs), Interactive Music Systems, Signal Processing, Sound Synthesis, Max, FAUST

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1 INTRODUCTION

The use of electrophysiological signals from the human body has come of age in the fields of human-computer interaction (HCI) and digital musical instrument (DMI) design. Indeed, many interactive music systems have been created by different musicians and researchers, with the goal of simplifying the process of developing digital musical instrument based on electrophysiological signals and bodily gestures [1, 8]. However, their efforts have often been isolated from mainstream scientific or musical communities, limiting how knowledge and practices can inform each other.

In the domain of EEG, i.e. Brain-Computer Music Interfaces (BCMI [9]) software that uses command-line interfaces [11, 12], complex architectures [1, 5, 14, 15], or procedural programming [12, 17] have made real-time EEG processing accessible to a subset of potentially interested users, i.e. those with the necessary technical skills. Furthermore, the choice and implementation of EEG analyses assumes a degree of neuroscience training or at least understanding. While the market has responded with increasingly user-friendly systems (e.g. [10] for a recent review), they do not often provide a software architecture that is sufficiently open and flexible for artistic practices. Commercial software can also be obstructively priced, and are often specialized for specific therapeutic or medical uses. In short, the need for a standardized system that accommodates electrophysiological signal processing into a flexible musical environment is currently lacking. Best practices in muscle group identification, electrode placement, and task design need to be transmitted to nonspecialist users.

The development of the software we will be discussing is a response to this situation, and part of a larger project called *Body Brain Digital Musical Instrument* (BBDMI). The aim of the project is to develop a digital musical instrument for musicians and artists without specialist knowledge in the fields of neuroscience and signal analysis [16]. In other words, the main objective of the BBDMI is to create a flexible and creative platform for experimenting with electrophysiological signals by providing a user-friendly interface to deal with signal processing from acquisition, to feature selection and sound mapping.

This paper is structured as follows. We first introduce related work that situates the current research. We next describe our system architecture in detail, the technical challenges encountered, as well as the potential relevance to the music community. We will then demonstrate our patching workflow, the modules for signal processing, as well as the mapping strategies developed during user studies and concerts. Finally, we will conclude with ideas for how to improve the system, possible future directions, and a link to our public repository. In the text we use the term *ExG* to refer to both electromyography (EMG) and electroencephalography (EEG).

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2 RELATED WORK

2.1 Artists / Collectives

The adoption of electrophysiological signals in sound art can be traced back to the early 60's with the work of experimental artists Alvin Lucier, David Rosenboom and Richard Teitelbaum. Their work has inspired new generations of artists who represent the foundation of today's musical community.

Recent biotechnological musical practice has been described by Donnarumma in a collected edition, including the biophysical musical instrument Xth Sense [7]. Art-science music collectives such as 1+1=3 bring together musicians, engineers and neuroscientists to harness EEG signals to manipulate sound and moving images, and create open-source tools [12]. Italian artist Federico Visi has been working with biophysical sensing devices integrating reinforcement learning techniques and artificial intelligence algorithms for live musical contexts [20]. These are the creative communities from which our system emerges, and with which we share the common goal of supporting musicians and researchers with the process of designing sustainable interfaces through a flexible, modular, and interactive approach. By combining complex processing techniques with a friendly user interface, we propose an accessible toolkit for both advanced users and those with no prior programming experience, to ultimately support the same creative communities we work with and return our experience and musical insights.

2.2 Interactive Systems / Packages

A large set of research practices within the fields of instrument making, sound synthesis and sound-gesture interaction design have matured towards the development of interactive music systems that share the common goal of easing user's interaction and expressivity in the signal processing and sound design phases, often adopting case-specific interfaces protocols.

Myo Mapper is a free and open source software capable of mapping data coming from the Myo armband to OSC messages, a user-friendly solution for sound-gesture experimentation. The Gestural Sound Toolkit (GST) is a collection of Max patches for quick gesture-sound prototyping, including modules for motion capture, signal processing, machine learning, and sound synthesis [4]. Their goal is to create a versatile tool to accommodate designers without programming knowledge. The Sound Design Toolkit (SDT) is a virtual Foley box containing a diverse set of sound-generating processes based on physical modeling, readily accessible to sound designers for sketching and prototyping interactive sonic behaviors [2]. The Gestural Interaction Machine Learning Toolkit (GIMLeT) provides an educational toolkit consisting of a series of Max patches and objects for performing gesture analysis and mapping tasks adopting the interactive machine learning (IML) workflow [19]. It uses a set of Max externals including a package for dynamic communication based on the OSC communication protocol, O.–odot, a framework created for the purpose of providing expressive communication protocols between diverse media systems [3]. Berklee Electro Acoustic Pedagogy (BEAP) is a library of patches included in the commercial distribution of Max and provides a flexible, modular approach which allows users to maintain the main functionality of a common eurorack modular synthesizer from creating simple synthesizers and sequencers to LFOs, CV generators and waveshapers.

3 ARCHITECTURE

Using electrophysiological signals for musical purposes, be it sonification, sound control or synthesis, requires moving through different stages, from signal acquisition, feature extraction, control processing and mapping to synthesis parameters and/or sound engines design. In our architecture, the same algorithms can be used in different parts of the chain, such as converting audio to control signals, and vice versa. At times signals need to be routed to many different places in the processing chain, which could make the patching of multiple cables tedious or time-consuming. In addition, most algorithms often tend to handle multiple functions all at once, making it hard to trace bugs or errors in the code. We deal with these issues through a clear modular design and the implementation of effective patching strategies.

3.1 Modularization

We developed our system using Cycling '74' Max, and Grame's FAUST language.

We follow a modular approach that allows users to flexibly interchange bespoke sound and modulation stages for creating multimodal instruments with different ExG devices, where each module represents a building block in the processing chain. The system allows working with different types of modules, from input signal generators to control processing algorithms such as smoothing, calibrating and scaling, feature extraction, sound synthesis and processing devices, utilities and output routers. These modules are presented with an adjustable user-friendly GUI, making it easy for the users to access the main control parameters and settings. Furthermore, to simplify the patching process, all modules share the logic of "one-cable" patching, eliminating the hassle of connecting multiple input and output cables.

The electrophysiological signals processing chain consists of a series of different stages: signal acquisition, feature extraction, control processing, and sound synthesis (Figure 1). In our system we use audio matrices, visualization modules, and signal-to-audio converters to aid in the processing chain. Sometimes pre-processing algorithms such as smoothing and filtering may be already implemented on the input device. In other cases, an input device may stream raw data which needs to be pre-processed before entering the processing chain.

(1) The first stage in the chain is the signal acquisition. This can be live, prerecorded or simulated. We tested our system with the EAVI EMG board [6], the Myo Armband [18], the OpenBCI boards for EEG ("Cyton") and EMG ("Ganglion") and the Explore (Mentalab GmbH, Munich), and the Unicorn (g.tec medical engineering GmbH Austria) EEG acquisition devices. We designed an ExG audio recorder as well as a FAUST [13] wrapper to contain ExG simulators.
(2) The second stage is feature extraction. Here electrophysiological signals are transformed into meaningful musical data such as gestural amplitude and muscular tension.
(3) In the control processing stage features are smoothed, calibrated, scaled and mapped to sound synthesis parameters.
(4) The final stage is the sound synthesis. Here parameters from the control processing stage are used to modulate sound, spatialization or control effects parameters.

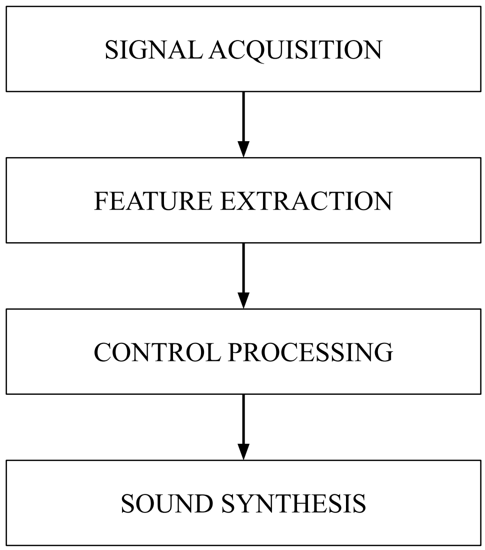

Figure 1: The electrophysiological signals processing chain: from signal acquisition to sound synthesis.

3.2 Audio / Control Signals

Working with electrophysiological signals requires keeping a strict timestamp in order not to lose precious details (such as the spectral content). Because Max treats audio differently from numeric data, it is important to be able to treat ExG data as audio, in order to force Max to handle the signal with a constant sample rate independent from, e.g., the CPU load. We therefore treat electrophysiological signals as either multichannel audio or control signals, depending on the stage of the signal processing chain and the specifics of the ExG acquisition device. Our approach is novel in its dual treatment (control, audio) of the biosignal, and also in the use of the biosignal in the audio signal processing chain.

Part of the system includes FAUST code built to simulate, filter and pre-process ExG signals, as well as algorithms for sound synthesis and ambisonic spatialisation [13]. Although FAUST code can be compiled as a Max object, the number of input and output channels is fixed at the moment of the compilation, and cannot be changed following the standard multichannel architecture. To overcome this issue we designed a wrapper based on scripting messages that activates as soon as the number of channels changes.

3.3 Modules

We will present an overview of the organization of the modules in the current system. The number of modules and their functionality is continuously expanding, but the following overview should give a general sense of the scope of the current version.

3.3.1 Input. The input modules deal with different sets of ExG devices and acquisition software, making sure the data becomes available as audio signal for further processing in Max. The system permits the acquisition and dynamic interchange of different electrophysiological signals from live, recorded or simulated sources. It currently features acquisition modules for the EAVI EMG board [6], the Myo Armband [18], synthetic EMG and EEG signals. The <bbdmi_emg_simulator~> module allows users to create multichannel audio signals with a spectrum similar to the one captured with surface electrodes. It allows the control of the intensity and the envelopes of the output signals, as well as simulating fast, slow, strong and soft muscle contractions. As EEG signals are much more complex in their behavior than EMG, the resulting signal may vary depending on each person, cognitive state, type of devices and electrodes used, as well as the position of the electrodes. Instead of trying to simulate the complexity of the brain, our simulator creates a basic spectrum with an additional controllable band between 8 and 12 Hz simulating the Alpha band, and around 20 Hz, simulating the Beta band, both of which are used in many BCI paradigms.

3.3.2 Feature extraction. The feature extraction modules are used to extract relevant musical information from audio signals and convert it into control messages that can be further processed in the signal processing chain. One widely used module for this purpose is the <bbdmi.rms~> object, which implements the root-mean-square (RMS) analysis of an audio signal to determine its average amplitude, or force. We are currently experimenting with more probabilistic approaches such as recursive Bayesian estimation (or Bayesian filter), where EMG amplitude estimation has shown better results compared to RMS in terms of signal-to-noise ratio and fast transient responsiveness.

3.3.3 Control Processing. The control processing modules provide a flexible and expressive means of manipulating input data. They consist of patches that process incoming control signals from the feature extraction module and transform them into a list of messages. This stage allows users to perform various signal transformations, such as calibrating, scaling, regressing, and smoothing the data. These messages can be used to directly control sound synthesis modules or can be processed further using "utilities" modules for tasks such as visualization, routing, or recording.

3.3.4 Output. The output modules contain patches that create communication bridges of signals though MIDI and OSC protocols, or other Max modules using internal message routing (send/receive), as well as routing and mixing signals to external audio devices.

3.3.5 Sound Synthesis. The sound synthesis modules contain a set of patches that deal with the production and modulation of sound. These are typically combined into a complex digital synthesizer that responds to data control data derived from the ExG signals. Currently the system contains a live granulator object designed in FAUST, and exported as a Max object for processing live input signals, as well as a Max granular synthesizer, the <bbdmi_live_granulator~> module. The architecture of the compiled FAUST objects follow the modular logic of our Max system. These modules allow a complete control over internal parameters, and their primitive functions are exposed in the BBDMI FAUST library so they can also be compiled separately.

3.3.6 Utilities. The utilities modules contain functional patches that support the designing process such as editing input–output connections, creating audio buffers, recording data and converting audio to control signals. An example is the <bbdmi.crosspatch~> object, which acts as a matrix between input and output channels.

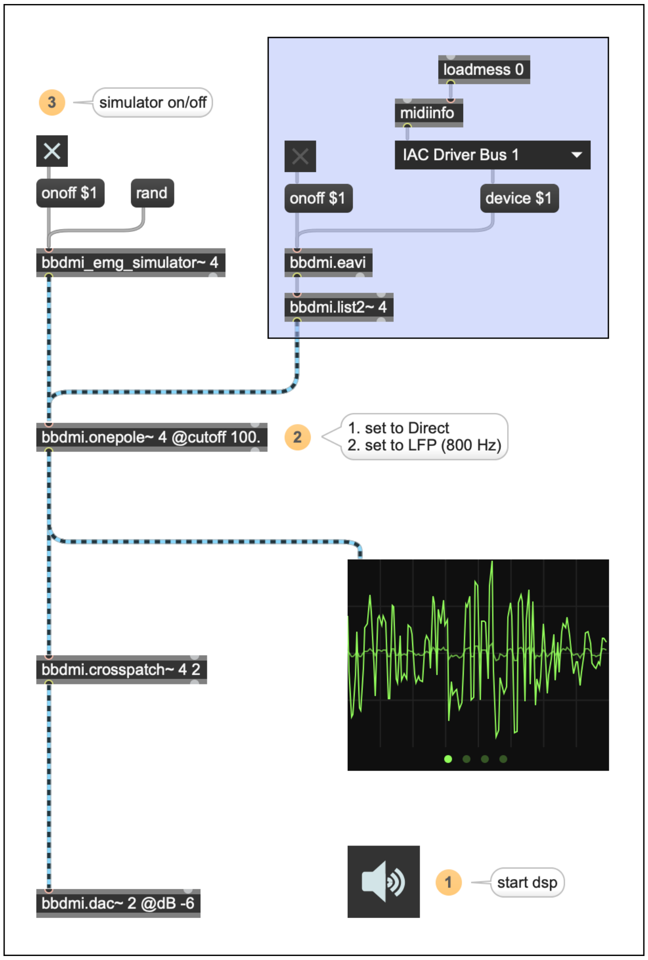

Figure 2: Mode 1. Abstractions (with objects exposed).

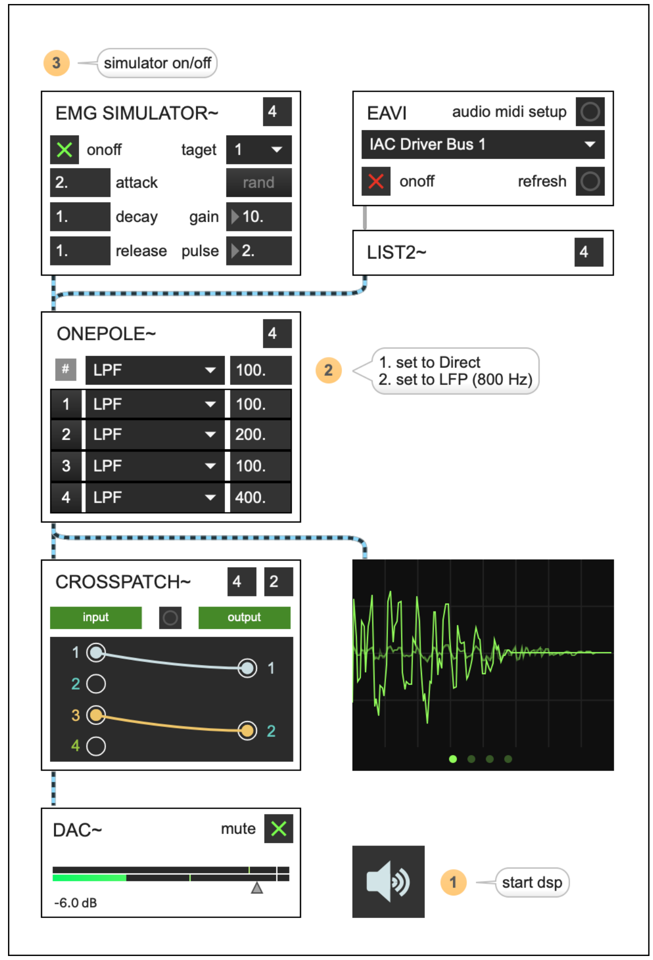

Figure 3: Mode 2. Bpatchers (with GUI exposed).

3.4 Modes of interaction

The examples in Figure 2 and 3 show a simple implementation of the sonification process of four EMG simulated signals, using two different modes of interaction:

(1) *Abstractions* (with objects exposed): Each module is instantiated in the main patcher window as an *abstraction* (Figure 2), where the main parameters can be modified using a designated message box (e.g. onoff 1). Once the simulator is turned on, the signal is routed through a single-pole low-pass filter using the <bbdmi.onepole~> module, reduced to a stereo signal (<bbdmi.crosspatch>), and sent out for listening through a <bbdmi.dac~> object.

(2) *Bpatchers* (with GUI exposed): The same process can be implemented by instantiating the relevant objects as *bpatchers*, exposing the main adjustable parameters in a graphical user interface (Figure 3). This mode gives us a wider overview of the signal processing chain, allowing faster prototyping, and visualization feedback. As patches tend to grow in dimensions very quickly, combining the two modes is preferable.

4 PRELIMINARY EVALUATION

The system has been used in concerts, user studies and musical conferences with a diverse range of musicians.

The first presentation of the software was made during the Max Summer School in Geidai (2022), where we introduced the BB-DMI project and a preliminary version of our system architecture. Although still in early development, we used the system in a patching exercise in front of 50 students over Zoom. Each processing stage was presented with a single object: starting by simulating one channel of EMG signal, it was then averaged and mapped to the frequency parameter of a simple low-pass filter resonator.

The system has been used to refactor a repertoire of older musical pieces that have been developed in Max since the 1990s. This has enabled the works to be updated and performed on the current version of Max, as well as served to extract idiosyncratic ways of working with biosignals to be standardized.

During the Journées Européennes du Patrimoine 2022 we set up the first demonstration of our system for a general audience, using a total of five ExG devices: two Myo Armbands (EMG), two EAVI boards [6] (EMG), and one EEG headset (Mentalab Explore). A diverse group of participants were invited to use the system, which highlighted the need for a flexible system in terms of adaptation, usability and expression. As we interchanged devices amongst different participants, the calibration module allowed us to adapt the number of channels and responsiveness "on the fly". We used a similar setup during the Visites Insolites du CNRS (2022), where professional musicians were invited to manipulate the sound of their instruments using their muscular (EMG) activity.

In December 2022 we gave a concert at MSH Paris Nord (Paris, France), inviting Robin Dussurget (in art Cicanoise), a neurodiverse musician with motor disabilities, to integrate our software and the EAVI EMG board [6] into his musical setup. As part of the preparations, we used our system to control a eurorack modular synthesizer by converting EMG signals through the use of dual resolution MIDI pitch-bend signals and a MIDI-to-CV module. This demonstrated the usefulness of the system in interfacing with external systems.

Together, these events resulted in valuable feedback from users in regards to system usability, interaction and musical expression, allowing the system to adapt and improve to real-life use cases.

4.1 Usability

Working with electrophysiological signals can involve complex and time-consuming processes such as electrode placement and data acquisition. To simplify these processes, we have incorporated modules for the simulation of EMG and EEG signals, allowing users to design their working environments without the need for an ExG device. Additionally, we have implemented a preset functionality, enabling users to save and recall module settings, which significantly facilitates development and the transitions between different presets during live performances.

Our system permits users to integrate their workflow with external packages and sound synthesis modules, by interfacing with standard communication protocols such as MIDI and OSC, or internal routing within the Max platform.

4.2 Interaction

During our interactions with various users, we recognized the importance of simplifying signal routing and scaling processes within the system. To address this, we introduced the <bbdmi.crosspatch~> object, which allows users to easily re-route ExG signals without the need to manually adjust electrode channels on their acquisition devices. Scaling the acquired ExG signals to a suitable musical range presents another challenge due to variations in range and dynamics among individuals, muscles, and changing conditions such as fatigue and electrode characteristics. To simplify this process, we developed the <bbdmi.calibrate> module, which facilitates the normalization of signals for different users and electrodes through a dynamic calibration procedure.

Additionally, the system's single-cable patching architecture, combined with a user-friendly graphical user interface (GUI) featuring adjustable parameters, enables users to dynamically and interactively experiment with each stage of the processing chain. By eliminating the need for independent scale objects, packing/unpacking, and intricate connections, our system optimizes workflow efficiency and empowers users to focus on the creative exploration of their electrophysiological signals.

4.3 Musical expression

The ease with which musicians could use electrophysiological signals to control sound processes in their music provided a versatile and engaging experience. The possibility of flexibly routing control signals into different sound treatments, such as audio effects, spatialization and synthesis, added an overall layer of complexity, enhancing their musical expression capabilities. Musicians reported feeling a sense of a "sonified body" when using the system.

5 CONCLUSION AND FUTURE WORK

We have presented an interactive modular system for analyzing, processing, and mapping electrophysiological signals to sound as part of the *Body Brain Digital Musical Instrument* (BBDMI) project. The system addresses the need for a flexible and standardized platform that enables musicians and artists without specialized knowledge in neuroscience and signal analysis to experiment with electrophysiological signals.

We have discussed the various stages of the signal processing chain, from signal acquisition, feature extraction, and control processing to sound synthesis, as well as highlighted the importance of treating electrophysiological signals as both audio and control signals.

We have shown how to combine different types of modules, including input signal generators, control processing algorithms such as averaging, calibrating and scaling to feature extraction, sound synthesis and processing devices, utilities and output routers, as well as two different modes of interaction. As the system is based on a modular and multichannel architecture, users can easily interchange different modules to create their own idiosyncratic musical instruments.

The system has been evaluated through concerts, user studies, and musical conferences, where it has received valuable feedback from diverse musicians. Users have praised the system's usability and its ability to support musical expression.

While our current system requires a proprietary software (i.e. Cycling '74 Max), we are committed to making our research results openly available to the wider community by bringing the system to open-source platforms such as Pure Data (Pd), as well as expanding modules based on the FAUST language.

As we refine and expand the system, we will continue collaborating with a wide range of users, including composers and performers, music students, and artists across the neurodiversity spectrum.

Finally, we aim to optimize the system's performance by exploring Max's polyphonic capabilities, and implement additional feature extraction modules and mapping strategies.

The system is available for download from our GitLab repository, which can be accessed using the following link: https://gitlab.huma-num.fr/bbdmi/bbdmi.

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