# JAZZ HANDS:

Open Hardware Hybrid Saxophone System

University of Antwerp

Royal Conservatoire Antwerp

AP Hogeschool Antwerpen

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# JAZZ HANDS

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# Introduction

This essay delves into the fascinating realm of the Arts by documenting the journey of a doctoral student in the creation of a hybrid saxophone. Fusing elements of electrical engineering, PCB design(1), and microcontroller(2) programming, the student embarked on an ambitious project to transform a traditional saxophone into a versatile MIDI(3) controller(4).

This essay not only explores the technical aspects of the project but also delves into the artistic implications and potential of this innovative system.

In the midst of the artificial intelligence (AI) revolution, the boundaries between art and technology are being blurred as artists with a strong technological background embark on groundbreaking projects. This essay documents a project that subscribes this fusion, delving into the journey of an artist who defies conventional norms by creating a hybrid saxophone system from scratch.

By bridging the realms of traditional musical instruments and cutting-edge technology, this project stands as a testament to the artist's vision of augmenting the saxophone rather than replacing it and serves as an innovative milestone in the field.

When this research journey began five years ago, the field of artificial intelligence (AI) was still relatively limited in its applications, primarily associated with large search engines and social media platforms.

The student embarked on a self-study program, gradually acquiring knowledge by consulting books, websites, and online forums.

The focus shifted from analog electronics to coding from scratch and mastering skills, such as hand soldering and navigating PCB design software(5), overcoming the challenges of untangling complex electronic layouts.

Over the course of the past two years, advanced AI tools emerged, ushering new possibilities. The student feels fortunate to have experienced the traditional methods before gaining access to these automated systems.

This firsthand understanding of the manual processes proved invaluable when transitioning to AI-based tools. With a clear understanding of the underlying concepts and challenges, the student eagerly embraced AI whenever opportunities arose. For instance, AI plugins like Freerouting (6) in KiCad (7), significantly expedited high-quality development and PCB panelization(8). Additionally, tools like ChatGPT(9) provided the next level of assistance, a step up from scraping code from various forums and online communities, and ultimately assist in the writing of this very essay.

# Goals & objectives

This PhD. in the Arts encompasses three primary objectives.

Firstly, it aims to foster self-education in the fundamental principles of electrical engineering, computer programming, and product development. These newly acquired skills are essential for the successful implementation of the hybrid saxophone system and will serve as valuable knowledge to be shared with students at the Royal Conservatory of Antwerp, where the researcher teaches.

Secondly, the research focuses on the design and proof-of-concept development of a hybrid saxophone, pushing the boundaries of traditional saxophone playing by integrating it into the digital realm.

Lastly, this doctoral study seeks to create an original work of art.
A unique performance that showcases the expressive possibilities offered by the hybrid saxophone system in the form of a live music concert.

# Art & Research

In the spirit of Morton et al. (2015) and Tress et al. (2005), this research delves into the realms of transdisciplinary exploration, surpassing traditional field-specific boundaries to create a musical 'inter-discipline'.[1][2] This unique endeavour draws inspiration from the works of Klein (2017), particularly in the domain of sustainability science.[3]
It's crucial to note that while Art as such may not align precisely with sustainability science, this research also describes a living, ever-evolving entity that defies formalized understanding.

Central to this exploration is the conscious effort to value and integrate knowledge from non-academic stakeholders, embodying a mission that transcends traditional academia.

Following the principles outlined by Seidl et al.(2013), the work embraces 'processes of mutual learning between art and society', drawing attention to the division between science and art.[4]

In doing so, the dual accountability of transdisciplinary research is embraced, aspiring not only to generate 'reliable knowledge' but also 'socially-robust knowledge' as described by Nowotny and associates, in 2003.[5]

It is important to note that the presentation of this research today is a testament to the unique nature of transdisciplinary work. This project stands as a work of art, defying traditional academic conventions.
Like a painter presenting their canvas, the content remains unaltered, inviting you to experience the convergence of an autodidactic journey through electrical engineering, computer programming, and the creation of a groundbreaking hybrid digital controller.

This endeavour culminates in a synthesis of technical ingenuity, documented in an accessible DIY guide, this journal-like essay that intentionally shuns academic formalism, and a grand concert, set within the esteemed walls of the Royal Museum of Fine Arts in Antwerp.

The emphasis on releasing all technical aspects into the open source community, fosters collaborative development beyond the confines of this presentation.

Furthermore, this research extends beyond the invention of the novel Hybrid Saxophone digital controller; it is embedded within a broader artistic practice.

As an artist, I position myself amidst the impending AI revolution, recognizing that the traditional pursuit of academic dissertations on highly speculative topics, may soon become obsolete. In light of this, I assert my refusal to conform, deliberately utilizing AI tools throughout this presentation to reinforce my artistic vision.

With this contextual framework, I invite you to join me on a journey that transcends boundaries, challenges norms, and celebrates the fusion of art and technology.
Let us embark on a dialogue that not only explores the depths of transdisciplinary research, but also redefines the intersections of art, technology, and society.

Lastly, it is imperative to recognize the transformative potential of this research in the realm of education. Within the paradigm of 'STEAM'(10) and 'STEM' education(11) encompassing the synergistic interplay of science, technology, engineering and mathematics with the arts, this work could offer a paradigm-shifting perspective.

While existing approaches to STEAM education, as highlighted by Colucci-Gray et al. (2019), have often been confined by a vertical discourse, presupposing that arts and sciences are merely tools to serve a predetermined agenda, the work introduced here, represents a departure from this conventional trajectory.[6]
It pioneers new avenues for a more fluid exploration of the multiplicities and intersections of sciences and arts, echoing the sentiments expressed by Davies & Trowsdale in 2021.[7] This departure from a rigid vertical discourse acknowledges and embraces the intrinsic and diverse values inherent in both artistic and scientific practices, breaking free from the confines that limit the true potential of the latter fields' intersection.

Such a departure aligns seamlessly with the urgent call, as emphasized by Colucci-Gray et al. in their recent paper from 2021, for a reimagined educational approach. The artist's work advocates for an education that enables a more fluid exploration of the multiplicities and meetings of mulitple disciplines, emerging organically from the socio-cultural, economic, and political conditions shaping the learners' world.[8] This resonates with the call to move beyond the narrow framework of a structured educational agenda, as articulated by Biesta in 2020, towards an education that nurtures a more dynamic engagement with the world in which learners take form and that ultimately gives them form.[9]

According to Ars Electronica's S.T.-ARTS(13) programme, commissioned under auspices of the European Commission's Directorate-General for Communications Networks, Content and Technology(12), I quote "Science, technology and arts, pronounced 'starts' for short, limn a nexus at which insightful observers have identified extraordinarily high potential for innovation. And innovation is precisely what's called for if we're to master the social, ecological and economic challenges that Europe will be facing in the near future. With the S.T.-ARTS initiative, the European Commission's focus is on projects and people that have the potential to make meaningful contributions to this effort."[10]

Being part of the experimental trio 'BotBop', founded on behalf of Brussels based art institution BOZAR(14), we've already been engaged twice to collaborate with the S.T.-ARTS programme, resulting in the creation of two distinct commissioned works. These accomplishments can be attributed to the acquisition of new knowledge garnered during the course of this doctoral research.

In conclusion, I am extremely honoured to announce that the next phase has been secured, thanks to the acquisition of a new two-year grant by the Flemish Department of Culture, Youth, and Media(15). This grant will facilitate the continued development of my pursuits in hybrid technology and its artistic applications.

# Background

Coming from a background deeply rooted in jazz saxophone, my journey into the realm of electronic music has been a continuous evolution over the past two decades. This fusion of traditional musicianship with electronic experimentation began early in my career when, at the age of 17, I released my first record on Byte Records(16). This album was produced using the rudimentary tools of the time: a home computer and an AKAI S3000 sampler(17), circa 1998.

However, my most notable achievement, at least until this juncture, was my involvement with the band 'STUFF.'. This group earned recognition on the Belgian music scene, gracing the stages of nearly every major festival in the country and achieving moderate success internationally, particularly in the UK.

Within 'STUFF.', my role evolved significantly. Initially, I balanced saxophone and the Electronic Wind Instrument (EWI)(18), gradually gravitating towards the latter. Over time, the saxophone phased out of our instrumentation entirely, both in studio recordings and live performances. This shift marked a pivotal moment, where I embraced the EWI, a MIDI controller(4) with distinct applications and implications that set it apart from other digital controllers.

Traditional MIDI controllers, such as the ubiquitous MIDI piano keyboard(19) or digital drum sets(20), provide a digital representation of the player's actions, offering a means to translate their physical input into a digital format.
However, these controllers typically lack an acoustic component; they do not produce sound themselves, nor do they add new features not found on its acoustic counterpart, other than the benefits of the MIDI standard(21).

The EWI, in contrast, bridges this gap by offering wind instrument players a unique set of features. These encompass an expanded octave range (up to 7 octaves), pitch bend(22), and glide (portamento)(23) capabilities that extend far beyond the confines of traditional acoustic wind instruments. This fundamental distinction redefines the realm of musical expression.

The essence of the Hybrid Sax project lies not merely in the digitization of the traditional saxophone's attributes but in extending its MIDI capabilities to match those of the EWI. It transcends the boundaries of acoustic limitations inherent to the saxophone, propelling it into a new era of musical potential.

As an artist perpetually driven to explore new avenues of artistic expression, I eagerly embraced the possibilities afforded by the EWI. This choice propelled me into a shifting landscape where opportunities for traditional saxophonists in professional roles became increasingly scarce.

The extended range and diverse sound palette of the EWI opened doors to new roles within modern fusion-oriented music bands.
I often found myself taking on the role of a synth bass player, leveraging rapid saxophone fingering and breath control to craft intricate
filter sweeps and delve into a realm where live-produced synthetic sounds became an integral part of my live music performances.

Nevertheless, after years of flourishing with the EWI, a subtle void began to emerge. While the EWI offered an expanded range and diverse sound palette, it was lacking the nuanced expressiveness that the acoustic saxophone could deliver. In jazz, particularly, saxophonists embark on a quest to discover their 'own sound', a unique sonic fingerprint that sets them apart and resonates deeply with fellow musicians and audiences. My background in sound programming and innovative playing techniques on the EWI certainly contributed to achieving this unique sound prevalent in modern pop and electronic music genres.

However, these parameters were closely tied to hardware-specific techniques and manual playing methods rather than the intricacies of natural acoustics.
The acoustic saxophone's timbre and tonal quality extend beyond the choice of saxophone, mouthpiece, and reed; they are intrinsically intertwined with a player's physicality, endurance, and level of expertise.

The EWI, as an electronic device, is bound by the limitations of its sensors. It lacks the nuanced sensitivity to factors such as temperature, humidity, and the physical variations in airflow resistance encountered when playing high and low notes or employing extended acoustic techniques like overtones and multiphonics. Practices such as overtone playing demand extensive practice and mastery but prove ineffective on digital wind controllers.

This realization prompted me to embark on a quest to find a solution to address the shortcomings of both the EWI and the traditional saxophone. What emerged was the concept of the Hybrid Sax, a system that would augment the saxophone into a MIDI controller without compromising its original acoustic sound, while expanding its sonic palette through the power of MIDI.

Surprisingly, prior to my exploration, there had been no experimental or commercial efforts to develop a functional system that could seamlessly transform the saxophone into a general purpose MIDI controller while preserving its authentic acoustic resonance.

With my background in creating complex patches and devising bespoke solutions for specific music-related technical challenges, I became convinced that I could potentially develop such a system. Thus, my quest began.

I am deeply grateful that my research proposal was embraced by my mentors and the research program at IDLab. It has afforded me the opportunity to develop the skills required to create this system on my own terms and at my own pace.

While I could have sought assistance from the talented engineers at the University of Antwerp, I was driven by a desire to acquire certain skills independently. This motivation stemmed from both curiosity and my role as an educator in the newly established Department of Live Electronics at the Royal Conservatory of Antwerp. I'm still convinced that learning textual programming, grasping the basics of electrical engineering and delving into PCB development are essential steps in preparing for the future.
In a world where remarkable technological advancements are reshaping the landscape, I firmly believe that musicians should possess a profound technical understanding of their tools.

Technical knowledge and applied science allows artists to create their own limitations, guided by artistic choices rather than constraints imposed by economic considerations or market research-driven decisions made by music tech companies.

# Technical Progression

**From patching to hardware design**
The first stages of the project initially built on prior knowledge of node-based programming(24), primarily using platforms such as Native Instruments Reaktor(25), Sensomusic Hollyhock(26), and the Axoloti platform(27).

Additionally, foundational knowledge in Python(28) was acquired through the introductory course in programming at the University of Antwerp.

Building upon this experience, the project expanded with Arduino's(29) and PCB design, exploring the possibilities of the open-source software Bespoke Synth(30) for music creation.

In the realm of electronic music and art, node-based programming, commonly referred to as patching, has been a crucial skill in the toolbox of electronic musicians and artists. Programs such as PureData(31) and MAX/MSP(32), have gained significant recognition within academic and music communities alike as observed by Miller Puckette in 2017.[11]

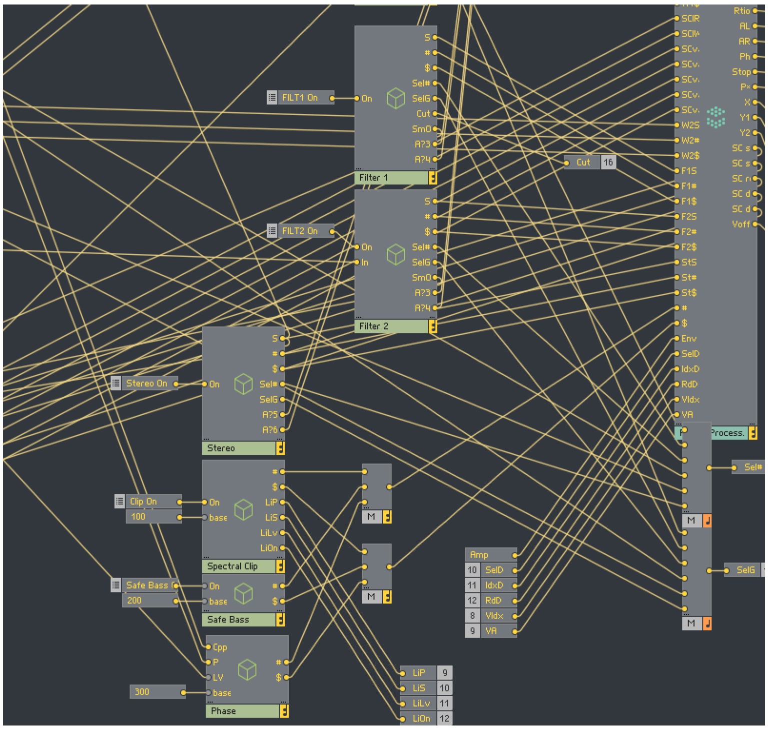
However, patching complex signalflows often leads to a plethora of virtual on-screen cables, resulting in a program that often resembles a tangled mess of spaghetti. Even a simple calculation like x+y=z can require up to four modules connected with at least three cables to obtain a useful output.

While coding may seem daunting for many artists at first, the power and elegance of a few lines of code still remains the best solution for tackling excessively complex visual patches. Proficiency in coding becomes necessary when programming microcontrollers like the Arduino and ESP32(33), which are widely used and well documented.

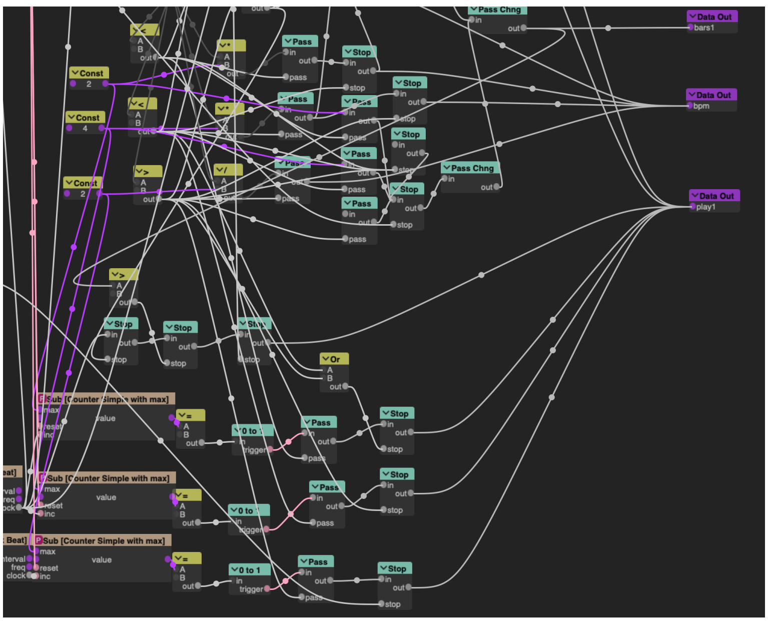
The advent of the open-source software Bespoke Synth provided a new opportunity to combine node-based modular patching, where it is tidy and convenient, with a Python scripting interface(34) for tasks that are more cumbersome to accomplish through patching alone.

Hence, embarking on this doctoral study program provided an ideal trajectory to dedicate time and effort to overcome the initially steep learning curve of textual coding.

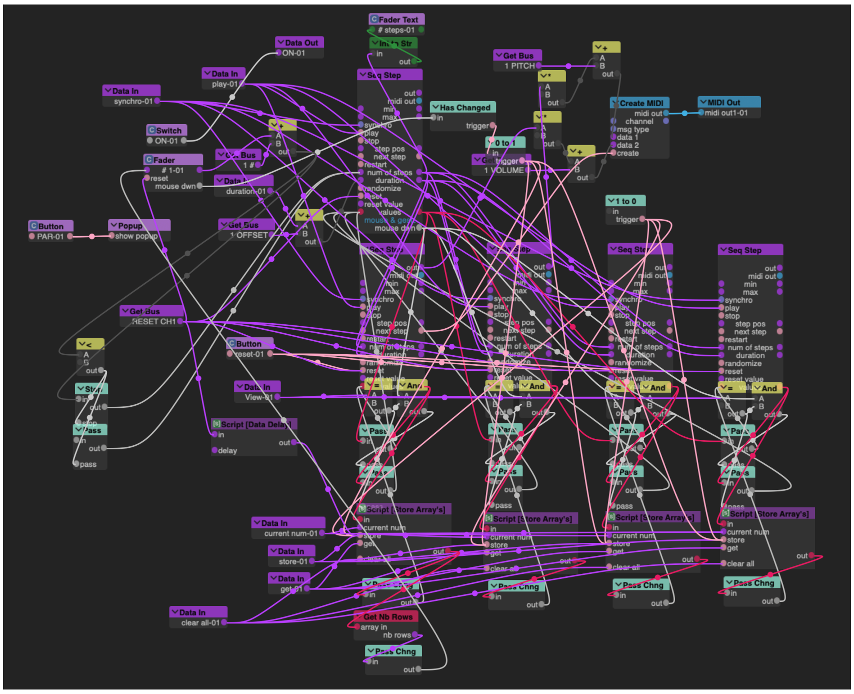
With a clear goal in mind, aimed at acquiring necessary coding skills, the journey took shape, ensuring a comprehensive understanding of novel coding approaches.



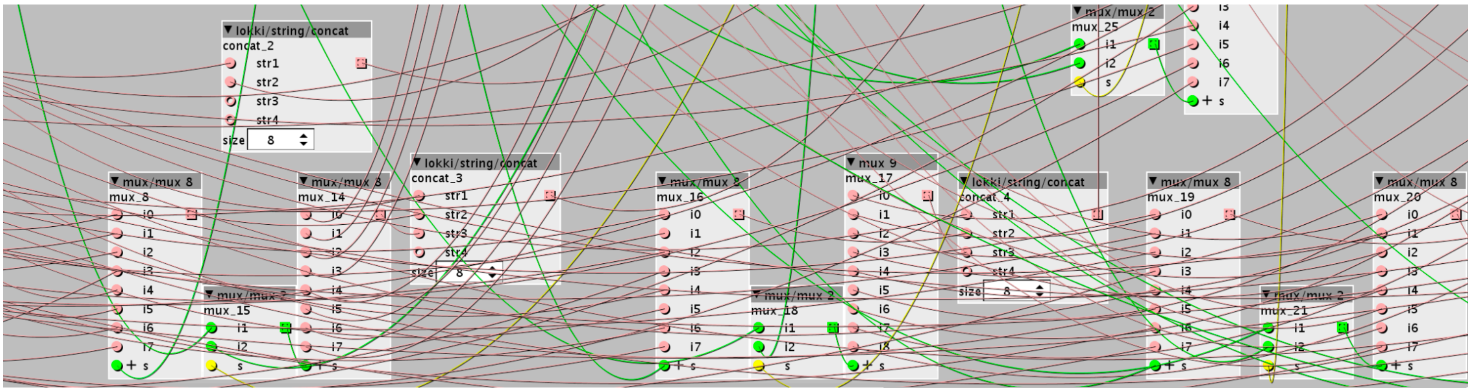

Native Instruments Reaktor spaghetti



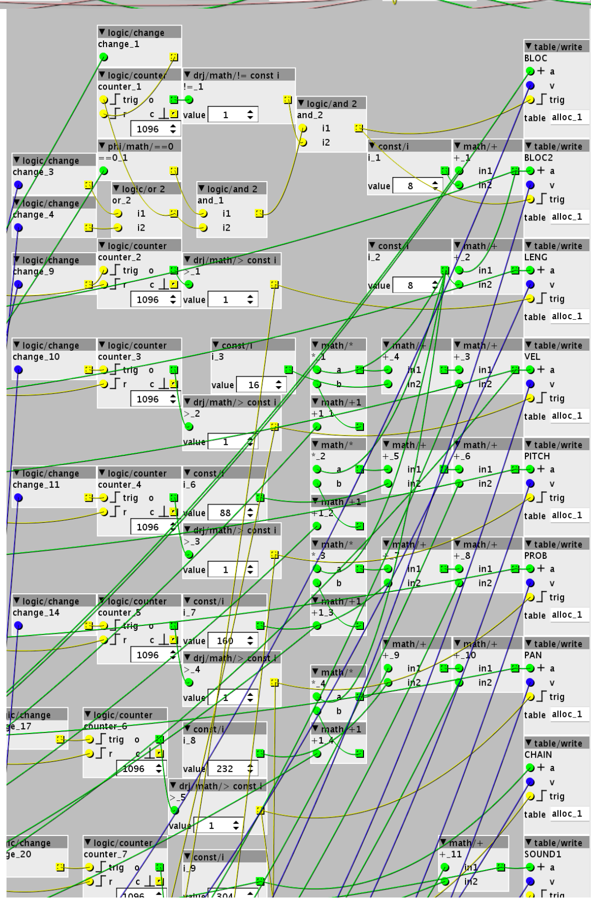

Usine Hollyhock logic patching linguini



Another Hollyhock tangle



The Axoloti incident



Node-based visual programming offers accessibility to musicians and artists working with complex DSP code(35), but debugging extensive logic pathways and calculations can be cumbersome and challenging to follow. However, the power of textual code should not be overlooked, despite its initial obstacle for creative individuals. For the student, text-based coding skills started to take off when he was introduced to the live coding music scene by long time friend and collegue Dagobert Sondervan.

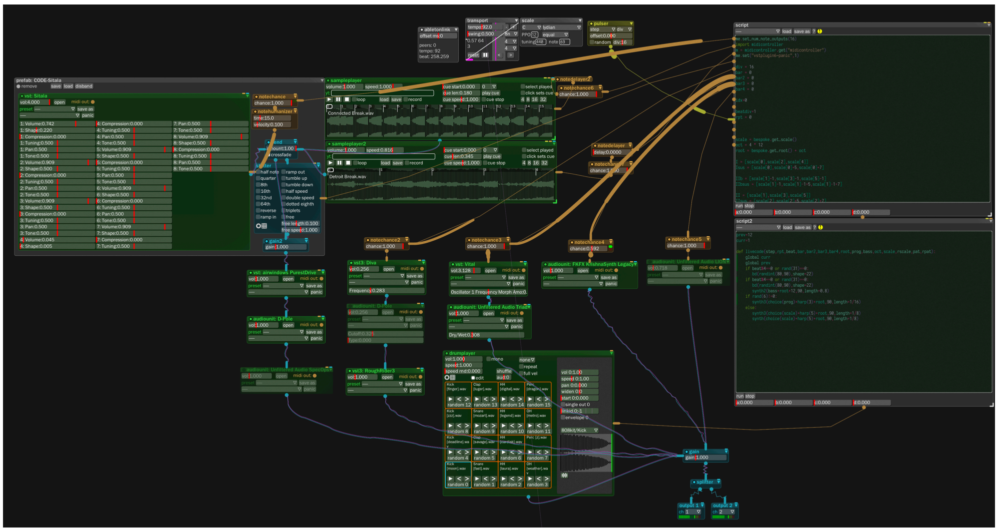
Live coding(36), a novel approach to electronic music performance, gave rise to community-driven parties called “Algoraves”(37), where musical coders create music from scratch using only code, projected for everyone to follow.
Open-source applications like Sonic Pi(38) and Tidal Cycles(39) are used predominantly. Witnessing the power of a few lines of code, replacing the complex patches proved very inspiring indeed.
However, the limitations of current live coding systems became apparent when trying to create dynamic systems based on live input(40), as compared to node-based visual patching. Wiring modules on a screen hiding complex DSP code still holds merit for quickly creating interactive music software with streamlined user interfaces and real time interaction.

Open-source music program, Bespoke Synth, was launched in 2021. Built on a modular paradigm, it deviated from the timeline structure of traditional DAW’s(41) and encouraged nonlinear music machine design, using high-level building blocks with specific features like fully-featured virtual analog synthesizer(42) modules with polyphonic oscillators(43), filters(44), and envelopes(45) could be effortlessly patched together, enabling a "live patching" workflow comparable to the speed of live coders. Bespoke Synth also features an embedded Python scripting interface, combining the best of both worlds in electronic music software development.

Equipped with only preliminary knowledge of coding, a bespoke live coding environment (pun intended) was created, using Python to write a short hand for live coding use. Bespoke Synth's compatibility with third-party plugins in the widely used VST format(46) opened up new opportunities for integrating additional tools.

The combination of visual node-based patching and clear code proved to be an elegant and efficient approach for creating dynamic systems that process musical data in real time. Complex modules with powerful DSP capabilities became more manageable through visual patching, while Python coding and scripting simplified logic decision trees and algorithmic composition(47) techniques.

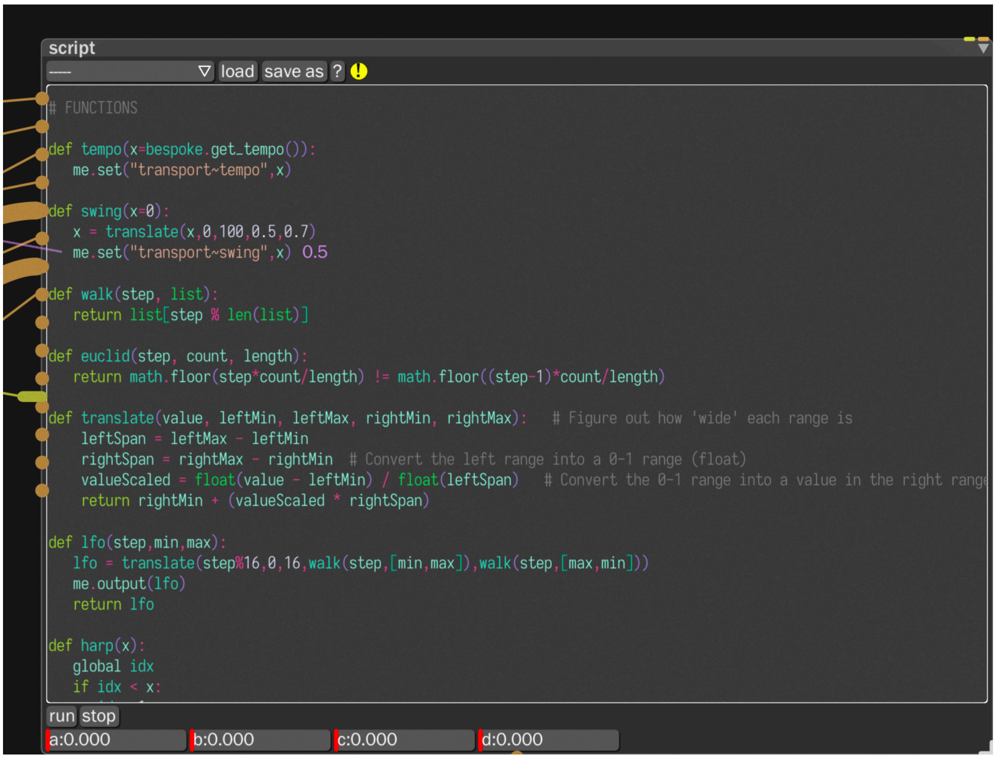
The development of the hybrid saxophone required a balance of complex patches for sensor development, analog prototyping(48), and structured code for the microcontroller's firmware(49). Bespoke Synth and the Arduino platform played a crucial role in solving problems in the digital realm, while a growing understanding of electric and electronic signal flow proved essential throughout the project.



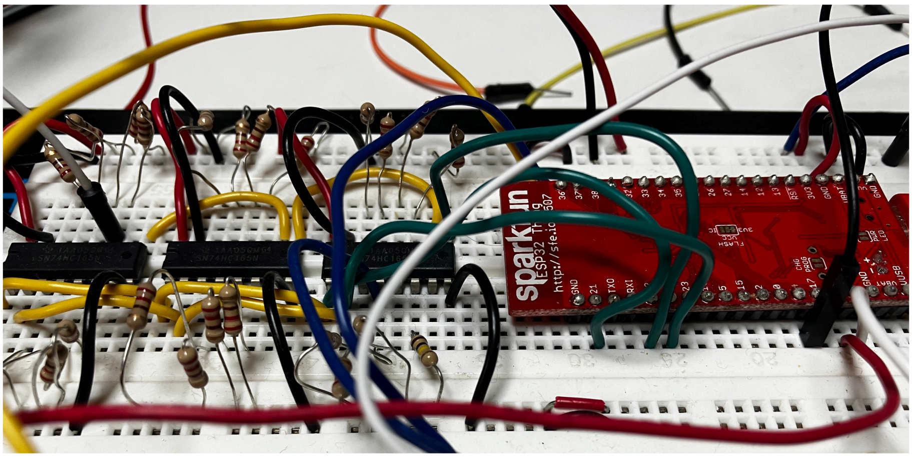
Complete environment for live coding in Bespoke Synth

```
def livecode(step,rpt,beat,bar,bar2,bar3,bar4,root,prog,bass,oct,scale,rscale,pat,rpat):
    global curr
    global prev
    if beat%4==0 or rand(31)==0:
       bd(randint(80,90),shape=22)
    if beat%4==0 or rand(31)==0:
       bd(randint(80,90),shape=22)
       synth2(bass+root+12,90,length=0.8)
    if rand(6)!=0:
       synth3(choice(prog)+harp(3)+root,90,length=1/16)
    else:
       synth3(choice(scale)+harp(5)+root,90,length=1/8)
       synth(choice(scale)+harp(5)+root,90,length=1/8)
```

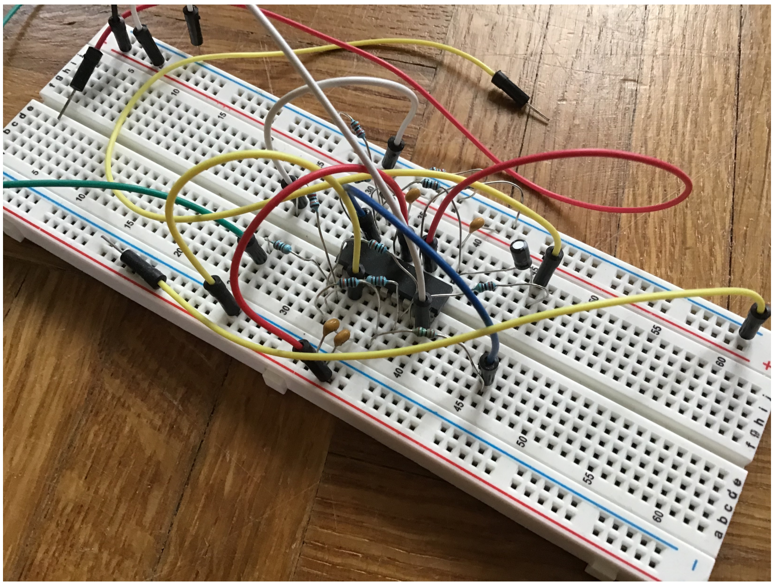
Algorithmic music using simplified code functions

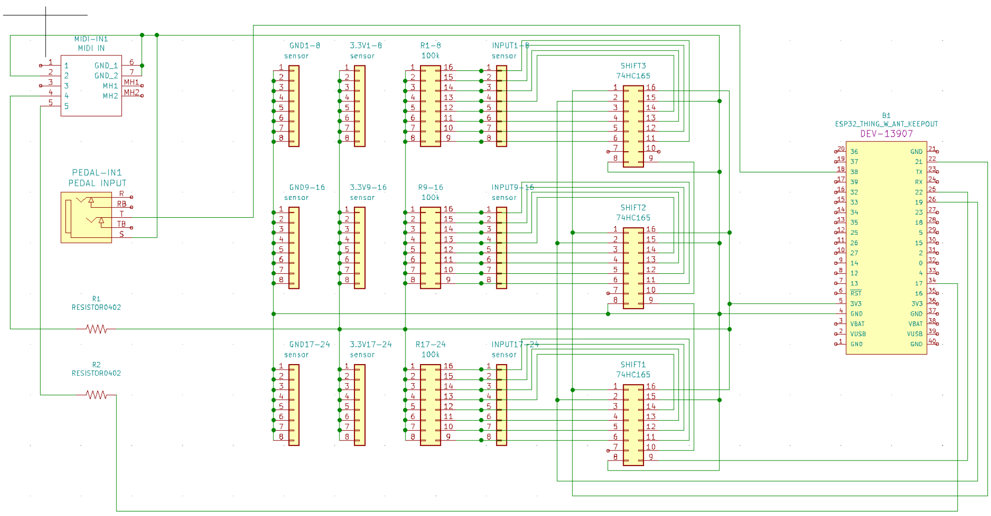



Implementation of functions using Python



Prototyping on breadboards






schematics in KiCad

**Towards a hybrid saxophone**

Leveraging newly developed skills, understanding electric circuit diagrams(50) and writing text based code, eventually a working proof-of-concept model for the hybrid saxophone was created. The instrument now combines the traditional acoustic saxophone sound with the capabilities of a MIDI controller.

Different strategies and exploration of various solutions led to the creation of a hybrid saxophone sensor system challenging modern wind controllers.

The project initially began with the objective of exploring novel methods to digitize the output of a traditional saxophone, broadly labeled "Jazz Hands".

Preserving the integrity of the original saxophone, ensuring it remains undamaged and unobstructed during regular playing, was of utmost importance. The aim was to equip a traditional saxophone with all the capabilities of modern wind controllers such as the Akai EWI, Roland Aerophone, Yamaha's digital saxophone or the Sylphyo wind controller, among others. However, a fundamental distinction lies in the absence of acoustic sound in these wind controllers.

Sound generation solely occurs through the MIDI protocol, relying on a separate, electronic sound source. Consequently, these "instruments" can be more accurately described as controllers rather than full fledged instruments in their own right.

Even the Synthophone(picture), which comes closest to the envisioned design, places all electronics inside the instrument, rendering the traditional saxophone completely mute and acoustically lifeless.

Current Akai EWI Solo model (source: Akai)

Yamaha YDS-150 Digital Saxophone
(source: Yamaha)


Softwind Synthophone (source: Softwind) from 1988.
Notice the closed bell. While a capable MIDI controller, this instrument cannot produce acoustic sound.

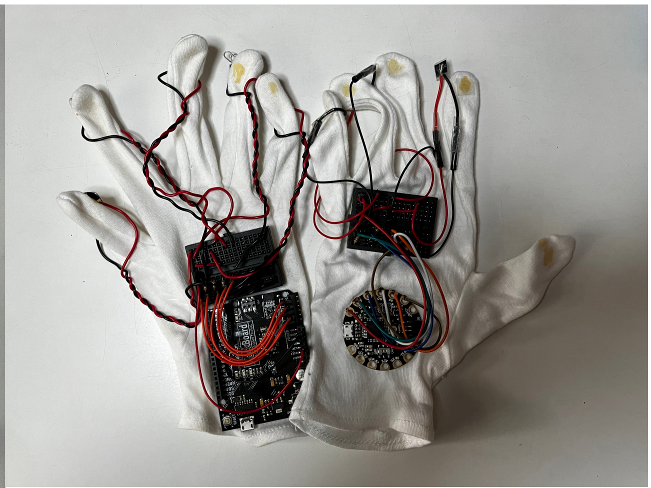
The initial concept revolved around the development of electronic gloves capable of tracking hand movements to extract the data of the played notes.
A universal saxophone controller in the form of gloves would have been a groundbreaking form factor, enabling any saxophone to function as a MIDI controller without any modications to the instrument itself. This audacious idea led to an exploration of the realm of analog sensors, traditional through-hole components(51) and engaging in tinkering with Arduino microcontrollers.

During this early phase, trial and error became the primary approach. Experimentation involved both the use of commercially available bend sensors(52) as custom-made pressure sensors(53). However, significant challenges soon emerged.

The bend sensors proved to be too sluggish for accurate readings, and the inclusion of the saxophone's palm keys and the multi-functionality of the saxophonist's little finger severely limited the effectiveness of the gloves. While maintaining a belief in a potential future innovation of digital glove controllers, the required technology would demand substantial advancements that surpass the current state of development. Advancements in LIDAR(54) technology and wearable innovations could prove essential.

Constructing a woven matrix with conductive fabric(55) could potentially realize the concept, but off-the-shelf technology currently available to tinkerers falls short of the requirements for creating such a huge matrix based controller.

Consequently, in collaboration with academic promotor Steven Latré, this particular avenue was temporarily abandoned.



MIDI Gloves with bend sensors (left) and DIY pressure sensors (above)

Continuing to ponder the concept of a universal controller that minimally impacted the instrument, another idea took shape: incorporating the necessary electronics within a novel 3D printed mouthpiece(56).

Inspired by advancements in audio-to-MIDI(57) and low-latency pitch tracking(58), a potential to create a cutting-edge design was observed.

Using a specialized chip(59) developed by SecondSound, integrated into the mouthpiece, low latency MIDI could be generated. This innovative approach would enable the creation of a nearly wireless system without the need for external sensors attached to the saxophone's body.

To explore the capabilities of the SecondSound chip, the student acquired an evaluation kit(60) from the developer. A first prototype was made, making use of this technology. The system was entrusted to artistic promotor Kurt Van Herck for exploration and testing.

The system comprised of a DACO EVK audio-to-MIDI circuit and a foot controller panel designed to control harmony. Kurt coined the potential of adding a hybrid system that would allow polyphonic playing of the instrument, a highly sought-after feature among woodwind players.

To facilitate this, a foot controller with four buttons was created to activate basic chord structures with a simple stomp of the foot. Additionally, an expression pedal(61) and audio looper(62) pedal were connected to a digital brain running on an Axoloti microcontroller running a patch.

The resulting system proved successful in digitizing the saxophone and expanding its capabilities with harmonization features. However, limitations of the previous computer based system would be the same: MIDI could only be generated when the saxophone is played audibly.

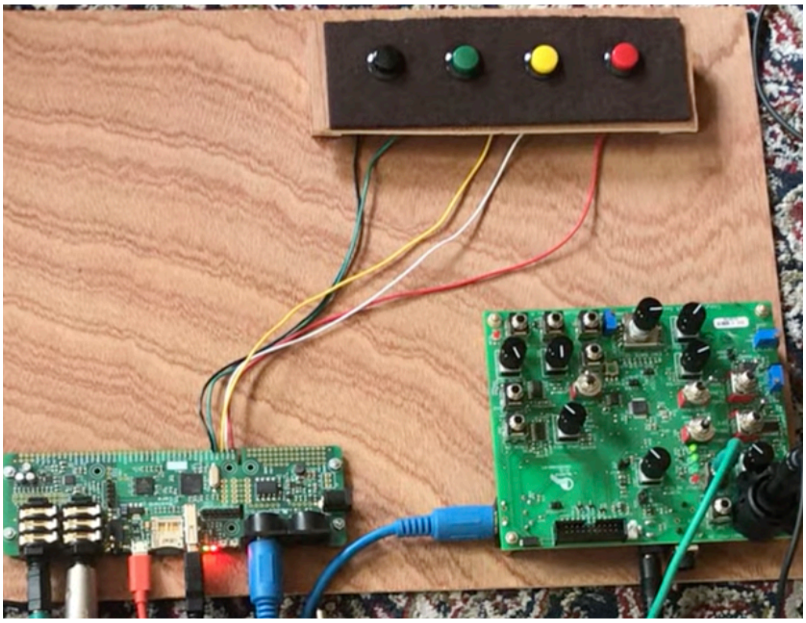
Consequently, this system does not send MIDI information when the saxophone is not being played acoustically, rendering it ineffective as a pure MIDI controller or for silent practicing purposes. Overcoming this crucial flaw would require novel technology beyond current reach.

As is the case with the former idea of MIDI capable gloves, a future implementation leveraging machine learning(63) technologies could potentially predict the "fingered" notes without the need for producing natural tones through reed vibration from the moutpiece.

While recognizing the potential elegance and non-invasiveness of a hybrid mouthpiece system that surpasses the current setup, it might prove difficult to achieve.

Training a model on current GPU-based processors(64), the acquisition of sufficient data, and the uncertain outcomes of such a study posed constraints to the practical real world objective of creating a functional low cost system.

A working proof-of-concept system using currently available and affordable technology was pursued instead.



Axoloti microcontroller, SecondSound DACO EVK and push buttons, achieving hardware standalone audio-to-midi operation, MIDI harmonization and subtractive digital sound synthesis


Cased Axoloti along with expression pedal, audio looper and MIDI controller

The new idea that emerged was to integrate sensors directly onto the saxophone itself, effectively mapping all mechanical movements of the instrument to the digital domain. This required devising a mechanism that could capture and transmit the saxophone's actions and translate them into digital signals. By placing sensors at key points, aimed at capturing the finger movements and other mechanical actions involved in playing the instrument.

The sensors would detect when a key is pressed, released, or manipulated in any way, converting these physical interactions into digital data. This approach would allow for real time tracking and precise representation of the saxophonist's performance in the digital realm.

During the course of the research, a significant breakthrough emerged when stumbling upon hall effect sensors(65). These magnetic sensors exhibit a reaction in the presence of a magnetic field. Available in both linear analog(66) and digital switch(67) forms, hall effect sensors are commonly utilized in the automotive industry.

Notably, these components are easily accessible, cost effective, and highly responsive. Designed to measure the revolutions per minute (rpm) in motors, their speed and sensitivity made them a promising candidate for accurately tracking the intricate key movements executed by even the most virtuoso saxophone player.

Driven by curiosity, experimentation with hall effect sensors commenced, and it quickly became evident that this technology held the potential to drive the envisioned system forward. The sensors checked all the necessary criteria for the project.

Being based on magnetism, makes them less susceptible to issues caused by humidity, present near the keyholes of the instrument. Additionally, they exhibit low power consumption and are available in various packages and form factors.

An advantage of these sensors is the ability to place them on the body of the saxophone instead of directly on the keys. This approach eliminates the need for cables connected to moving parts of the sax, potentially enhancing the overall reliability of the system.

With the successful identification of the right sensors for tracking saxophone key movements, the focus shifted towards the practical implementation of the system.

One of the primary challenges at this stage involved equipping the saxophone with a maximum of 24 discrete sensors, each corresponding to a specific key, while ensuring that the instrument remained unharmed throughout the process.

The objective was to develop a non-invasive solution that could be fully reversible, leaving no trace or damage on the saxophone itself.

Careful consideration was given to the placement of the sensors to achieve optimal tracking accuracy without interfering with the instrument's natural playability. The sensors needed to be strategically positioned to detect the opening and closing of each key, translating the physical actions into electronic signals. This required meticulous planning and precision in fixing the sensors to the saxophone without compromising its structural integrity or affecting the instrument's acoustic properties.

Throughout this phase, a keen focus was placed on preserving the instrument's original condition and ensuring that the modifications could be easily reversed if necessary. Approaching the task with utmost sensitivity, seeking to harmoniously integrate the sensors into the saxophone's design without leaving any permanent marks or alterations. This commitment to reversibility and preservation of the instrument's integrity reflects a deep respect for the saxophone as a traditional and cherished musical artefact.

Sensors mounted on the body of the saxophone

Hall switches are attached to the body and magnets are mounted to the moving keys

Sensors connect to the PCB brainbox, routing inputs to ESP32 Thing microcontroller


Additional capacitive touch sensors for expanded selection of octaves in the MIDI domain using left thumb

On the software side, the development process benefited from the extensive range of existing libraries(68) and resources available within the Arduino ecosystem. Leveraging these pre-existing tools and code libraries streamlined the software implementation, allowing a focus on customizing and fine-tuning the system to suit the specific requirements of the hybrid saxophone. This approach enabled a more efficient development workflow and reduced the complexity typically associated with creating software from scratch.

By combining the hardware implementation of the hall effect sensors with the straightforward software integration facilitated by the Arduino ecosystem, refining the instrument's playability, responsiveness, and overall performance was comprehensive. This integration of hardware and software components form the backbone of the hybrid saxophone system, seamlessly bridging the analog and digital realms to create a cohesive and expressive musical instrument.

```
#include <Arduino.h>
#include <BLEMidi.h>
#include <MIDI.h>

struct Serial2MIDISettings : public midi::DefaultSettings
{
  static const long BaudRate = 31250;
  static const int8_t RxPin  = 16;
  static const int8_t TxPin  = 17;
};

MIDI_CREATE_CUSTOM_INSTANCE(HardwareSerial, Serial2, DIN_MIDI, Serial2MIDISettings);

int myResult[24]; // Array with digital code of the sensorvalues

int noteSounding; // Current note
int getNote; // Is there a new note?
int envValue;
int state;
unsigned long breath_on_time = 0L;
int initial_breath_value;
int atVal;
unsigned long atSendTime = 0L;

// Octave sensor
int octaveKey = 23;
int octave2Pin = 12;
int octave3Pin = 14;

int octaveValue = 0;

// Sound Detector
int gatePin = 18;
int envPin = 32;
#define NOTE_ON_THRESHOLD 80
#define MAX_PRESSURE 1000
#define NOTE_OFF 1
#define RISE_WAIT 2
#define NOTE_ON 3
#define AT_INTERVAL 70
#define RISE_TIME 2

//Shift Register
const int dataPin = 22;   /* Shift Register Q7 */
const int clockPin = 19;  /* Shift Register CP */
const int latchPin = 21;  /* Shift RegisterPL */
const int numBits = 24;   /* Set to 8 * number of shift registers */

//PEDAL
#define INTERVAL 6   // t ime between reads
```

Excerpt from the Arduino code

After successfully mapping the saxophone keys, a breath sensor(69) is needed to complete the system. It was essential to capture not only the sound pressure levels produced by the player's breath but also the pressure information generated without the emission of sound. This approach aims to ensure that the hybrid saxophone could provide meaningful data and control, even when played without producing any acoustic sound.
By incorporating pressure sensing capabilities into the system, the hybrid saxophone could deliver a comprehensive representation of the player's expressive intentions, regardless of whether they are playing acoustically or relying solely on the MIDI system.
This functionality is crucial in achieving the goal of eliminating the need for a separate MIDI controller for woodwind players, such as the Akai EWI, and enabling saxophonists to fully engage with the MIDI domain using their original instrument.

Exploring the possibilities of a "hybrid mouthpiece" again, the investigation delved back into the realm of mouthpiece design and functionality, aiming to determine the feasibility of integrating additional sensors or mechanisms that could capture and transmit breath-related data.

The development of a hybrid mouthpiece presented its own set of challenges, as it required careful consideration of factors such as acoustics, design and playability.

Several avenues were explored to achieve the desired outcome. One option considered was using a traditional dynamic microphone(70) to capture sound pressure levels and convert them into voltage control signals(71) using an analog envelope follower circuit(72).
However, the susceptibility of dynamic microphones to crosstalk from other instruments or ambient sounds posed a significant limitation, particularly in a live concert setting, where interference could disrupt accurate readings.
A more effective solution was found in the form of piezoelectric microphones(73).
These small components, when mounted inside the saxophone mouthpiece, offer a noise-free pickup system capable of transducing vibration to electricity.

One notable product in this category is the Viga Music Tools intraMic(74), which not only provided clean audio output but also proved an excellent microphone for amplifying the saxophone's acoustic sound. However, the weak signal generated when blowing through the mouthpiece without producing reed-vibrating sound posed a challenge when amplifying the signal, without introducing excessive audible artefacts from the saxophone's mechanical components, rendering it unfit for use as a silent breath controller.
It's noteworthy that a smart filtering system would likely be possible in the near future, again leveraging machine learning technology strategies or the advances in high frequency FPGA(75) chips in order to accomplish the reliable spectral filtering needed.

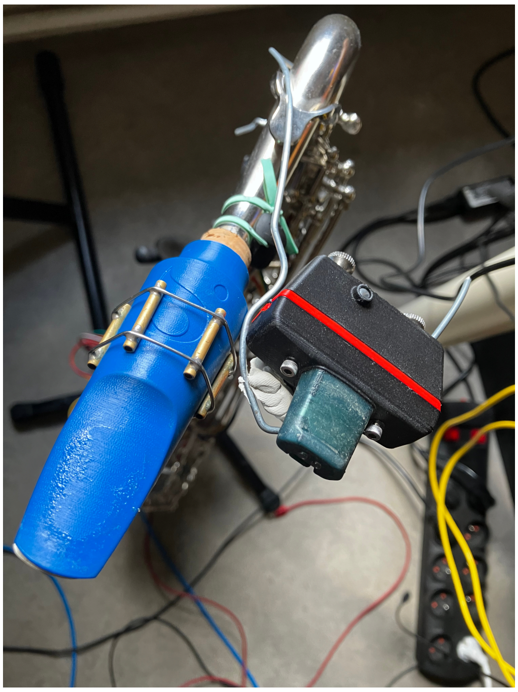
Another consideration in adopting the piezo-based system is its cost. The commercial nature of products like the intraMic meant that the expense associated with incorporating them would dominate the total cost of the hybrid sax system by far, which is not an ideal solution. Furthermore, while the intraMic excels in loud stage environments, cheaper alternatives such as inexpensive microphones could suffce for users who employ the hybrid saxophone for purposes such as transcription, study or sound layering in a studio setting.

Recognizing the importance of breath control as an expressive element, an additional expression pedal input was added to the hybrid saxophone system.
This input could accommodate standard expression pedals commonly used by electronic musicians and guitarists alike, enabling the player to use their foot to control the amplitude of the MIDI data generated by the saxophone.
This feature allows for independent control of the acoustic saxophone's amplitude and the digital signal, unlocking interesting combinations and effects.
However, relying solely on foot-controlled expression through the use of a pedal has its limitations, as it inherently lacks the precision and nuance of a trained musician's breath control.

To mitigate this limitation, another idea took shape to equip the saxophone with a second, fully digital mouthpiece. Leveraging the existing screw and placeholder intended for a music stand in marching band settings present on every sax, this secondary mouthpiece can be attached to the saxophone.

Initial exploration involved engaging with developers Rudy Verpaele and Chris Graham, who were working on the development of a premium breath controller mouthpiece known as the "photon" mouthpiece. Using a prototype, this device serves as the second, fully digital mouthpiece of the sax. Unfortunately, due to post-pandemic chip shortages, this option is not yet commercially available.

Continuing the search for a suitable digital mouthpiece alternative, KontinuumLab - a DIY engineer on the online video platform YouTube -presented an intriguing solution.
This solution involved using recycled plastic, a balloon and a small photosensor component (QY70) to create a simple, inexpensive, yet highly capable breath sensor.
This discovery aligned closely with the project's objectives and will be incorporated into final design, offering an accessible cost effective, yet highly capable solution for breath sensing in the hybrid saxophone system.



Mounting the Photon breathcontroller next to the acoustic mouthpiece, enabling ‘silent MIDI’ operation, effectively transforming the instrument to a MIDI controller

Using the marching band music stand adapter screw for connecting the digital mouthpiece (Photon)

KontinuumLab's nifty low cost DIY breathcontroller

After extensive work involving breadboarding, soldering, studying, and experimenting with various adhesives, the final design started to take shape.
To streamline the process, the electrical circuits were made using the open-source Computer-Aided Design Software Suite KiCAD.
Using this software, two PCB boards were created, which were sent for fabrication in Europe through Multi-CB Germany.

The first PCB, the sensor board, was designed to accommodate the ESP32 Thing open hardware board by Sparkfun, the digital brain of the system.
It incorporates three shift registers IC's(76) to provide additional digital inputs, along with the necessary pullup resistors(77) for the system to function properly.

Additionally, the PCB includes the footprints(78) for the MIDI out connector, an expression pedal input socket using industry standard 1/4" jacks(79), connections for the octave capacitive touch sensors(80), and an analog breath sensor input.
The bare PCB is designed to be populated with easily accessible Through-Hole Technology components and could be assembled in approximately one hour.

A second PCB was developed with the goal of reducing the footprint of the hall sensors and ensuring consistency in the system.

This second PCB, although simply resembling a printed prototyping stripboard(81) with three lateral connections, proved to be highly practical during the construction phase.

To maximize cost efficiency, the PCB was designed as a panel housing 12x12 sensors, with the individual sensor PCBs easily detachable through "mouse bites" - small, consecutively drilled holes across the board outlines - that allow for convenient manual separation from the panel.

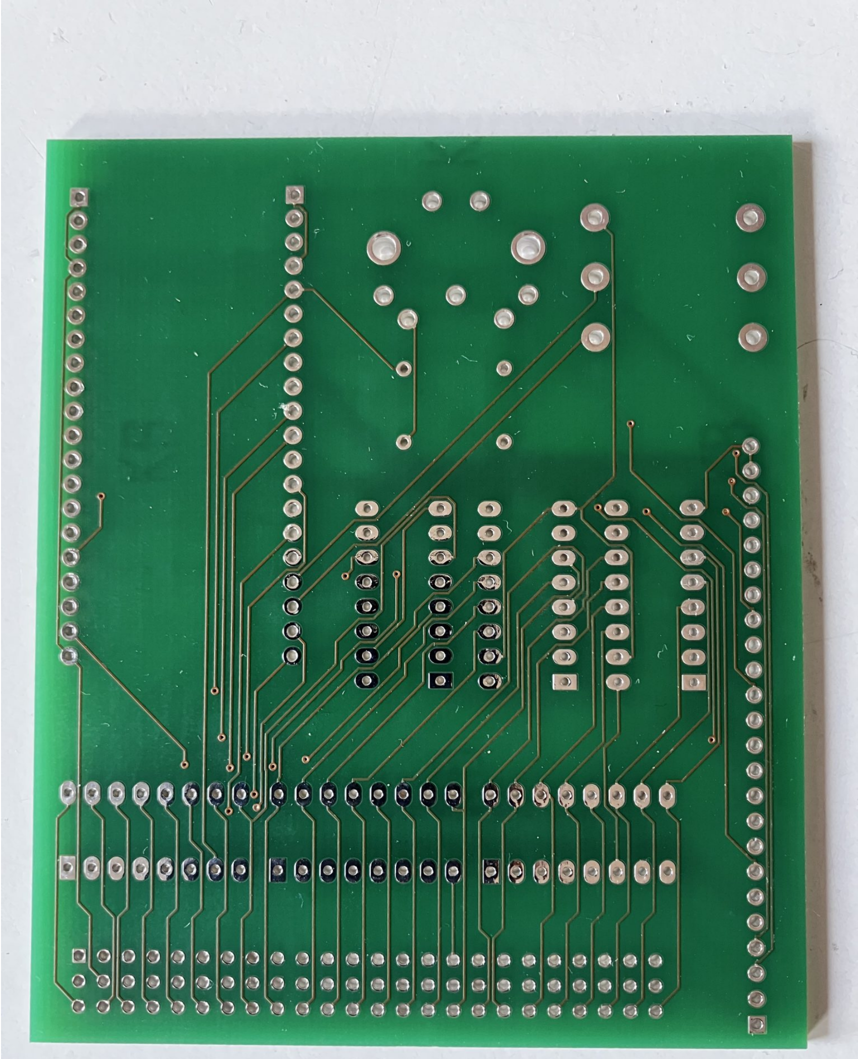
In the upcoming final version of the project, which is scheduled to be released before the pre-defense, the 12x12 sensor PCB, housing 144 individual sensors, will be consolidated to a single PCB fabrication file.

This unified design will offer a total of 32 sensor units that can be easily detached from the main sensor board using these "mouse bites".

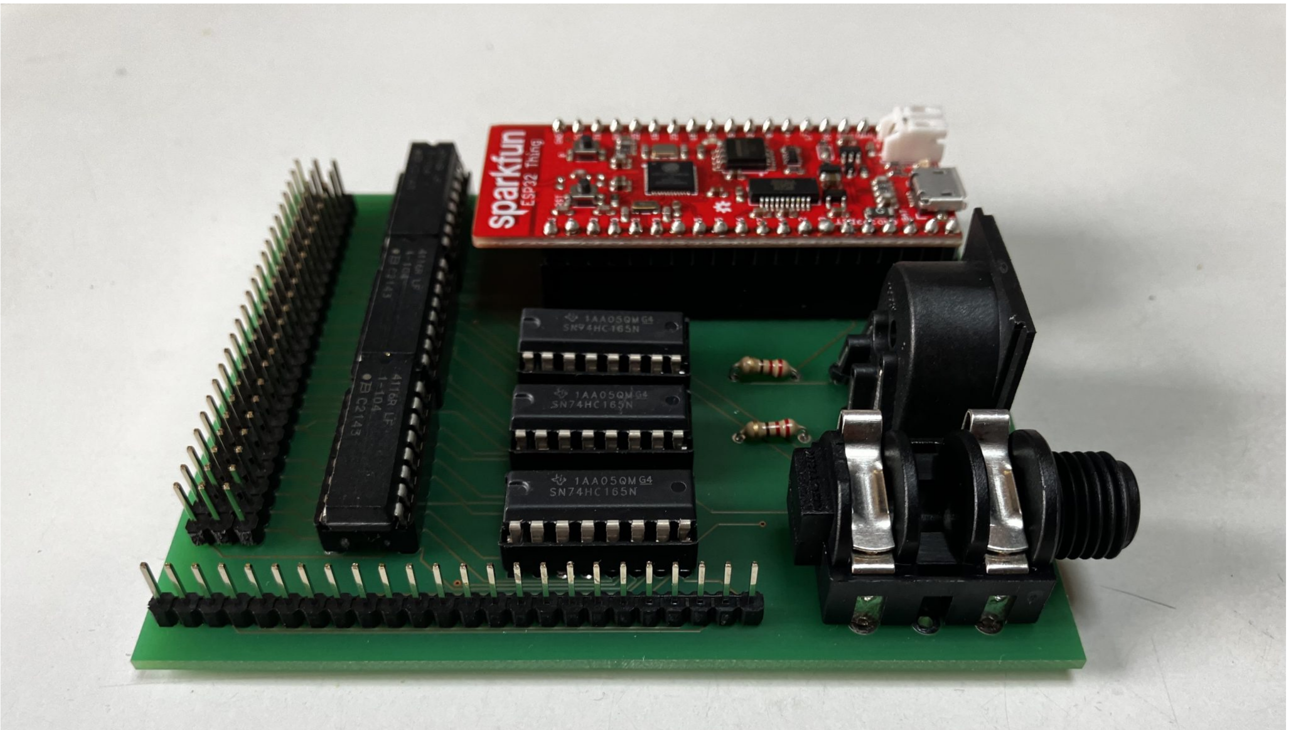
By integrating the individual small sensor PCB's into the main sensor board design, fabrication costs are further reduced, and any potential waste from the previous 12x12 design is minimized. This approach not only enhances cost-efficiency but also ensures a more sustainable manufacturing process for future builders.

In the search for attaching the sensors to the saxophone body, various adhesives were tested. After careful evaluation, a product called 'Sugru' by Tesa(82) emerged as the most suitable choice.

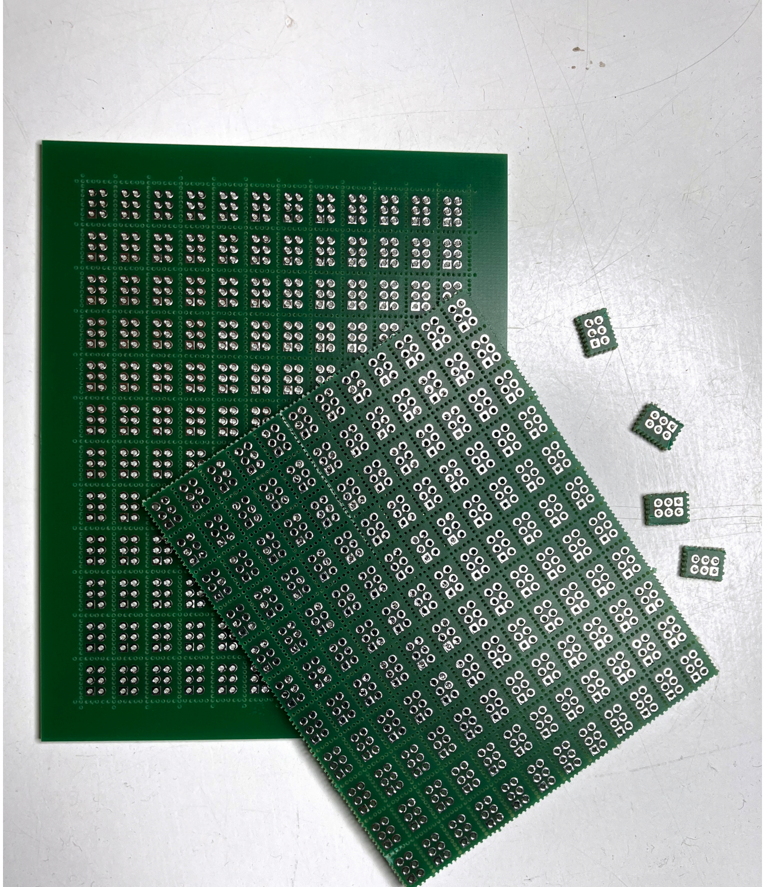
Sugru is a unique paste-like substance that shares similarities with malleable sticky paste, similar to what is found in commercially available "Pritt poster buddies"(83). However, it cures into a non-toxic hard rubber within a few hours. Its exceptional adhesive properties makes it ideal for adhering the sensors to the predominantly brass surface of the saxophone. Another feature is its ability to securely bond the sensors to the saxophone while leaving no traces when removed. This feature is particularly important as it ensures the instrument remains unharmed and can be restored to its original condition at any time.



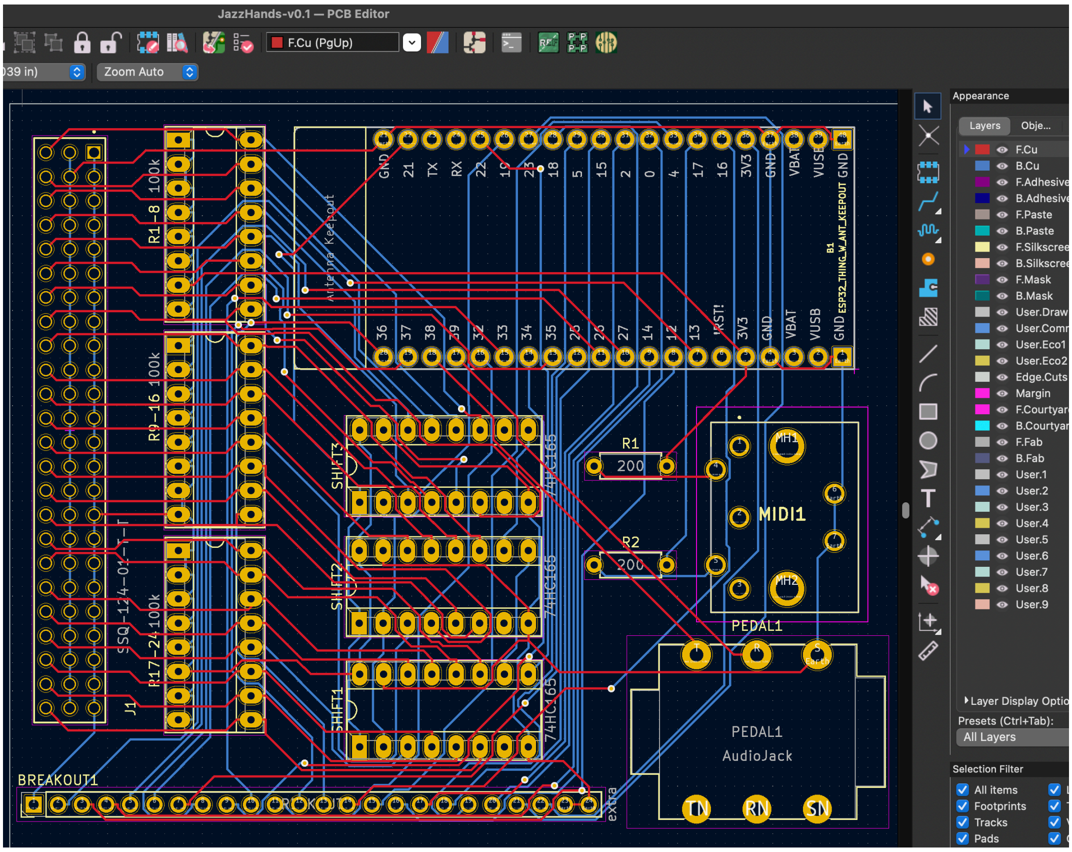
Fabricated PCB for the sensor board hosting the microcontroller and inputs




Populated PCB after soldering the headers and components



Panelized PCB design for the individual sensors using ‘mouse bites’, providing the smallest possible form factor for Trough Hole Technology components




Sensor board PCB design in KiCad


sparkfun
ESP32 Thing

# Current features

**Full MIDI implementation of the saxophone key work**
The sax can be played audibly and transmits MIDI data in real time.
The system transmits all key positions, including alternate and top tone fingerings.
The system is fully programmable, enabling further MIDI implementations.

**Extended octave range**
Play up to 3 octaves down using the attached touch sensors with the left thumb.

**Analog breath sensor input**
KontinuumLab DIY Breath sensor and industry standard Freescale MPX series pressure sensors are fully supported, transforming the sax to a full blown windcontroller with similar specs as the original Akai EWI and above.

B**luetooth MIDI and DIN MIDI output**
Simultaneous output over BLE and classic DIN connector.
Connect synths, computers, tablets and smartphones.
MIDI note, velocity, breath (CC2) and MIDI Program Change are supported.

**Expression pedal input**
Control MIDI volume separately with a standard expression pedal.

# Remaining objectives

**Guide Creation and Future Models**
To share the knowledge gained throughout the project, a comprehensive step-by-step guide for constructing the hybrid saxophone will be made. This guide will be published on instructables.com, accompanied by the release of all software and fabrication files on GitHub as open-source resources.

Instructables.com is an online platform that provides a space for makers, DIY enthusiasts, and artists to share step-by-step instructions for a wide range of projects. It serves as a hub for creators to document and showcase their work, providing detailed instructions, images, and sometimes even videos to guide others through the process of replicating their projects. Furthermore, Instructables.com encourages collaboration and feedback within its community.

By sharing a step-by-step makercfile on this platform, the hybrid saxophone design could be made available. This exposure could lead to further collaboration, feedback, and potential advancements or adaptations of the project by other makers in the community.

It is important to note that the creation of a step-by-step guide is a secondary goal of the research project and is planned to be published by the time of the pre-defense of this PhD.

While the primary focus of the project is the development of a hybrid saxophone proof of concept design and a forthcoming concert, documenting and sharing the process in the form of a comprehensive guide adds value to the research.

With everything in place, at least two streamlined prototypes will be created.

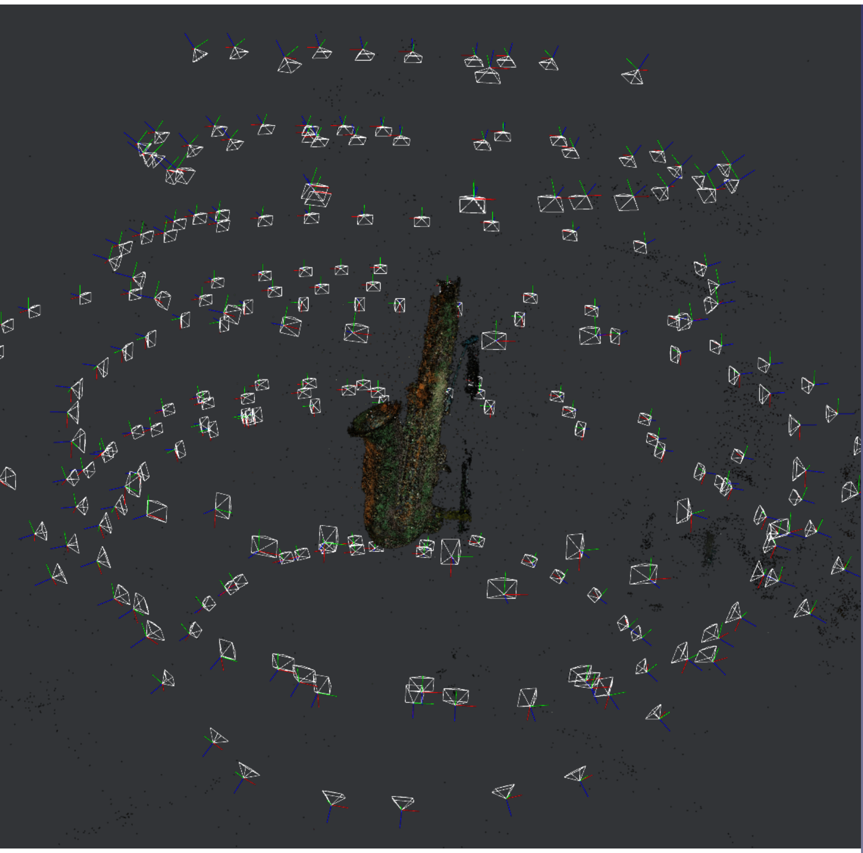
The process will be documented as the step-by-step guide, photographs and detailed annotations.

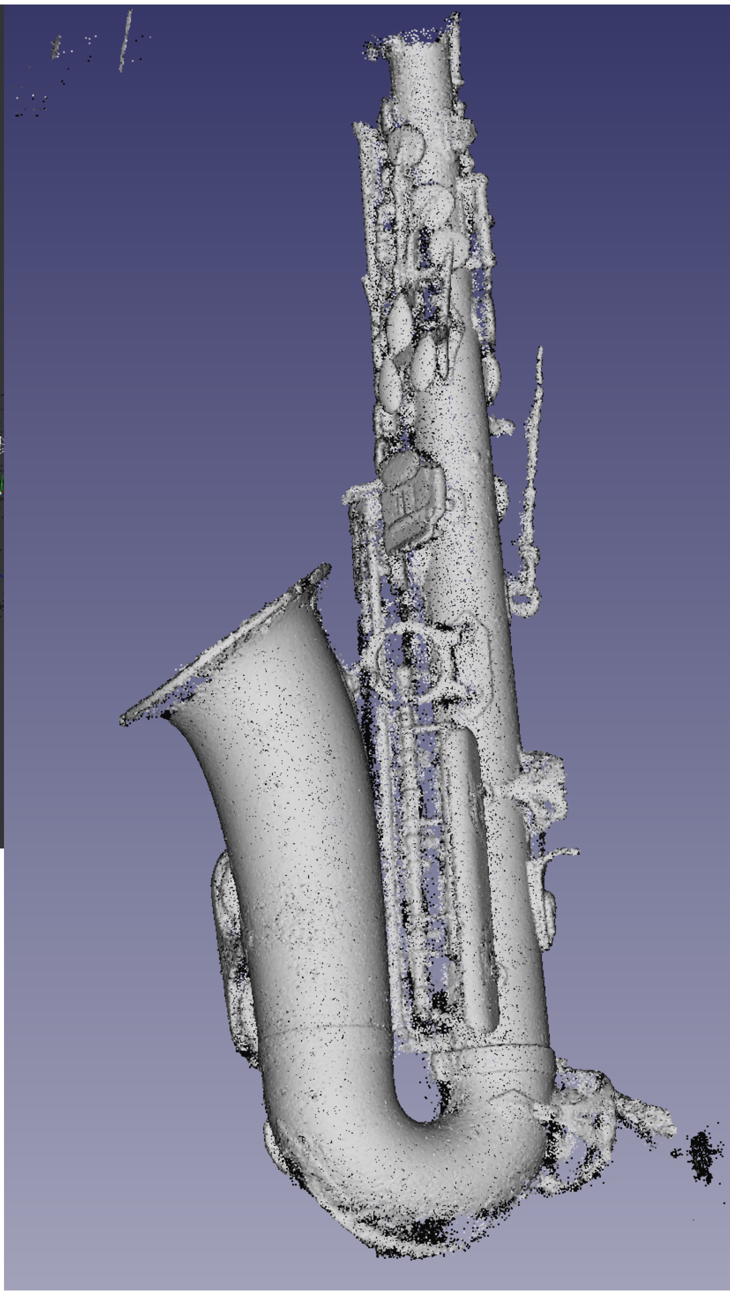
The first of these new prototypes will be entrusted to artistic promotor Kurt Van Herck. His expertise and feedback will be invaluable in refining the design and ensuring its suitability for professional use.

Additionally, a second prototype will be crafted and to be played at the premiere concert December 21st.

In addition to the progress made thus far, there is room for further refinenement in the creation of the PCBs. Small improvements can still be made to enhance its overall performance and the current dual PCB design will be merged into one panel as outlined in the previous chapter.

While the use of DIY builds remains prevalent, future plans include the development of a more advanced PCB that employs Surface Mount Device (SMD) techniques(84).





3D point cloud rendering(86) of an alto saxophone by Johannes Taelman.
Made for use as a guide for creating a more streamlined approach to attach the sensors, leveraging flexPCB(85) technology.
Due to the many structural differences in individual instruments, this route was dismissed for now.

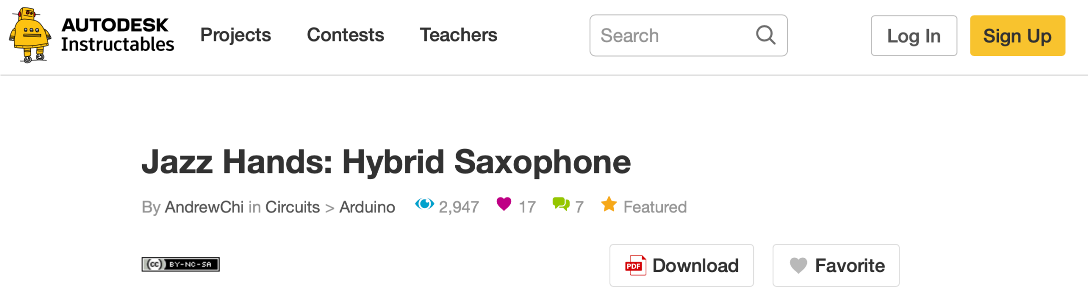
# Addendum

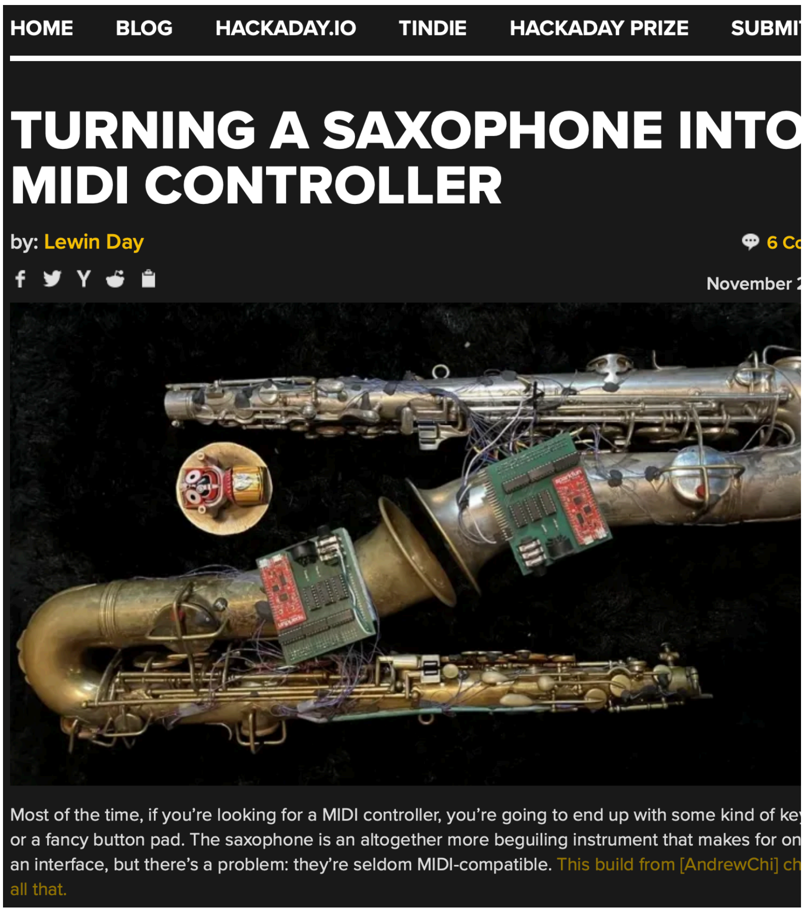
On November 20th 2023 the DIY guide was published on www.instructables.com.
The step-by-step guide was promptly featured on the site and earned a Bronze Medal within its first week after publication.

Two days later, the esteemed www.hackaday.com online platform for creatives in the realm of technology, made a post featuring the Jazz Hands porjects' Instructable guide.

As of today, Thursday December 7th, the Instructable reached 2947 views.

Please find the complete guide attached as Appendix 1.



# Research Implications and Related Projects

**STUFF.**
Throughout the project, intriguing side effects were experienced fostering collaborative endeavors. The essay highlights two notable projects: 'STUFF. plays Howard Shore' and the ongoing BOTBOP saga.
The Antwerp-Ghent based jazz fusion quintet STUFF. has played a pivotal role in fostering appreciation of jazz music in Flanders. The group has left an indelible mark on the local music scene, reaching the pinnacle of success by headlining Belgium's two largest jazz festivals, Jazz Ghent and Jazz Middelheim in 2019 and 2022.
Their influence extends somewhat beyond national borders, having embarked on extensive tours across the United Kingdom, gracing renowned venues such as London's The Roundhouse(87).

Harnessing the EWI (Electronic Wind Instrument) as a primary lead instrument, the band's numerous performances eventually led to a yearning for the familiarity of the traditional saxophone, sparking contemplation on a hybrid solution. This longing became the starting point for exploring the possibilities of combining electronic and acoustic elements.

The band's project "STUFF. plays Howard Shore", featured a curated repertoire of compositions by the esteemed film composer Howard Shore, known for his collaborations with film director David Cronenberg.
This ambitious audiovisual performance featured a first version of the hybrid saxophone, largely abstaining from using the EWI on key parts. Instead, newly achieved capabilities were harnessed to facilitate a crude 'midification' of the classic saxophone.
To accomplish this, state-of-the-art audio-to-MIDI tools were applied in conjunction with a specially crafted patch on the Axoloti microcontroller platform for a smoother and reliable MIDI output.

During these performances, which attracted medium-sized audiences of around 300 or more, a technique dubbed "silent MIDI" - generating MIDI output without hearing the natural saxophone sound - was achieved through playing the saxophone away from the microphone, thereby preventing the acoustic sound from being heard by the audience, while still generating MIDI data.

While this approach worked effectively in the larger venues, it should be noted that the saxophone was indeed still being played audibly to produce the desired MIDI output. Although the MIDI control may have deceived the audience into believing that true MIDI output was already being achieved, the limitations of audio-to-MIDI systems meant that MIDI data could only be generated when the saxophone was played audibly.

Nevertheless, this project proved successful in igniting the necessary inspiration to further develop a comprehensive MIDI system for the saxophone. Hence the band STUFF. and their ambitious projects played a crucial role in shaping this research journey, pushing the project towards the exploration and refinement of a robust MIDI solution for the saxophone.

STUFF. plays Howard Shore, Antwerp Bourla

STUFF. from L to R: Joris Caluwaerts, Dries Laheye, Lander Gyselinck, Andrew Claes & Mixmonster Menno

**BOTBOP**
Another significant project that emerged during the course of this research is the band BOTBOP, which originated from a commissioned work for BOZAR in Brussels.
Amidst the challenging circumstances of the COVID-19 pandemic(88), BOZAR collaborated with the esteemed Ars Electronica Festival(89) in Austria to support innovative musical projects involving early-stage AI tools for music creation.

In collaboration with Dagobert Sondervan, an intensive programming endeavour was made to integrate machine learning techniques into the duo's already well-established live electronics setup, which had been previously meticulously tailored for electronic music improvisation, using the node based programming style as well as live coding techniques.

Adaptive MIDI-looping(90) strategies were developed and implemented to enable real-time adaptations of the music being played within an improvisational context.

Both the performance as well as a public panel discussion delving into the future of music in the era of AI, was streamed live on all major online platforms during the festival(91).

Following the success of the performance, BOZAR did not hesitate to invite the newly formed band to represent Belgium once again, this time at the prestigious ST-ARTS festival. This event, organized by the European Union in collaboration with the renowned Sonar electronic music festival(92) in Barcelona, provided a platform for showcasing groundbreaking musical projects.

For this second commissioned work, BOZAR's musical director Roel Van Hoeck suggested the inclusion of an acoustic element to create a contrast in the predominantly digital scene. In response, a collaboration with a classical string quartet was proposed, envisioning real-time arrangements generated from live improvised input form the electronic saxophone (EWI).

To facilitate this, special software was developed by Kasper Jordaens, who joined the band at this juncture. The software allowed MIDI streams to be visualized as musical scores in near real-time, with a processing time lag of precisely four measures in any give tempo.

The application successfully serves as an interface between the digital music format (MIDI) and traditional scores used by classical trained musicians.

The algorithms responsible for arranging the MIDI data for the string quartet were created using Python scripting in Bespoke Synth open source software.

Pushing practical coding skills, initially sparked through introductory classes by Jeroen Famaey at UAntwerpen, the updated algorithms employed a blend of algorithmic music composition techniques as pioneered by composers such as John Cage, Karel Goeyvaerts, and Karlheinz Stockhausen, alongside simple yet effective methods like the humble canon(93).

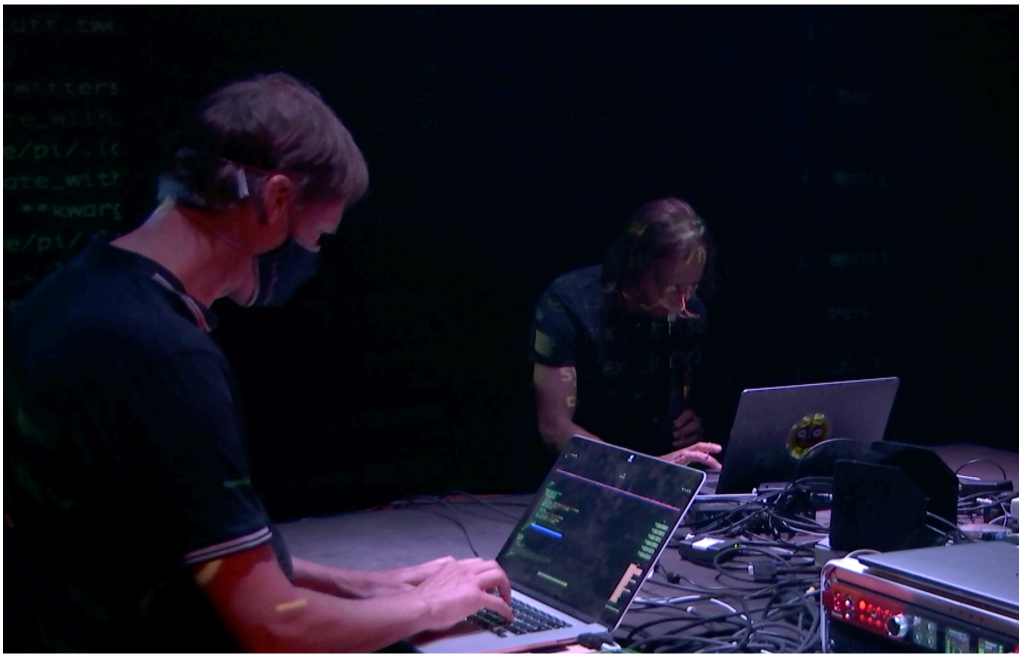
Optimized for real time operation and combined with cutting-edge machine learning techniques, leveraging Google's Magenta(94) and TensorFlow(95) software libraries for generative music(96), a new artistic toolkit was created.

The captivating performance, entitled "Integers & Strings," made its world premiere at the prestigious Sonar Festival in Barcelona, captivating audiences with its innovative blend of music and technology.
Building on this success, the band went on to perform another concert at BOZAR back in Brussels, and performed at the research festival Articulate(97), held at the Royal Conservatory of Antwerp.
The performances led to participation at the International Convention for Live Coding (ICLC)(98) held in Utrecht, the Netherlands, further cementing their reputation as trailblazers in the field.

Currently, the project is undergoing an exciting evolution, transitioning to its eagerly awaited third instalment aptly named "Floats & Strings".
This new phase will witness a shift in focus towards harnessing the potential of more robust AI tools, moving beyond live coded algorithmic composition techniques to embrace the latest advancements in Neural Networks(99), Machine Learning and leveraging the power of open source Large Language Models(100) such as GPT4All(101). The aim is to train smaller models using meticulously curated input, resulting in highly personalized artistic outputs.

By infusing artistic choices and preferences, new layers of complexity will enable creators to develop unique workflows and explore novel avenues for integrating AI tools without compromising their inherent passion for creating art. The tools already developed through "Integers & Strings" have proven invaluable for the modus operandi of the closing concert of this PhD. research.

The final concert, presented as the public defence, will again feature a string ensemble and computer-aided arrangements as its foundation, incorporating the knowledge and insights gained from the collaboration with a string quartet with BotBop.
These initiatives explored the (early) potential of AI, machine learning, and computer-aided music creation and subsequent development of algorithms and software, enabling innovative musical expressions in electro/jazz improvisation and classical music performance.



BotBop live stream during COVID19 pandemic in 2021, BOZAR, Brussels


BotBop's Integers & Strings, 2022 Barcelona Sonar/ST-ARTS


BotBop from L to R: Kasper Jordaens, Dago Sondervan & Andrew Claes

# Conceptualizing the public presentation

**World premiere**
The culmination of this doctoral study will be a grand concert that not only demonstrates the capabilities of the hybrid saxophone but also integrates newly discovered possibilities. Building on BotBop's "Integers and Strings" , real time music scoring software will be used to support an acoustic performance with a timeless appeal.
The addition of a MIDI-powered solenoid(102) system further merges the digital and acoustic realms, creating a unique auditory experience.

The renowned Museum of Fine Arts in Antwerp, KMSKA(103), launched its esteemed Artist In Residence (AIR) program, which spanned a remarkable five years leading up to its highly anticipated grand reopening in 2022.

The band STUFF. being selected to participate in KMSKA's prestigious AIR program and taking advantage of the band's temporary hiatus after an eventful nine years of relentless touring and album production, the opportunity was ceased to forge a unique collaboration with KMSKA.

Joining forces with fellow artist-in-residence, the 'Goeyvaerts String Trio'(104), a captivating performance will be curated showcasing the remarkable hybrid saxophone and its creative potential.

This third and final phase of this doctoral research marks a significant shift in focus, transitioning from the educational and autodidactic development of essential skills in phase one, the technical realization of the proof-of-concept in phase two, to the pinnacle of artistic expression: a live premiere - the culmination of this PhD. in the Arts.

The concert aims to harmoniously blend all the invaluable lessons learned throughout this transformative journey, placing the hybrid saxophone at its core, while building upon the tools and skills that have emerged as serendipitous byproducts of this profound study.
This highly anticipated concert will be presented as a remarkable addition to the established "KMSKA Late Night" series, a monthly event initiated by the museum since its reopening.

This series treats museum-goers to exclusive performances by the museum's own Artists In Residence, held right after the regular closing time. It fosters a unique opportunity for the audience to engage with the living arts in a distinctive and immersive setting.
An exceptional week of collaboration has been planned to build, experiment and finetune the performance, in collaboration with the talented string trio.

To enrich the ensemble's sonic palette and extend the lower range, a double bass will be added to the ensemble, serving the distinct contemporary style, which draws inspiration from a myriad of diverse and contrasting genres.

Ranging from historic serial(105), aleatoric(106), spectral(107), minimal(108), and maximal(109) music to contemporary jazz(110), pop(111), world(112) and various forms of electronic dance music(113), exemplifying artistic hyper-diversity.

This creative amalgamation finds its roots in a highly personal profound belief in 'Unity in Diversity,' a philosophical concept originally espoused by the renowned Indian spiritual leader, A.C. Bhaktivedanta Swami Prabhupada(114).

According to this philosophy (vaishnavism)(115), there exists a transcendental body within all aspects of material reality at the level of the soul and consciousness. It posits that the manifold forms of matter are subordinate to a higher, all pervading reality, perceivable only through a spiritual lens.

This profound insight opens new doors for the fusion of different styles, approaches, and workflows, borrowing from numerous sources without disrespecting or appropriating them, by acknowledging its Divine Source.

Subscribing the notion that at its core, art should be re-appreciated as a human expression that surpasses mere logical thought processes and even transcends the emotional realm. Furthermore, art should strive to capture a tangible, yet inexplicable experience of the timeless, unchanging, and incomprehensible truth that is Life itself.

Therefore, materialism(116), scientism(117), and individualism(118) should be transcended to pave the way for a more balanced, healthy, and personal relation with our planet, its inhabitants and its Creator.

The public defence of this study will consist of two distinct parts.

The first part will involve a keynote presentation, which will broadly follow the narrative outlined in this essay. This presentation will serve as an informative session for both the jury and the wider audience, providing a detailed account of the entire doctoral journey. The initial two phases of the project will be outlined, focusing on the acquisition of new skills through self-guided learning in the digital age, as well as the successful creation of the working proof-of-concept model.

Following the keynote presentation, everyone in attendance will be invited to enjoy a unique concert.

This highly anticipated performance will mark the premiere of the groundbreaking hybrid saxophone system, with the esteemed collaboration of the Goeyvaerts String Trio, expanded to a quartet specifically for this defining occasion.

The concert promises to showcase the artistic possibilities and potential of the hybrid sax, offering a unique musical experience that encapsulates the culmination of the entire doctoral research project.

Subsequent to the concert, a reception will be held, providing an opportunity for attendees to engage in discussions, ask more questions, and engage in meaningful conversations.

This celebratory gathering will serve as a platform for further exploration and exchange of ideas, fostering a collaborative and intellectually stimulating environment.

Overall, the public defence of the doctoral trajectory promises to be an enriching and memorable event, combining the informative keynote presentation with a captivating concert performance. It will not only provide an in-depth understanding of the research journey but also offer an immersive experience of the innovative hybrid saxophone on its maiden voyage.

# Future plans

This doctoral research has been a rewarding journey, both artistically and technically, culminating in the creation of an original hybrid instrument.

After a successful concert premiere and the release of a DIY maker guide, along with the code and fabrication files, the main goals of the research will be achieved, along with several meaningful side tracks and insights.
However, as the research nears completion, it is essential to address the future possibilities of this novel enhanced instrument and consider potential improvements to mitigate some of the downsides of its current design.

First and foremost, it is evident that the system is not a polished, finished product. Its current presentation has a DIY steampunk aesthetic(119), reminiscent of something out of a Mad Max movie. The abundance of cables, the use of larger and older through-hole components, and the extensive application of Sugru adhesive contribute to its somewhat bulky DIY appearance.

This design approach contrasts with the sleek and crafty aesthetics of the traditional saxophone, which features an elegant design, typically found in the age of early industrial revolution.
While the system itself is highly responsive and proves reliable when carefully constructed, its appeal will probably be limited to a small niche of technically skilled musicians within the community of tinkerers and amateur builders.

Although perfectly acceptable, it is important to note that the current system, despite clear instructions and user-friendly documentation, may not reach the wider community of saxophone players at large.

New builds of the instrument for fellow saxophonists upon request are planned, but the significant potential should be addressed.
Current design limitations can be attributed to the design of the saxophone itself: the multitude of small design variations, found not only within different saxophone types (soprano, alto, tenor, and baritone) but also in evolutionary changes of saxophone mechanics over time.

Some older saxophones feature lower tone holes on the opposite side of the bell and numerous other small, yet significant changes, can be observed in different successive models. These variations make it nearly impossible to create a more elegant "one size fits all" design.

As a result, the decision was made to work with discrete sensors for each key, providing a universal design suitable for any saxophone and laying the groundwork for potential expansion to other instruments such as clarinets, oboes, flutes, and bassoons.

However, this approach does result in exposed cables and a somewhat bulky overall design. In light of these considerations, it becomes evident that there is room for improvement in refining the instrument's aesthetics, reducing its size and cable clutter, and enhancing its accessibility to a broader community of saxophone players.

These challenges present opportunities for future research and development, paving the way for more elegant and versatile iterations of this hybrid saxophone. By addressing these known issues and envisioning a future with improved design solutions, maximizing the instrument's potential impact and ensuring its wider adoption within the saxophone player's community might prove valuable.

Although outside the scope of this research, visionary plans for a radical and innovative design that could potentially transform this DIY project into an affordable, full fledged commercial product for musicians worldwide have been contemplated.

While the Electronic Wind Instrument (EWI) could be considered a predecessor and source of inspiration for this system, the hybrid saxophone system offers some significant benefits over current available MIDI wind controllers.

Considering the hybrid saxophone's advantage of being an actual saxophone rather than a plastic controller imitating a saxophone, potential is observed for a successful business venture.

The instrument's unique blend of traditional saxophone mechanics with modern digital capabilities could capture the interest and demand of a wide range of musicians. By providing an affordable alternative to the EWI, while maintaining the familiarity and tactile experience of playing a real saxophone, the hybrid saxophone could potentially find its place in the hands of musicians worldwide.

While the realization of this vision requires further development, refinement, and market considerations, the potential for the hybrid saxophone to become a sought-after instrument among saxophonists and musicians alike is at least promising.

Aspirations for a future iteration of the instrument demonstrate possibilities of bridging the worlds of technology and music, and the potential to bring this innovation to a global audience as a commercial product.

While practical ideas involving 3D printing and SMD components have already been considered, professional collaboration to bring this innovative instrument to a possible market is needed. To further develop and refine the hybrid saxophone system, a partnership with experts in acoustics, 3D printing, saxophone repair, and product development is needed.

# Acknowledgements

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By joining forces and combining diverse areas of expertise, a new development phase can be initiated, building upon the findings of this research.

If you are interested in working together on this exciting journey and contributing to the further advancement of the hybrid saxophone, please feel free to reach out. Your expertise and insight could prove invaluable in realizing the full potential of this system.

To conclude the essay, it is important to note this research, and particularly the hybrid saxophone system itself is a tested, working and full fledged self contained system, ready for DIY builds and further development by artists, scientists, students and enthusiasts alike. The possible introduction of a commercial release of the invention is beyond the scope of this PhD. in the Arts, more befitting a production design and subsequent marketing study. Nonetheless, this doctoral journey provides a robust system, a reliable proof-of-concept and a well documented artistic performance to build upon, marking this study's endpoint.

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www.axoloti.com
www.arduino.com
www.instructables.com
www.youtube.com
www.bespokesynth.com
www.gordon.blogspot.com
www.onmyphd.net
www.sparkfun.com
www.kicad.com
www.pjrc.com
www.brainmodular.com
www.secondsound.com
www.syos.co
www.vigamusictools.com
www.imoxplus.com
www.openai.com
www.leonardo.ai
www.design.ai
www.alldatasheets.com

**Following books were used as resources for learning and debugging**

Arduino for musicians: a complete guide to Arduino and teensy microcontrollers Edstrom - Oxford University Press - 2016
ISBN: 0199309329

Elektronica voor dummies Shamieh et al. - BBNC uitgevers - 2021
ISBN: 9789045354927

The Forrest Mims engineer's notebook Mims - LLH Technology Publishing - 1992
ISBN: 9781878707031

Think Python Downey - O'Reilly Media, Inc. - 2016
ISBN: 9781491939369

Python all-in-one Shovic and Simpson - John Wiley et Sons - 2021
ISBN: 9781119787600

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# Glossary

**(1) Printed Circuit Board (PCB)**
A board used for electrically connecting electronic components using conductive pathways, tracks, or signal traces etched from copper sheets laminated onto a non-conductive substrate. [Source: "The Electronics Handbook," Jerry C. Whitaker]

**(2) microcontroller**
A compact integrated circuit designed to govern a specific operation in an embedded system. It includes a processor, memory, and input/output peripherals on a single chip. [Source: "Microcontroller Theory and Applications with the PIC18F," Raj Kamal]

**(3) MIDI**
A technical standard that describes a protocol, digital interface, and connectors, allowing a wide variety of electronic musical instruments, computers, and other devices to connect and communicate with one another. [Source: "MIDI: A Comprehensive Introduction," Joseph Rothstein]

**(4) MIDI controller**
An electronic device, often resembling a musical instrument, that generates and sends MIDI data to MIDI-enabled devices to control sounds or functions of such devices. [Source: "The MIDI Manual: A Practical Guide to MIDI in the Project Studio," David Miles Huber]

**(5) PCB design software**
Computer programs used for designing the layout of printed circuit boards. They allow the user to design the circuitry electronically before physically producing the circuit boards. [Source: "Complete PCB Design Using OrCAD Capture and Layout," Kraig Mitzner]

**(6) Freerouting**
An open-source routing software used in PCB design to automatically route the connections defined in the schematic. [Source: "PCB Design Makeover Manual," Kirsch Mackey]

**(7) KiCad**
A free software suite for electronic design automation (EDA). It facilitates the design of schematics for electronic circuits and their conversion to PCB designs. [Source: "KiCad Like a Pro," Peter Dalmaris]

**(8) PCB panelization**
The process of grouping multiple PCBs on a single board for manufacturing. This process is used for efficiency and cost-effectiveness in mass production. [Source: "Printed Circuit Board Designer's Reference: Basics," Chris Robertson]

**(9) ChatGPT**
An AI language model developed by OpenAI, capable of understanding and generating human-like text based on the input it receives. [Source: "Artificial Intelligence: A Guide for Thinking Humans," Melanie Mitchell]

**(10) STEAM (Science, Technology, Engineering, Arts, Mathematics)**
An educational approach that integrates the arts into the traditional STEM model, emphasizing creativity and innovation. [Source: "STEM to STEAM: Using Brain-Compatible Strategies to Integrate the Arts," David A. Sousa, Thomas J. Pilecki]

**(11) STEM(Science, Technology, Engineering, Mathematics)**
An educational paradigm that integrates these four disciplines into a cohesive learning model based on real-world applications. [Source: "STEM Education for High-Ability Learners: Designing and Implementing Programming," Bronwyn MacFarlane]

**(12) Directorate-General for Communications Networks, Content and Technology**
The department of the European Commission responsible for EU policy on digital technology and its implementation. [Source: European Commission Website]

**(13) S.T.-ARTS**
A program or initiative that combines science, technology, and the arts, focusing on innovative approaches to interdisciplinary work. [Source: European Commission Website]

**(14) BOZAR**
The Centre for Fine Arts in Brussels, a cultural venue hosting a wide range of events including exhibitions, concerts, film screenings, and theater performances. [Source: BOZAR Official Website]

**(15) Flemish Department of Culture, Youth and Media**
The governmental department in Flanders, Belgium, responsible for policy-making and support in the fields of culture, youth, and media. [Source: Official Website of the Flemish Government]

**(16) Byte Records**
A record label known for its contributions to the dance music scene, particularly in Belgium. [Source: "Belgian Dance Classix Top 100," Jan Vervloet]

**(17) Akai S3000 sampler**
A professional digital sampler, part of the Akai S series, widely used in music production for its ability to record and manipulate sound samples. [Source: "The Sampling Handbook," Andy Jones]

**(18) Akai EWI**

An Electronic Wind Instrument developed by Akai, a MIDI controller resembling a saxophone, used to control synthesizers and generate electronic sounds. [Source: "Electronic Wind Instrument (EWI) Technique," Steve Tavaglione]

**(19) MIDI keyboard**

A piano-style electronic musical keyboard, typically used for sending MIDI commands to other musical devices or computers. [Source: "The MIDI Manual: A Practical Guide to MIDI in the Project Studio," David Miles Huber]

**(20) Digital Drumset**

An electronic musical instrument designed to simulate the sound of traditional drums using digital samples and typically played using drum pads. [Source: "The Drummer's Guide to Electronic Drums," Bob Terry]

**(21) MIDI standard**

A set of rules and specifications that allow electronic musical instruments and computers to communicate. [Source: "MIDI for Musicians," Craig Anderton]

**(22) MIDI pitchbend**

A MIDI message used to change the pitch of a note, similar to bending a string on a guitar. [Source: "The MIDI Manual: A Practical Guide to MIDI in the Project Studio," David Miles Huber]

**(23) MIDI portamento**

A MIDI control message that allows the pitch of a note to glide smoothly from one note to another. [Source: "MIDI: A Comprehensive Introduction," Joseph Rothstein]

**(24) Node based programming**

A programming paradigm where processes are represented as nodes in a graph, and the data flows between them, often used in audio, video, and graphics processing. [Source: "Real-Time Digital Signal Processing from MATLAB to C with the TMS320C6x DSPs," Thad B. Welch, Cameron H.G. Wright, and Michael G. Morrow]

**(25) Native Instruments Reaktor**

A modular software music studio developed by Native Instruments, allowing users to create synthesizers, samplers, and effects. [Source: "How to Make a Noise: a Comprehensive Guide to Synthesizer Programming," Simon Cann]

**(26) Brainmodular Hollyhock**

A software for live performance, composition, and sound design, featuring a modular interface for audio and video creation. [Source: BrainModular Official Website]

**(27) Axoloti Platform**

An open-source hardware and software platform for creating standalone digital audio instruments and effects. [Source: Axoloti Official Website]

**(28) Python**

A high-level, interpreted programming language known for its readability and broad applicability in various fields, including web development, data analysis, artificial intelligence, and scientific computing. [Source: "Python Crash Course: A Hands-On, Project-Based Introduction to Programming," Eric Matthes]

**(29) Arduino**

An open-source electronics platform based on easy-to-use hardware and software, used for building digital devices and interactive objects that can sense and control objects in the physical world. [Source: "Arduino Cookbook," Michael Margolis]

**(30) Bespoke Synth**

A modular digital synthesizer that allows users to create unique sounds by connecting different audio modules in a custom configuration. [Source: Bespoke Synth Official Website]

**(31) Pure Data (Pd)**

An open-source visual programming language for multimedia, used for creating interactive music and multimedia works. [Source: "Designing Sound," Andy Farnell]

**(32) Max/MSP**

A visual programming language for music and multimedia, used by composers, performers, software designers, researchers, and artists to create interactive software without writing lines of code. [Source: "Electronic Music and Sound Design - Theory and Practice with Max/MSP," Alessandro Cipriani, Maurizio Giri]

**(33) ESP32**

A series of low-cost, low-power microcontroller chips with integrated Wi-Fi and dual-mode Bluetooth, used in a wide range of IoT applications. [Source: "ESP32 Programming for the Internet of Things," Sever Spanulescu]

**(34) scripting interface**

A programming environment that allows users to write scripts – short programs written in a scripting language – to automate tasks or extend the functionality of an application. [Source: "Scripting Intelligence: Web 3.0 Information Gathering and Processing," Mark Watson]

**(35) Digital Signal Processing (DSP)**

The use of digital processing, like computers or more specialized digital signal processors, to perform a wide range of signal processing operations. [Source: "Understanding Digital Signal Processing," Richard G. Lyons]

**(36) Live Coding**

The act of writing and modifying algorithms in real-time to generate music or visuals, often used in live performances and installations. [Source: "Live Coding: A User's Manual," Thor Magnusson, Chris Kiefer, and Sam Aaron]

**(37) Algorave**

A live performance that features music and visuals generated from algorithms, often created in real-time by live coders. [Source: "Hacking the Art of Noise: Algorave and Live Coding Practice," Shelly Knotts, Nick Collins]

**(38) Sonic Pi**

A live coding synth for creating music, designed to be simple enough for educational purposes, yet powerful enough for professional musicians. [Source: "Code Music with Sonic Pi: The Essential Guide to Creating Music on Your Computer," Sam Aaron]

**(39) Tidal Cycles**
A language for live coding patterns, used for making music and controlling visuals in real-time. [Source: "Making Music with Computers: Creative Programming in Python," Bill Manaris, Andrew R. Brown]

**(40) live input**
The real-time capture and processing of audio or MIDI data during a performance. This can involve the use of microphones, MIDI controllers, or other devices to input sound or control signals into a digital audio workstation (DAW) or similar software for immediate use or manipulation. [Source: "Computer Music: Synthesis, Composition, and Performance," by Charles Dodge and Thomas A. Jerse]

**(41) Digital Audio Workstation (DAW)**
A DAW is a software platform used for recording, editing, and producing audio files. DAWs are used in music production, audio editing, and sound design and can host a wide range of virtual instruments and effects. [Source: "The Cambridge Companion to Electronic Music," edited by Nick Collins and Julio d'Escriván]

**(42) virtual analog synthersizer**
A virtual analog synthesizer uses digital signal processing (DSP) algorithms to emulate the sound of traditional analog synthesizers. These synthesizers are software-based but aim to replicate the warm tones and imperfections of their hardware counterparts. [Source: "Analog Synthesizers: Understanding, Performing, Buying," by Mark Jenkins]

**(43) polyphonic oscillators**
In synthesizers, polyphonic oscillators allow for the generation of multiple notes simultaneously, enabling the creation of chords and complex harmonies. This contrasts with monophonic oscillators, which can produce only one note at a time. [Source: "Electronic Music: Systems, Techniques, and Controls," by Allen Strange]

**(44) filters**
In electronic music, filters are used to modify the timbre of a sound by selectively attenuating certain frequencies while allowing others to pass. Common types include low-pass, high-pass, band-pass, and notch filters. [Source: "Handbook of Sound Studio Construction: Rooms for Recording and Listening," by Ken Pohlmann]

(45) **envelopes**
In synthesizer and sound design, an envelope controls how certain aspects of the sound (like amplitude or filter cutoff) change over time, typically described in terms of attack, decay, sustain, and release (ADSR). [Source: "The Synthesizer: A Comprehensive Guide to Understanding, Programming, Playing, and Recording the Ultimate Electronic Music Instrument," by Mark Vail]

**(46) Virtual Studio Technology (VST)**
VST is an audio plug-in software interface that integrates software synthesizers and effects units into digital audio workstations. VST and similar technologies use digital signal processing to simulate traditional recording studio hardware in software. [Source: "Music Technology from Scratch," by Mortimer Rhind-Tutt]

**(47) algorithmic comosition**

This is the technique of using algorithms to create music. Algorithms can be used to generate rhythms, melodies, or harmonic structures in an automated or semi-automated way. [Source: "Algorithmic Composition: A Guide to Composing Music with Nyquist," by Roger B. Dannenberg and Mary Simoni]

**(48) analog prototyping**

In electronics, analog prototyping refers to the creation of a preliminary model of a device that uses analog electronic components. This is done to test concepts and functions before final production. [Source: "Analog Circuit Design: Art, Science and Personalities," edited by Jim Williams]

**(49) firmware**

Firmware is a specific class of computer software that provides the low-level control for a device's specific hardware. It can be thought of as the software that makes a device behave in a certain way. [Source: "Firmware Engineering: A Practitioner's Approach," by Arnaldo Castellucci]

**(50) electric circuit diagrams**

These are graphical representations of electrical circuits. They show the components of the circuit as simplified shapes, and the power and signal connections between the devices. [Source: "Electrical Engineering 101: Everything You Should Have Learned in School... but Probably Didn't," by Darren Ashby]

**(51) through hole technology (THT)**

THT is a method of fitting components with wire leads into holes on a printed circuit board (PCB) and soldering them in place. It is contrasted with surface-mount technology (SMT), where components are mounted directly onto the surface of PCBs. [Source: "The Art of Soldering for Electronics Technicians," by Dan Herrick]

**(52) bend sensors**

These are sensors that detect bending or flexing. In electronic music, they can be used as expressive controls in instruments, changing sound parameters in response to physical bending movements. [Source: "Handbook of Modern Sensors: Physics, Designs, and Applications," by Jacob Fraden]

**(53) pressure sensors**

Pressure sensors are used to detect the amount of force applied, often used in electronic instruments to add expressiveness, such as varying the volume or timbre based on how hard a key or pad is pressed. [Source: "Sensors and Transducers," by Ian R. Sinclair]

**(54) Light Detection and Ranging (LIDAR)**

LIDAR is a method for measuring distances by illuminating the target with laser light and measuring the reflection with a sensor.[Source: "Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere," edited by Claus Weitkamp]

**(55) conductive fabric**

This is a fabric that can conduct electricity, often used in wearable technology. In music technology, it can be used to create interactive clothing that controls sound or music through movement or touch. [Source: "Smart Textiles for Designers: Inventing the Future of Fabrics," by Rebeccah Pailes-Friedman]

**(56) 3D printed saxophone mouthpiece**

A 3D printed saxophone mouthpiece is an innovative adaptation of traditional mouthpieces, created using 3D printing technology. This technology allows for precise customization of the mouthpiece's shape, size, and internal structure, potentially improving comfort, playability, and sound quality for the musician. One of the notable innovators in this field is Pauline Eveno, who has significantly contributed to the development and popularization of 3D printed saxophone mouthpieces. Her work in this area reflects the broader trend of integrating advanced manufacturing techniques, like 3D printing, into musical instrument production, enabling more personalized and experimentally designed musical tools. [Source: "3D Printing Technologies in Music: The Rise of Personalization and Customization," Journal of New Music Research]

**(57)audio-to-MIDI**

This technology converts audio signals (like those from a voice or an acoustic instrument) into MIDI data. This allows for the manipulation of these sounds with MIDI-compatible devices or software, such as synthesizers or digital audio workstations. [Source: "Audio Programming Book," by Richard Boulanger and Victor Lazzarini]

**(58) pitch tracking**

In music technology, pitch tracking is the process of determining the pitch of an audio signal, typically in real-time. It's often used in voice recognition, music transcription, and effects processing. [Source: "Computer Music: Synthesis, Composition, and Performance," by Charles Dodge and Thomas A. Jerse]

**(59) Integrated Circuit (IC)**

An integrated circuit chip is a set of electronic circuits on a small flat piece (or "chip") of semiconductor material, usually silicon. ICs are used in virtually all electronic equipment and have revolutionized the world of electronics. [Source: "Digital Integrated Circuits," by Jan M. Rabaey, Anantha Chandrakasan, and Borivoje Nikolic]

**(60) evaluation kit**

In electronic product development, an evaluation kit is a product offered by chip manufacturers to demonstrate the features of their chips. These kits help developers understand how to integrate these chips into their designs. [Source: "Embedded Systems Design with Platform FPGAs," by Ronald Sass and Andrew G. Schmidt]

**(61) expression pedal**

An expression pedal is a type of foot pedal used to control various aspects of the sound in electronic musical instruments. It's similar to a volume pedal but can be assigned to control other parameters like filter frequency or modulation depth. [Source: "The Keyboardist's Picture Chord Encyclopedia," by Leonard Vogler]

**(62) audio looper pedal**

This is a device used by musicians to record short sections of audio which are then played back in a repeating loop. It is widely used for practicing, composing, and live performances. [Source: "Guitar Effects Pedals: The Practical Handbook," by Dave Hunter]

**(63) machine learning**

Machine learning is a subset of artificial intelligence that involves the use of data and algorithms to imitate the way that humans learn, gradually improving its accuracy. It's widely used in various fields, including music recommendation and composition. [Source: "Machine Learning: A Probabilistic Perspective," by Kevin P. Murphy]

**(64) GPU-based processors**

These are processors designed primarily for handling the complex mathematical calculations required for rendering images, animations, and video. In music technology, they can be used for advanced audio processing and music synthesis. [Source: "Fundamentals of Computer Graphics," by Steve Marschner and Peter Shirley]

**(65) hall effect sensors**

These sensors detect magnetic fields and are used to measure proximity, position, or speed. In electronic music, they can be used to create novel controllers or interactive installations. [Source: "Hall-Effect Sensors: Theory and Application," by Edward Ramsden]

**(66) linear analog sensor**

A linear analog sensor provides a continuously varying output voltage or current proportional to a physical quantity like pressure or light. In music, these sensors can be used in expressive controllers. [Source: "Sensors and Transducers," by Ian R. Sinclair]

**(67) digital switch**

A digital switch is an electronic component that can open or close a circuit, transmitting a digital signal. In music technology, it's often used in MIDI controllers and other interactive devices. [Source: "Digital Switching Systems: System Reliability and Analysis," by Syed A. Ahson]

**(68) software libraries**

In computer programming, software libraries are collections of pre-written code that users can utilize to develop software more efficiently. In music technology, libraries often include code for sound synthesis, processing, or analysis. [Source: "Introduction to Computing and Programming in Python," by Mark J. Guzdial and Barbara Ericson]

**(69) breath sensor**

A breath sensor is a device that detects the airflow from a musician's breath and translates it into an electronic signal. This is commonly used in wind controllers to add expression to the generated sounds. [Source: "Electronic and Experimental Music: Technology, Music, and Culture," by Thom Holmes]

**(70) dynamic microphone**

A dynamic microphone uses a coil of wire suspended in a magnetic field to convert sound into an electrical signal. They are robust and well-suited for live sound and recording loud sources. [Source: "Handbook of Sound Studio Construction: Rooms for Recording and Listening," by Ken Pohlmann]

**(71) voltage control signal**

In synthesizers and modular systems, a voltage control signal is an electrical signal used to control a parameter, such as pitch or filter cutoff. The signal's voltage level corresponds to the amount of control exerted. [Source: "Patch & Tweak: Exploring Modular Synthesis," by Kim Bjørn and Chris Meyer]

**(72) analog envelope follower circuit**

This circuit converts the amplitude variations of an audio signal into a control voltage. It's commonly used in synthesizers and effects units to control parameters dynamically based on the input signal's loudness. [Source: "Handmade Electronic Music: The Art of Hardware Hacking," by Nicolas Collins]

**(73) piezo electric microphone**

A piezo-electric microphone uses a piezoelectric crystal to convert vibrations into an electrical signal. They are often used for acoustic instruments and can be more resistant to feedback and loud environments. [Source: "Microphone Manual: Design and Application," by David Miles Huber]

**(74) Viga Music Tools intraMic**

This is a specialized microphone designed for use inside acoustic instruments, capturing the sound directly from the source with minimal interference from external noise. [Source: "Microphones for the Recording Musician," by Phil English]

**(75) Field-Programmable Gate Array (FPGA)**

An FPGA is an integrated circuit designed to be configured by the customer or designer after manufacturing – hence "field-programmable". They are used for specialized processing tasks in various technologies. [Source: "FPGAs: Instant Access," by Clive Maxfield]

**(76) shift register**

A shift register in electronics is a type of sequential logic circuit, primarily used for storage and transfer of data. It consists of a series of flip-flops, which are basic data storage units. Each flip-flop can store a single bit of data, either 0 or 1. The data in a shift register is moved in a linear sequence where the output of one flip-flop becomes the input of the next, typically on each clock cycle. This shifting process allows for the serial input (one bit at a time) and can convert it to parallel output (multiple bits at once) or vice versa. Shift registers are widely used in digital circuits for tasks such as data manipulation, buffering, and transferring data between different parts of a system, or with peripheral devices. They play a crucial role in applications such as digital signal processing, data storage, and communication systems.[Source: "Digital Design," by M. Morris Mano, Prentice Hall]

**(77) pullup resistors**

Pull-up resistors are used to ensure that a wire is at a high logical level in the absence of an input signal. They are commonly used in digital circuits to prevent undefined states. [Source: "Practical Electronics for Inventors," by Paul Scherz and Simon Monk]

**(78) PCB footprint**

The PCB footprint refers to the layout pattern of pads and through-holes on a printed circuit board for mounting a component. It ensures that each component fits and connects properly. [Source: "Printed Circuit Board Designer's Reference; Basics," by Chris Robertson]

**(79) 1/4" jack connector**

This is a type of electrical connector commonly used for audio signals. It's widely used in musical instruments, professional audio, and consumer audio applications. [Source: "Handbook of Sound Studio Construction: Rooms for Recording and Listening," by Ken Pohlmann]

**(80) capacitive touch sensor**

These sensors detect the presence or absence of a conductive object (like a human finger) by measuring changes in capacitance. In music, they are used for touch-sensitive controls on instruments and devices. [Source: "Capacitive Sensors: Design and Applications," by Larry K. Baxter]

**(81) stripboard**

Stripboard is a type of electronics prototyping board characterized by a grid of holes with parallel strips of copper cladding running in one direction. It's used for building and testing circuit designs. [Source: "Practical Electronics for Inventors," by Paul Scherz and Simon Monk]

**(82) Sugru by Tesa**

Sugru is a flexible, adhesive repair putty that sets into a durable silicone rubber. It's used for fixing, bonding, or attaching components in various DIY projects, including in music technology for customizing or repairing instruments and gear. [Source: "The Maker's Manual: A Practical Guide to the New Industrial Revolution," by Paolo Aliverti, Andrea Maietta, and Patrick Di Justo]

**(83) Pritt poster buddies**

These are adhesive, removable, and reusable putty-like substances used for mounting posters or light objects. In music technology, they can be used for temporary fixture or positioning of components during prototyping. [Source: "The Art of Tinkering," by Karen Wilkinson and Mike Petrich]

**(84) Surface-Mount Device (SMD)**

SMD components are electronic components that are mounted directly onto the surface of PCBs, as opposed to being inserted into holes. They are smaller than traditional through-hole components and used in compact electronic devices. [Source: "Surface Mount Technology: Principles and Practice," by Ray P. Prasad]

**(85) 3D point cloud rendering**

In 3D graphics, point cloud rendering involves visualizing data points in three-dimensional space. [Source: "3D Point Cloud Processing," by Yulan Guo et al.]

**(86) flexPCB**

A flexible printed circuit board (FlexPCB) is a type of PCB that can flex and bend. They are used in electronic devices where space is limited or where the PCB needs to conform to a particular shape. [Source: "Flexible Printed Circuitry," by Thomas Stearns]

**(87) The Roundhouse (London)**

The Roundhouse is a performing arts and concert venue located in London, known for its distinctive architecture and history as a cultural hub. It hosts a variety of performances, including music concerts and theater productions. [Source: "London's Contemporary Architecture: A Visitor's Guide," by Kenneth Allinson]

**(88) COVID19 pandemic**

A global health crisis caused by the novel coronavirus SARS-CoV-2, leading to widespread illness, lockdowns, and significant impacts on various sectors, including music and technology. [Source: "COVID-19 pandemic," World Health Organization]

**(89) Ars Electronica**

An annual festival and a year-round platform for digital art, technology, and society, focusing on the interlinking and co-evolution of these fields. [Source: "Ars Electronica," Ars Electronica]

**(90) MIDI looping**

The process of recording and replaying MIDI data in a continuous loop, often used in live performances to create layers of sound. [Source: "MIDI looping," MIDI Manufacturers Association]

**(91) BOZAR/Ars Electronica**

A collaboration between BOZAR, the Centre for Fine Arts Brussels, and Ars Electronica, focusing on innovative digital art and technology projects. [Source: "BOZAR/Ars Electronica collaboration," BOZAR]
**https://www.youtube.com/watch?v=8kOKv8DQ__U**

**(92) Sonar Festival Barcelona**

An international festival of advanced music and new media art held annually in Barcelona, Spain. [Source: "Sonar Festival," Sonar]

**(93) canon**

A musical form where a melody is imitated and overlapped in different voices, creating a round-like effect. [Source: "Canon," Oxford Music Online]

**(94) Google Magenta**

A research project by Google exploring the role of machine learning in the process of creating art and music. [Source: "Google Magenta," Google Research]

**(95) Tensorflow**

An open-source software library developed by the Google Brain team for machine learning and neural network research. [Source: "TensorFlow," Google Research]

**(96) generative music**
Music that is algorithmically generated, often through the use of computer programs or artificial intelligence. [Source: "Generative music," Computer Music Journal]

**(97) Articulate festival**
An annual festival held at the Royal Conservatoire of Antwerp that showcases research in the arts. [Source: "Articulate Festival," Articulate]

**(98) International Convention for Live Coding (ICLC)**
A gathering focused on the practice of live coding, where algorithms are written and modified in real-time to create live artistic performances. [Source: "ICLC," International Convention for Live Coding]

**(99) neural networks**
Computational models inspired by the human brain, used in machine learning to recognize patterns and make decisions. [Source: "Neural networks," Nature]

**(100) Large Language Models (LLM)**
Advanced algorithms capable of understanding and generating human-like text, used in various applications including natural language processing. [Source: "Large Language Models," IEEE Spectrum]

**(101) GPT4All**
A free-to-use, locally running, privacy-aware chatbot. No GPU or internet required. [Source: “GPT4All”,GPT4All.io]

**(102) solenoid**
An electromagnetic device used to convert electrical energy into linear motion, often used in mechanical and electronic applications. [Source: "Solenoid," IEEE Transactions on Magnetics]

**(103) Koninklijk Museum voor Schone Kunsten (KMSKA)**
The Royal Museum of Fine Arts in Antwerp, Belgium, known for its collection of paintings, sculptures, and drawings from the 14th to the 20th centuries. [Source: "KMSKA," Royal Museum of Fine Arts Antwerp]

**(104) Goeyvaerts String Trio**
A string trio known for their performances of contemporary classical music, particularly minimal and spectral music. [Source: "Goeyvaerts String Trio," Contemporary Music Review]

**(105) serial music**
A technique of composition that uses a series of values to manipulate different musical elements. Key composers include Arnold Schoenberg, who pioneered the twelve-tone technique, and his students Alban Berg and Anton Webern. [Source: "Serial Music," The New Grove Dictionary of Music and Musicians]

**(106) aleatoric music**
Music in which some elements are left to chance. Key composers include John Cage, renowned for his innovative use of indeterminacy, and Witold Lutosławski, who used controlled aleatory in his compositions. [Source: "Aleatoric Music," The Oxford Companion to Music]

**(107) spectral music**
A genre focusing on the spectral properties of sound. Key composers include Gérard Grisey and Tristan Murail, founders of the spectral music movement in France, and Kaija Saariaho, noted for her use of computer-aided composition techniques. [Source: "Spectral Music," Contemporary Music Review]

**(108) minimal music**
Characterized by repetitive motifs and gradual changes. Key composers include Steve Reich, known for his phase shifting techniques, Philip Glass, renowned for his additive processes, and Terry Riley, credited with pioneering the style. [Source: "Minimal Music," Music Theory Spectrum]

**(109) maximal music**
This style contrasts minimal music by employing complexity and rich textures. Key composers include Charles Ives, known for his dense and complex layers, and Gustav Mahler, recognized for his expansive and intricate symphonies. [Source: "Maximal Music," Journal of Music Theory]

**(110) contemporary jazz**
A form of jazz that incorporates influences from various musical styles and eras, reflecting current trends and innovations. [Source: "Contemporary jazz," The Oxford Companion to Jazz]

**(111) pop music**
A genre of popular music characterized by its appeal to a broad audience and typically having a strong rhythmic and melodic component. [Source: "Pop music," Encyclopedia of Popular Music]

**(112) world music**
A broad category encompassing different music styles from around the globe, often emphasizing cultural or regional musical traditions. [Source: "World music," The Garland Encyclopedia of World Music]

**(113) Electronic Dance Music (EDM)**
A genre of music primarily produced for dance-based entertainment environments, characterized by electronic sounds and strong rhythmic beats. [Source: "Electronic Dance Music," Journal of Popular Music Studies]

**(114) A.C. Bhaktivedanta Swami Prabhupada**
The founder of the International Society for Krishna Consciousness (ISKCON), known for spreading the practice of Bhakti yoga and Vaishnavism worldwide. [Source: "A.C. Bhaktivedanta Swami Prabhupada," Journal of Vaishnava Studies]

**(115) vaishnavism**
A branch of Hinduism focused on the worship of Vishnu and his avatars, such as Krishna. [Source: "Vaishnavism," Oxford Research Encyclopedia of Religion]

**(116) materialism**
A philosophical viewpoint that regards material or physical things as the fundamental reality, often contrasted with spiritual or immaterial perspectives. [Source: "Materialism," Stanford Encyclopedia of Philosophy]

**(117) scientism**
The belief that science is the ultimate path to truth and that its methods should be applied in all fields of inquiry. [Source: "Scientism," Philosophy of Science]

**(118) individualism**
A social theory favoring freedom of action for individuals over collective or state control. [Source: "Individualism," American Journal of Sociology]

(119) **steampunk aesthetic**
A style of design and fashion that combines historical elements with anachronistic technological features inspired by 19th-century industrial steam-powered machinery. [Source: "Steampunk Aesthetic," Journal of Victorian Culture]

**(120) physical modeling synthesizer**
A synthesizer that uses mathematical algorithms to simulate the physical properties of real instruments, creating realistic sound simulations. [Source: "Physical Modeling Synthesizer," Computer Music Journal]

**(121) Slack online platform**
A digital communication platform used for messaging, file sharing, and collaboration, often in professional environments. [Source: "Slack Online Platform," Harvard Business Review]