

Electric Drum Hit Localization Using Time Difference of Arrival Analysis

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1 Introduction

1.1 Problem

When it comes to electric drums, the limiting factor for many commercial offerings is linked to the number of local zones on the surface, each of which may trigger sounds that correspond to a type of hit from a bank of recorded samples. Too few zones results in a noticeable lack of realism when compared to a real acoustic drum which has continuous variation from the center to the rim. Typically, electric drums that have more than two zones are offered by few companies at a high cost premium, and those with ten or more zones are exponentially more exclusive. An additional limitation of these high zone count, premium drums, is that they do not offer customizable output zone mapping. The typical enthusiast electric drum handles the sample triggering layer internally, and usually only outputs up to two MIDI (Musical Instrument Digital Interface) channels for external use. This limits the flexibility of the drum to a vendor specific ecosystem.

1.2 Solution

Our proposed solution to this problem is to implement a limited number of inexpensive piezoelectric sensors arranged in a concentric ring to perform time difference of arrival (TDOA) positional estimation in order to achieve a high number of zones with a low overhead cost. Our system will also have the unique ability to output each individual zone as a separate MIDI note for external use by the user. The system will consist of four systems: Piezo array / mounting, analog preprocessing, STM32 MCU, and a USB power and I/O module.

1.3 Visual Aid

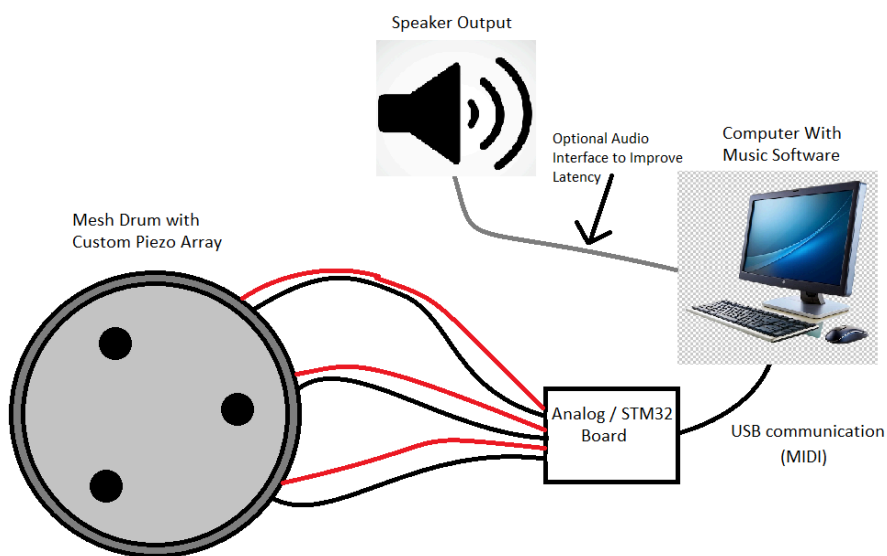


Figure 1 Visual Aid

1.4 High Level Requirements

- The system shall distinguish between at least ten radial zones on a 13-inch-diameter drum surface with at least 90% accuracy over a minimum of ten test strikes per zone.
- The combined MCU processing and USB transmission latency, measured from the first detected piezo threshold crossing to receipt of the corresponding MIDI message by the host computer, shall not exceed 15 ms for at least 95% of test strikes.
- The device shall be recognized by a host computer as a USB-MIDI interface in ten consecutive connection attempts and shall transmit the MIDI note assigned to each detected strike zone.

2 Design

The core of our design will be modeled around a 13 inch acoustic snare drum, that will have its acoustic head replaced with a silent mesh head, typical in electric drums. This approach is well documented in other cases of acoustic to electric drum conversion. The acoustic drum has the added benefit of being much larger, allowing for more mounting space and total area for dividing MIDI zones. 3D printed mounts and 90 degree printed angle brackets will be used to attach onto the radial lugs on the perimeter of the drum pictured below. These mounts will have adjustable slots in the event that the piezo mounting locations need to be fine tuned. A CAD model is pictured below (fig 2). The piezos will then be wired to a printed circuit board, containing the analog preprocessing module. This module converts the output of the piezos into normalized sources that may be passed into the analog pins on the STM32, which will be used as inputs to the ADC in the MCU. The MCU has a few key tasks. First, it must sample the piezos constantly, and monitor level thresholds. When a threshold event occurs, the internal clock measures the time differences between the second and third threshold events (potentially more depending on the best configuration from our testing), from which a location estimate can be calculated. Other approaches for location estimation, like peak amplitude comparison, may be integrated into the position estimation algorithm. The MCU must then drive a USB output signal based on the MIDI configuration, to trigger the appropriate playback based on whatever end software is running on the other end (ex: BFD Player, Superior Drummer, Serum). The final module adapts the USB power to the needs of the analog preprocessing module and MCU module respectively.

2.1 Block Diagram

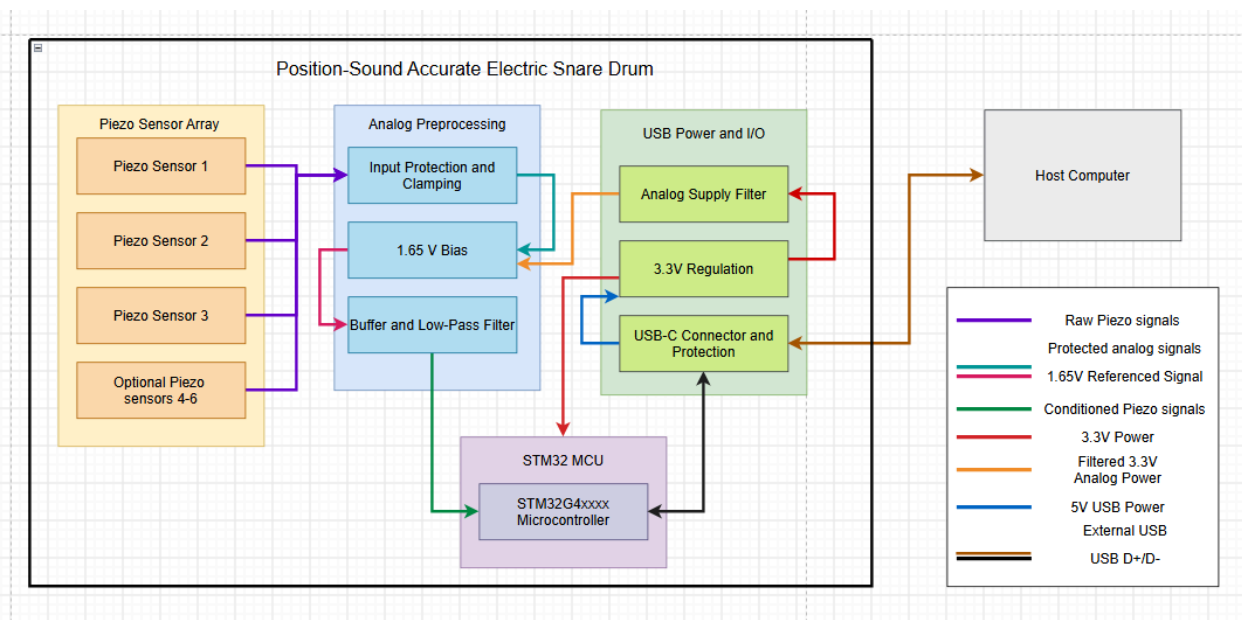


Figure 3 System Overview

2.2 Subsystem Overview

2.2.1 Piezo Array

The piezo sensor array detects mechanical waves produced by strikes on the mesh drum head and provides the signals used to estimate strike position. The array will contain at least three piezoelectric sensors mounted at equal radial distances from the center of the drum and distributed evenly around its circumference. Additional sensors may be added if testing shows that additional measurements improve accuracy or rejection of reflected waves. Each sensor will provide an independent bipolar analog signal to a corresponding channel of the analog preprocessing subsystem. The known sensor locations and relative arrival times support system-level requirements of distinguishing at least ten radial strike zones. Possible sensor position implementations are shown below.

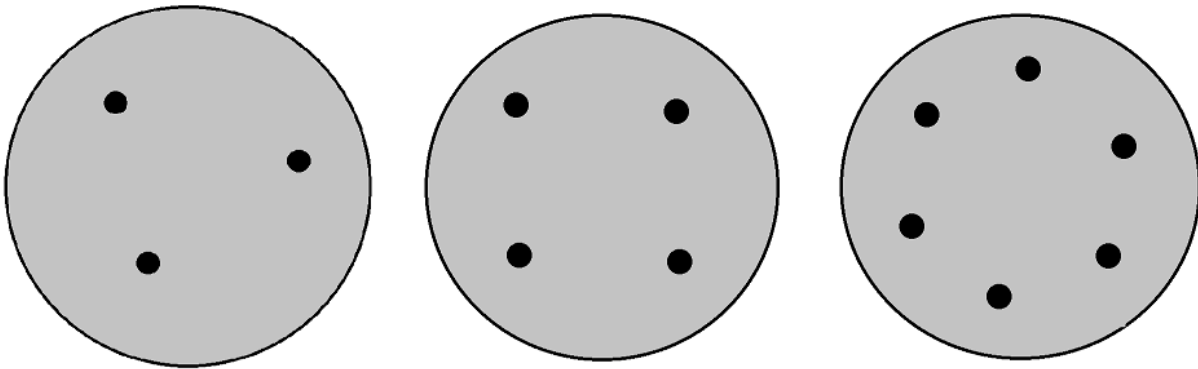


Figure 4: Possible Sensor Arrangements

2.2.2 Analog Preprocessing

The analog preprocessing unit will convert the bipolar outputs of the piezoelectric sensors into signals that can safely be measured by the STM32 ADC. It will contain at least 3 matched analog channels with one channel assigned to each installed sensor. Each channel will include input protection, a 1.65 V bias reference, an op amp buffer, and low pass filtering. The subsystem will receive filtered 3.3 V power from the power subsystem and provide the MCU with conditioned analog signals limited to its 0 - 3.3V input range. By preserving the relative timing and amplitude of the sensor signals while protecting the MCU, this subsystem supports the strike-position and latency requirements.

2.2.3 STM32 MCU

The STM32 MCU subsystem will acquire the conditioned piezo signals, estimate the strike location, and transmit the corresponding USB-MIDI output to the host computer. An STM32G4 - family microcontroller was selected because it provides multiple high-speed ADCs, sufficient processing capability, memory, and native USB support. The MCU will receive the analog signals from the preprocessing subsystem, compare their relative arrival times and amplitudes, and classify the strike into one of the defined radial zones. The calculated zone will then be mapped to a corresponding MIDI note. This subsystem directly supports the system-level requirements for ten-zone detection, USB-MIDI operation, and processing latency.

2.2.4 USB Power and I/O

The USB Power and I/O subsystem will receive a nominal 5 V supply through a USB-C connection and provide USB communication between the STM32 microcontroller and a host computer. A voltage regulator will convert the USB supply to a regulated 3.3 V rail shared by the MCU and analog preprocessing circuitry. Input protection, bulk capacitance, and local decoupling capacitors will be included to protect the device and maintain stable power during operation. The analog circuitry will derive its signal-bias reference from the regulated 3.3 V rail. By providing stable power and the physical USB connection, this subsystem supports reliable analog acquisition as well as the system-level USB-MIDI and latency requirements.

2.3 Subsystem Requirements

2.3.1 Piezo Array

Mounting of Piezos will be accomplished by 3D printing guide rails attached with 90 degree printed brackets and secured by existing bolts that hold the drum's tuning lugs. The array shall contain a minimum of three independently connected sensors, with support for additional sensors. The sensors shall be distributed evenly around the drum and mounted at the same nominal radial distance from its center. After mounting, the location of each sensor will be measured and recorded for use by the MCU's TDOA algorithm. The mounts must prevent sensor movement during normal drum strikes so that the calibration remains valid. Each installed sensor shall provide an independent bipolar analog output to the analog preprocessing subsystem. These requirements allow the array to provide the spatially separated measurements needed to distinguish between the system's ten radial strike zones.

2.3.2 Analog Preprocessing

The analog preprocessing subsystem shall provide one matched signal-conditioning channel for each of the installed piezoelectric sensors. Because piezoelectrics have a high source impedance, each channel shall use an op-amp buffer with sufficiently high input impedance to prevent excessive loading of the sensor. The bipolar piezo signals shall be referenced to a nominal 1.65V bias and limited to the STM32 ADC input range of 0 - 3.3 V. Each channel shall use the same circuit topology and component values so that the channel to channel differences do not introduce inconsistent timing thresholds. An RC low-pass filter with preliminary cutoff frequency of approximately 34 kHz shall reduce high-frequency noise and aliasing while retaining the transient information needed for arrival-time estimation. The subsystem shall accept filtered 3.3V power and provide independent analog outputs to the MCU. These requirements allow the MCU to compare the sensor signals using a common voltage and timing reference for distinguishing the drum's radial strike zones.

2.3.3 STM32 MCU

The MCU subsystem shall accept the conditioned analog inputs within the 0 - 3.3 V range and sample each active channel at a minimum rate of 100 KS/s using a common hardware-controlled timing reference. The sampled signals shall be used to determine their relative arrival times and estimate the strike location. The propagation speed used by the algorithm will be calibrated by striking known locations and comparing the measured timing between sensors, while the measured sensor coordinates will be stored for use in the position calculation. The MCU shall classify detected strikes into at least ten

radial zones and assign each zone a distinct MIDI note. It shall communicate with the host computer through a USB 2.0 Full-Speed interface and complete signal acquisition, position estimation, and MIDI transmission within the system's latency requirement. The PCB shall also provide SWD programming connections and accessible test points for debugging the ADC inputs and USB interface. A general explanation and sample implementation of TDOA localization is provided by MathWorks [1].

2.3.4 USB Power and I/O

The USB Power and I/O subsystem shall accept an input voltage from 4.75 V to 5.25 V through the USB-C connection without requiring USB Power Delivery. It shall provide a regulated 3.3 V ± 150 mV output while continuously supplying up to 300 mA to the MCU and analog preprocessing circuitry. During normal operation, the complete device shall draw no more than 500 mA from the USB host. These requirements will be verified by measuring the input voltage, output voltage, and supply current while the complete system operates under its maximum expected load.

The subsystem interfaces consist of nominal 5 V USB input power, regulated 3.3 V outputs to the MCU and analog subsystems, and a USB 2.0 Full-Speed differential data connection between the USB-C receptacle and STM32G4. The interface shall support the USB Full-Speed rate of 12 Mbit/s.

The subsystem shall include the required USB-C configuration resistors, transient and ESD protection for the USB power and data lines, and bulk and local decoupling capacitors. A ferrite bead and additional local capacitance shall reduce noise coupled from the digital circuitry into the analog supply while maintaining a common ground reference across the system.

2.4 Tolerance Analysis

The largest source of uncertainty in this project is the accuracy of the location-solving algorithm. This uncertainty results from variation in the propagation speed of the mesh, reliable threshold and peak detection from each piezo channel, and latency introduced by the solving algorithm. To address these issues, a few alternative options should be considered, in the case that one of these areas causes problems.

A 13-inch drum has a radius of approximately 16.5 cm, resulting in a radial zone width of approximately 1.65 cm when divided into 10 equal zones. The wave is estimated to travel the 16.5 cm radius in approximately 1-3 ms. Using the fastest estimated case gives a maximum propagation speed of $v = 0.165 \text{ m} / 0.001 \text{ s} = 165 \text{ m/s}$. At this speed a 1 cm change in propagation distance corresponds to approximately 60.6 μs . At the proposed sampling rate of 100 kS/s per channel, samples are separated by 10 μs , providing approximately six samples for each centimeter of propagation-distance change. A one-sample timing uncertainty corresponds to approximately 1.65 mm, which is substantially smaller than the 16.5 mm width of one radial zone. Therefore, the proposed sampling rate provides sufficient theoretical timing resolution for ten-zone classification.

Rather than calculate a fixed wavespeed and apply it to all calculations, it may be additionally advantageous to calculate propagation speed on a per sensor basis for every strike (between sensor

pairs). Alternatively, a heuristic approach may be taken, where a table of known strike positions is built while recording the time differences between each pair of sensors.

Instead of solving the TDOA equation: $\Delta t_i = \frac{d_i - d_1}{v}$

A table of measured time differences could be recorded, with a vector T representing the time differences between each sensor.

$$T = [\Delta t_2, \Delta t_3, \Delta t_4, \Delta t_5, \Delta t_6]$$

(In the case of a six sensor arrangement, five time values are recorded as the first sensor triggers the start of recording)

Then, an interpolation function would make a guess of the location based on the recorded values for each hit.

$$(x, y) = f(T)$$

This approach would allow wavespeed to be ignored completely.

If peak detection issues arise, one approach would be to use a high sensor count arrangement in which extra data points are available. This would allow for peer confirmation and the rejection of outliers. Cross correlation is also a possibility, though it brings a large computational burden that would increase latency.

3 Ethics, safety and societal impact

The development of a PCB and sensor array for an electric drum requires consideration of ethical, safety, and societal responsibilities following the IEEE Code of Ethics. In accordance with the obligation to prioritize public safety and communicate technical claims honestly, the team will test the completed PCB for short circuits, overheating, exposed conductors, and component failures before normal use. The device operates from a low-voltage USB supply, and its electrical circuitry will be enclosed to prevent accidental contact or damage during drum strikes. Input protection, current limiting, and mechanical strain relief will reduce risks caused by electrical transient or damaged cables. Testing involving audible output will be performed at controlled volume levels to reduce the risk of hearing damage.

The design will follow the applicable USB Type-C, USB 2.0, and USB MIDI interface specifications. Because the device contains digital circuitry and could act as an unintentional radiator, electromagnetic interference will be considered through PCB layout, decoupling and testing. The team will accurately report the measured positioning accuracy, latency, and limitations of the prototype rather than presenting unverified performance claims.

The project may provide a lower-cost and more configurable alternative to commercial electronic drum systems, benefiting students, amateur musicians, educators, and independent music producers. Configurable MIDI mapping allows the device to support different musical styles and uses without tying the user to a single manufacturer's software ecosystem. To reduce environmental impact, the design will favor durable mounting components, replaceable sensors and cables, and commonly available electronic parts. Remaining limitations, including compatibility requirements and the need for access to a host computer, will be disclosed so that the project's societal and economic benefits are not overstated.

4 References

- [1] MathWorks. (n.d.). *Object tracking using time difference of arrival (TDOA)*. MATLAB & Simulink. <https://www.mathworks.com/help/fusion/ug/object-tracking-using-time-difference-of-arrival.html> [Accessed: Sep. 18, 2026].
- [2] STMicroelectronics. (n.d.). *STM32G4 series—Documentation*. STMicroelectronics. <https://www.st.com/en/microcontrollers-microprocessors/stm32g4-series/documentation.html> [Accessed: Sep. 18, 2026].
- [3] IEEE, "IEEE Code of Ethics." [Online]. Available: <https://www.ieee.org/about/corporate/governance/p7-8.html>. [Accessed: Sep. 18, 2026].
- [4] USB Implementers Forum, "USB Type-C cable and connector specification, Release 2.4." [Online]. Available: <https://www.usb.org/document-library/usb-type-cr-cable-and-connector-specification-release-24>. [Accessed: Sep. 18, 2026].
- [5] USB Implementers Forum, "Universal Serial Bus device class definition for MIDI devices, Release 1.0," Nov. 1999. [Online]. Available: <https://www.usb.org/sites/default/files/midi10.pdf>. [Accessed: Sep. 18, 2026].
- [6] USB Implementers Forum, "Universal Serial Bus specification, Revision 2.0," Apr. 2000. [Online]. Available: <https://www.usb.org/document-library/usb-20-specification>. [Accessed: Sep. 18, 2026].