Generating a Dynamic Acoustic Levitation Display to Create a Tool for Musicians 2022

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Acoustic levitation is an emerging field in which small objects are levitated through the use of sound waves. Using previously developed procedures a phased array acoustic levitator was constructed to levitate and provide real-time three-dimensional movement to small, low density objects. The array was designed as a visual display that can provide information to musicians based on their input. Objects within the field are dynamically manipulated using a MIDI controller. MIDI is a standard of the music industry and is ideal for demonstrating how musical inputs can be used to move an object. Connection between the controller and levitator is performed using a digital audio workstation and an microcontroller that interprets the MIDI signal from the workstation to send phase commands to the levitator. The project is designed to be a useful tool to aid in a musicians live performance. This report details the design, development, verification and validation. Additionally it notes limitations of the system and proposes improvements and extensions.

I. Introduction

Acoustic levitation is a developing field of research in which mechanical sound waves cause the levitation of small low density objects. The first experimental observation involving the trapping of small particles at pressure nodes due to standing waves developed in 1866 by August Kundt [1]. Typical setups are static with arrays of transducers orientated to maximise the strength of the field. Acoustic levitation relies on acoustic radiation forces to suspend objects in mid-air and thus counteract gravitational forces [1]. Sound waves carry momentum that traps small objects using radial forces in locations referred to as focal points or traps [2].

Recent advancements, particularly by Upna Lab [3] but also by other research groups [2] [1], have lowered the cost of producing these levitation systems by employing setups using 3D printing and relatively cheap components [2]. This has spawned various DIY levitation kits available for private use and has reignited the conversation about how acoustic levitation can be used in practical cases. Although the discovery of acoustic levitation has existed for the past century it is only in the last several years that major strides had been made in the field [4]. Acoustic levitation has gone from trapping particles in the air to suspending and manipulating objects. Features such as three-dimensional movement and translation have demonstrated the potential for acoustic levitation to be ideal in contactless small object movement and combining [1]. For example, in biomedical engineering, contactless manipulation of liquids in a phased array could allow the efficient mixing of various chemicals without the risk of contamination [5]. Other key areas that would benefit from acoustic levitation are nano assembly, levitation of biological samples, study of fluid dynamics, various chemical applications, and in this case the music industry [5] [6] [7] [8].

The music industry, or more specifically the electronic music industry, is one area that has not been actively considered by leading researchers in acoustic levitation. Digital displays have already been developed to provide visual indication of a musicians performance, this project fits into the same category as it also will utilise the Musical Instrument Digital Interface (MIDI) to produce a display to entertain audiences and inform the musician [9][10]. MIDI is the standardised communication protocol and to this day is the global standard for electronic musical instruments or controllers [11]. While MIDI was primarily designed for audio applications, the communication protocol has also been used to control lighting effects, automation,

*MR, School of Engineering and Information Technology, ZEIT4501 and robots [12]. This is because MIDI is a communication protocol of bytes that's development is entirely open source and designed to be simple so it could be employed across the industry. Additionally, libraries for receiving and sending MIDI are available in Arduino to interface with hardware controllers, typically containing buttons knobs, and sliders [13]. This makes MIDI control ideal to create a display for musicians.

I.A. Aim

The aim of this project is to combine a dynamic acoustic levitation system with the control offered by a MIDI controller. The acoustic levitation system will be a useful tool for musicians capable of displaying various properties to the musician in a 3D display that can both be used during live performances and in the studio. The musician tool can be used to indicate delay, reverb, equaliser, distortion, and wet/dry knob settings to the user. The aim is to demonstrate how MIDI control can be added to provide real time 3D manipulation of the objects within the field as a tool for musicians. The system must behave in real-time to inputs from the user and integrate with the MIDI standard protocol to ensure that the various electronic instruments available in the music industry can interface with the system. This control interface is also useful for other purposes. Control through buttons, sliders, and knobs rather than a screen could assist with chemical and assembly applications [6] [7] [8] using a MIDI interface and readily available MIDI hardware.

I.B. Scope

This report will primarily focus on the development of a phased array of transducers which is then communicated to and controlled via an ESP32 device. The Ardunio code generates "animations" based on MIDI inputs to the code passed through by a physical MIDI controller containing various buttons, knobs and sliders. Various physical devices produce MIDI signals that can be passed to Ableton which can interpret the message and send relevant inputs to the ESP32. Ableton is a Digital Audio Workstation (DAW) software used to produce music and is a familar tool for live electronic artists. Arduino interprets integer values received from Ableton instead of direct MIDI signals as the Ableton software is capable of interpreting and deciphering the MIDI inputs [13].This project involves the development of a phased array of transducers based on the work of Upna Lab's 256 transducer ultrasonic phased array to provide the levitation display [3]. Two of these arrays can be placed facing each other with a separation of roughly 24 cm to provide the three-dimensional movement of objects within the field. The boards were wired together with the ESP32 sending command codes to the two Field-Programmable Gate Array's (FPGA) on each array board. The ability for the phased arrays of transducers to respond to changes in the field to produce animations was closely examined and documented. A MIDI controller was routed to a computer running Ableton which directs the acoustic levitator, providing commands to the objects within the field. Once this has been established several tools to assist musicians were developed which demonstrate the capabilities of the display as a musician tool.

I.C. Acoustic Levitation Utilising Phased Arrays of Transducers

Acoustic levitation is not unique as the only form of levitation [14]. There also exists aerodynamic levitation, optical levitation, electrical levitation, radio frequency levitation, magnetic levitation and even superconducting levitation [14]. While these methods could see use as a 3D display, acoustic methods can levitate both non-magnetic and non-conducting materials [14]. The simplicity, affordability and ability to levitate a vast array of objects led to an acoustic levitation system being considered for the design.

There are several different acoustic levitation methods. These are standing wave, near-field, inverted near-field, far-field and single-beam levitation [1]. For this project only the standing wave method is considered as the other methods are either unable to levitate the object far from the surface or they are limited in practical examples [15]. In standing wave levitation, objects typically weigh a few grams [7]. These small objects are levitated at the pressure nodes of the standing wave. At the centre of the pressure node zero forces are exerted but outside of this point levitation forces apply a force radially inwards towards the trapping point [6]. This force means that the levitator can be tilted and even turned completely parallel to the horizontal plane while still levitating the object [7]. One limitation of acoustic levitation is that asymmetries in both the field and object levitated can cause uncontrolled rotation of the object [7].

A static single axis acoustic levitator can be built using two circular cones of transducers with a 3D printed frame in the TinyLev [2]. In this single-axis levitation case, standing waves are produced by a transducer that is either reflected from a surface back to the transducers or transducers are placed above sending the return signal [16]. The standing wave produces trapping points every $\lambda/2$ metres [16]. These trapping points are capable of suspending objects that are half the operating wavelength and are ideally low density. The system operates at 40 KHz, giving a roughly 8.5 mm wavelength, meaning objects suspended should not exceed the half wavelength of approximately 4 mm [2][17]. However, recent developments have demonstrated how large objects can be suspended through acoustic levitation [18].

The wavelength constraint has practical limitations as it means that to levitate large objects would require the sound wave frequency to be reduced. This would mean the transducers used to levitate the object would have to be large in dimension to generate these low frequencies. This design would be bulky, loud and have high power consumption [1]. However, it has recently been demonstrated that a polystyrene sphere measuring 50 mm in diameter at 3.6 times the operating wavelength was levitated by using a tripod arrangement of transducers [18]. Additionally near-field levitation would also allow for planar objects of up to 10 Kg in weight to levitate stably near a vibrating plate [19]. While it would be beneficial to be able to levitate objects of this size in this project it would either be static in the tripod setup or have insufficient height in the near-field setup to be viewed as three dimensional. Additionally, Metamaterials are capable of providing greater spatial resolution than a PAT setup however they also generate static fields and thus will not be considered for this project [16].

To provide the 3D movement of multiple objects within an acoustic field, phased arrays of transducers were chosen. The emission amplitude and phase of each of the 256 transducers on the array system chosen can be controlled individually by a computer allowing dynamic change of the acoustic field [3]. The individual transducers operate at 40 KHz and use time delays (phase offsets) to generate pressure fields capable of levitating small objects at various locations within the display. The Sonic Surface board designed to levitate the objects consists of an FPGA, shift registers, drives and decoupling capacitors assembled on a PCB. Signals for the transducers are generated by the FPGA. Shift registers demultiplex the 32 digital lines coming from the FPGA into eight separate channels and drivers boost the voltage of channels from the logic voltage up to the supplied power voltage to drive the individual transducers [3]. Calculations for phases are performed by an external device (ESP32 microcontroller in this case) and then sent to the FPGA using UART protocol[3].

Phased arrays of transducers require only a single array to move the object in the plane parallel to the array with a reflector plate [20]. This reflector plate can be as simple as a flat piece of wood[3]. The amplitude is varied on transducers surrounding the main focal point transducer to generate a stronger radial force in the direction desired by the operator [20]. A second array is required to generate three-dimensional movement as the vertical movement is generated by varying the phase offset to move the nodes up or down [21].

Although a phased array of transducers is the ideal system for this project there are several limitations that must be considered. Transducers operate at 40 KHz requiring a high precision to achieve standing waves. The system also functions poorly when the suspended object is too close to the transducers of either array board [17]. Additionally, the larger the array the greater the levitation space, however, as the levitation space increases linearly so too does the size, weight and cost of the system [17]. This limits its ability to be taken by a touring musician who will need to carry this large expensive equipment with them. The transducers also generate a faint audible noise during transmission which could frustrate a musician when trying to record clear audio [17]. These limitations and safety factors limit the available options for the display systems design but phased arrays of transducers are still the best method for producing a dynamic three-dimensional display.

I.D. Musician Control Aspect

From a musicians point of view the display is designed to both be a helpful tool and an interesting visual medium to a live audience. This means the display must be informative, visually exciting and be capable of handling live performances. This closely matches the work of others who have tried to generate similar displays through real-time music visualisation on a 2D display as responsive imagery [9] or the more 3D LED display that lights up when certain notes are played [10]. Both designs make full use of utilising MIDI using the MAX/MSP environment to generate real world artistic and informative displays responding to the actions of the musician [9][10]. However, again in both cases neither project considered the potential of a truly 360° display. The system would have a larger viewing angle and help with ease of use for impaired musicians. The larger viewing angle could allow multiple musicians or even a musician moving around the stage to be able to continuously view the display. Producing 3D display technology is extensively researched but levitation is not often included as a potential display form [22]. For those who are partially visually impaired or have difficulty viewing the small digital displays presented on most MIDI controllers the levitator could also assist them. Various MIDI projects exist to make impaired musicians ability to create unhindered, such as the design of a MIDI keyboard to assist those with amniotic band syndrome as well as various others [23]. It has also been shown that viewing graphs in a 3D environment is three times as effective for readability and comprehension than a 2D diagram [24]. All of these factors suggest an acoustic levitator controlled through MIDI could be highly beneficial to the music industry.

The only reasonable alternative to MIDI that would be logically considered by musicians is the interpretation of digital audio signals. Daw's utilise both MIDI and digital audio inputs in their software [13]. Having audio as the input signal interpreted by the ESP32 would also have several advantages. It has more extensive research, simplifies analysis and requires minimal interpretation within the code. However, while DAW's are capable of reading audio it is generally unwise to use them for true live capture due to latency constraints [25].For musical ensembles the performance can be naturally synchronised for delays of 8ms to 25 ms which is the time delay introduced by the separation between musicians [25]. If the delay is increased past this timing threshold then musicians struggle to synchronise with one another [25]. Under this same understanding if the phased array is sufficiently delayed compared to the musician then it can be difficult for the two to remain in sync. If audio is used the latency is likely to affect the tools effectiveness as a display.

In comparison MIDI's fixed data rate means delays between various instruments sending messages are trivial to calculate, consistent and relatively small [26]. Through testing for MIDI latency it was found that the average latency was under 10 ms for all systems tested with a maximum standard deviation of 1.3 ms [26]. This demonstrates how MIDI is consistent across multiple systems with only slight variations. This is why MIDI was selected as the primary communication protocol for the project. Its reputation in the industry as well as its low latency make it ideal for the control of the acoustic levitation system.

II. Design & Development

The first stage of development involved the construction of the phased array of transducers. The array allows for a small object, roughly 4mm in diameter, to be levitated and maneuvered within the field by changing the various phases of transducers within the array. For this project 1-3 mm polystyrene foam spherical beads were selected as the object to levitate in the acoustic field. The stand alone phased array acoustic levitator was originally designed by Upna Lab as part of their ongoing work in acoustic levitation [3]. While their use for the machine primarily focused on the array's capability to produce ultrasonic amplitude patterns, this project instead attempts to utilise the initial open source design to develop a three dimensional display.

The levitator design consists of two identical PCB boards placed parallel to one another in a housing frame separated by the space in which the objects float. Each board consists of 256 ultrasonic (40 KHz) Manorshi transducers which are aligned in a 16x16 grid on one side of the board. On the other side there are 128 drivers (MIC4127 SOIC8), 32 shift-registers (74hc595 SOIC16), 160 0.1 F decoupling capacitors and a FPGA (CoreEP4CE6, Altera Core Board)[27]. The signals for each transducer are generated within the FPGA, the shift registers demultiplex the digital lines of the FPGA's eight channels and the drivers boost the voltage of the channels based on the DC supply voltage up to 20 Vpp [27]. This results in two power ports to the acoustic levitator system. One 5 volt connection to power the FPGA's and one higher voltage DC connection which defines the peak to peak voltage for the emitters. The FPGA is capable of generating a 40 KHz square wave for each of the 256 transducers with phase delay control of 32 divisions. This translates to a offset of $\frac{\pi}{16}$ or 0.2mm for each division. The FPGA shift clock operates at 10.24 MHz (8 multiplexed channels $\times$ 40 KHz $\times$ 32 divisions) [3].

Initially both PCB's were manufactured and pre-assembled with the components as well as additional wiring pins for power and a DC barrel connector to provide the Vpp for each of the emitters. A first board was setup initially. This required uploading the code *FPGAPrimaryNoCalib.jic* into a single FPGA with an *Altera USB Blaster* using the *Quartus* environment. The initial instruction set suggests using *Quartus 13.0 sp1* which was non functional without a paid license. As such it is advised to instead use *Quartus 21.1 Prime Lite* which is a free alternative. A laser cut spacer was placed on the transducer side of the PCB board and transducers were soldered, making careful note that the transducers are polarised but not appropriately marked. The FPGA was then plugged into the header pins and 5 V was supplied. Each transducer was checked by attaching a spare transducer to an oscilloscope to ensure each transducer was emitting. After verifying that no transducers were faulty the sine wave output of each transducer was phase matched to a square reference signal produced by the FPGA. This requires going through each of the 256 transducers and increasing/decreasing the 32 division phase offset using the provided java software till the two signals are in alignment. This is done to ensure all transducers are in phase with one another and ensure that there is minimal phase offset when generating the acoustic field. The phase offsets are then uploaded to the FPGA code as the calibrated version. A single board can use a reflector plate to generate an acoustic field capable of moving the object in the parallel plane. A secondary board was developed under the same methodology to allow for control in the perpendicular axis as well as increase the trapping force. With both boards setup the two were connected in series with one board being the primary while the other was the secondary. The two boards were connected using wires and bins. A 3030 T-slot aluminum frame was then built to house the boards which sat in cutout pieces of wood. This setup can be seen in figure 1.

Figure 1. Completed Acoustic Levitator housed within 3030 series T-slot Aluminium frame utilising 50cm vertical rods×4 and 30cm horizontal rods×8

The phase calculations to produce a specific acoustic field are generated externally by a computer that communicates over a UART. By default the design suggests using an Arduino Nano alongside the premade java software [27]. This was quickly changed to an ESP32 utilising the provided *CommandSenderESP32* files which was then set to a baud rate of 115200. The initial ESP arduino code contained code to assist in calculating the phases as well as a few basic commands that could be entered into the serial port.

With the acoustic levitator constructed the rest of the system architecture could be developed. The full system overview is demonstrated in figure 2.

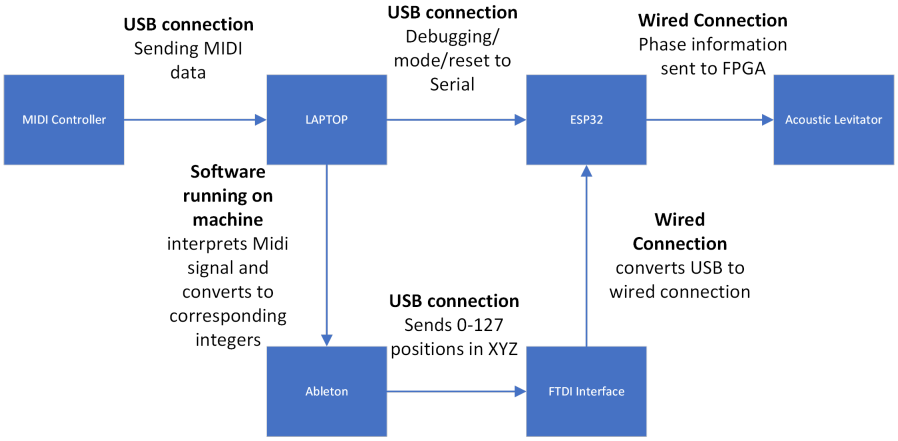

Figure 2. System Diagram Overview.

The system utilises a MIDI controller interface for the musician to control the levitator. MIDI data is sent through a USB connection to a laptop running the Ableton DAW, a musical software standard of the industry which is designed for live performance [28]. In Ableton a MIDI plugin (developed in the MAX/MSP environment) can be placed on a single track which can read the incoming MIDI signals and convert these to defined integers to send to the ESP32. In total, 6 integers are sent from Ableton to a port specified in the interface. In this design the FTDI converts the USB connection data stream to a stream suitable for one of the three available UARTs on the ESP32. This interface is used to receive commands from Ableton on GPIO5. Transmit on GPIO18 is not currently used but could be, to allow the ESP32 to control the Ableton software. The inbuilt USB connection on the ESP32 is connected to the laptop for programming the ESP32, sending commands and providing feedback via a terminal application on the laptop. The ESP32 and the levitator's 5v rail are also powered from the laptop through this interface. The third UART, on GPIO21, provides a connection to the acoustic levitator to transmit the phase information to the FPGA's. There is no communication from the levitator back to the ESP32. The ESP32 acts as the main controller, interpreting messages from two of its serial ports, performing calculations and then outputing the relevant phase information on a third. The ESP32 transmits on GPIO21 to the acoustic levitator, which has no functionality to transmit back to the ESP32. This can all be seen in the wiring diagram in the appendix.

Figure 3. Ableton MIDI plugin control panel display, contains a section to turn dials to move the object each axis, an on screen monophonic keyboard that shows what key has been pressed, a COM port selection panel and an unused receive panel.

The musician interface is shown in figure 3. For this specific project the MIDI controller was a Novation Launchkey MK2 61 key model. The control panel shown below the controller is the MIDI plugin interface shown to the musician in Ableton. The plugin contains four panels. The first panel in the top left is the 3 dial control. In this tool the dials can be mapped to any slider or knob on the MIDI controller and then can be tuned to give XYZ values for 128 values. 128 values were chosen because this is the range of a knob/slider in MIDI. The panel below this is the computers COM port selection to transmit over. The middle panel was an extension of the three dial control which is a monophonic keyboard display that presents the last played key. When a mapped dial is adjusted or a key is played a trigger is initiated which sends a sync value of 255, 3 integers corresponding to the dial values, one integer corresponding to the monophonic key and one integer for the velocity the key struck. This set of data is sent to the ESP32 any time any of these values are adjusted. The ESP32 will then perform animations based on these inputs using the most recently provided data.

Typical Data input to ESP32: 255 4 64 128 60 0

The ESP32 takes these numbers as the sync byte, X position dial byte, Y position dial byte, Z position dial byte, Note played byte, and note velocity byte. The ESP32 uses them to generate the following musician tools:-

1. *Three-dimensional dial control tool.* This tool allows the musician to map the XYZ positions in the levitator to three dials or sliders on the keyboard. The 128 positions on each axis gives a total of 2097152 possible object positions in the levitator. The dials can also be mapped to tools such as a low pass filter, an lfo, a delay, a reverb, a wet/dry knob etc. so that the levitator can be informational.
2. *The monophonic single axis keyboard tool.* This tool separates the 128 keys to 128 positions along the X axis.
3. *Metronome tool.* Using the command "bpm=" followed by the tempo sets a rate for the object to oscillate at.

These three tools became the basis of the display design. All three tools work by adjusting the focal point to a new location. To avoid the levitated object being moved faster than the array can achieve, the object is moved in steps at the maximum possible velocity to the specified location. If the object fails to reach the specified location prior to receiving a new target the target is abandoned in favour of the newer target.

III. Verification & Validation

There are three key parameters in controlling the levitator display. These being:-

1. The step size of the object per frame.
2. The time between animation frames.
3. The working range of each axis.

The step size and frame time relate to the velocity of the object within the display, the higher the velocity, the better. The working range is the maximum and minimum achievable in each axis which defines the space to operate within. Having too small a range means that neighbouring keys or dial positions will be difficult to distinguish as the system divides based on $\frac{working\ range}{128}$.

The first quantity examined was the time per animation frame. using Arduino's inbuilt *micros()* function it was found that the buffer to calculate and update the phases for a given focal point and send to the array averaged 23$\pm$0.008 ms. This was over more than 100 trials. This means there is a hard limit of 23 ms for the time between newly generated focal points. The frame time was further increased to 25 ms to allow the system to have enough time to compute the next frame, receive commands etc. This is at the edge of the 8ms to 25 ms natural synchronisation for musicians to play together [25]. The frame time is set as a constant, so to maximise the velocity of the object the step size should also be maximised.

The limit on the step size is the the stability of the object. To determine the maximum step size the object was moved in a square spiral in the XZ plane. Invoking the command "test" will cause the object to move towards the center of the array in X and Z at (0,0) before moving in both axes to create a spiral pattern until the object reaches the allowed maximums and minimums within the field. After the system has completed the spiral, the focal point is moved back to the center of the array, increased/decreased in the vertical Y axis and the procedure is done again. The object was determined to be stable if it could complete at least three full cycles for the ranges specified in XYZ for the given step size. The results of the test can be seen in table 1.

	X-Axis	**Y-Axis**	**Z-Axis**
Minimum	-6.5 cm	7 mm	-6.5 cm
Maximum	6.5 cm	18.6 cm	6.5 cm
Step Size	1 mm	0.25 mm	1 mm

Table 1. This table shows the minimum and maximum positions achievable for a given step size in each axis. The Y-Axis is notably different as it is the vertical axis perpendicular to the two array boards. The center of the array is located at (0, 12.15 cm, 0) and is the point of maximum trapping force. At a 1mm step size in X and Z the test pattern will run forever.

There is a trade off between maximising the ranges and maximising the step size with the theoretical step sizes shown in figure 4.

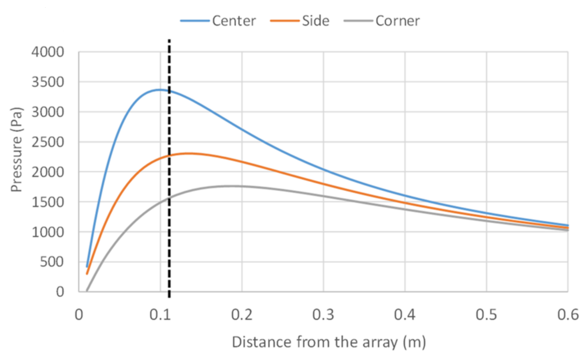

Figure 4. Effect on pressure as the object moves further from the array[29].

The stable region for the two horizontal axes was determined to be ±6.5 cm, however, this can be extended further when centred vertically, to approximately ±7.5 cm. If only utilising a single axis (through the center of the array) the trapping force is strong enough to go slightly beyond the dimensions of the array and have the ball floating with no transducer above or below it. Therefore, the stable region is not a cube but a cube was used for the musicians display as it is convenient to interpret. With a cube, the corners of the array are theoretically the limiting factor on the stable range according to figure 4 but in practice objects were observed, when moved too fast, to drop elsewhere. Prior to the object dropping from the field it generally behaves unstably, so increasing instability is an indication that the step size limit is being approached.Various step sizes were tested and instability was seen in a slightly larger step size of 1.25 mm. It can be observed when moving through the allowable region that the object is more stable in some regions than others, suggesting the phase offsets are more accurate in some regions than others. A step size of 1.25 mm would be fine over most of the region but the display can not fail mid performance.

The X and Z axes with a step size of 1 mm translates to a velocity of 40 mm/s. This speed is effectively instant when moving between neighbouring keys on a keyboard but starts to become noticeable when the object is forced to move across a large portion of the possible range. The slow speed means a fast performance, particularly one that makes use of alternate low and high values for the keys/dials generates a display that is observably trailing behind the musician.

While the X and Z axes behave similarly the Y axis has different results. The center position in the Y axis is 12.15 cm which means the stable range is not equal on both sides of the array center. The object was able to go down to as low as 7 mm from the bottom array while only being able to achieve 18.6 as a maximum from the bottom array. The range was found to be highly variable. At times the object could complete multiple full cycles within this range, at other times the object fell out before it got even close to 7 mm. To ensure consistent stability the Y axis limits were set to ±6.5 cm above or below the 12.15 cm position to ensure reliability and to be consistent with the other two axes. The Y axis is the most limiting axis requiring the step size to be 0.25 mm to ensure the object did not fall out of the field. This gives a velocity of 10 mm/s which means the Y axis trails the musician more that the X and Z axes and for this reason most movements are made in the XZ plane.

A calibration process is undertaken to synchronise the 256 transducers by measuring the phase with a microphone at the surface of each transducer and adjusting an offset until they match the reference signal. There are 32 possible offsets equating to a resolution of 0.2 mm. The calibration process was conducted twice a few weeks apart and the differences between calibrations can be seen in figure 5.

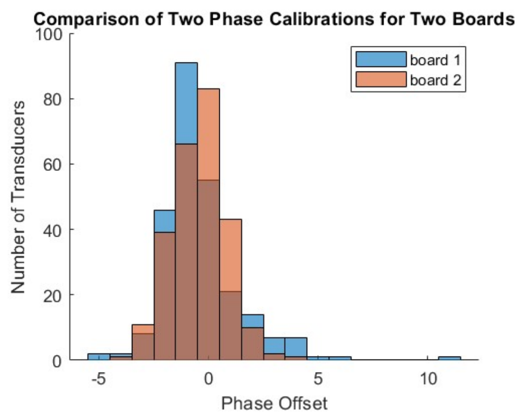

Figure 5. Phase offset for the two phase calibration trials conducted on both boards.

Figure 5 shows phase offset differences follow an approximate normal distribution with standard deviations of ±0.03586 mm and ± 0.2531 mm for each board respectively. This phase error is at the surface of the transducers and is much higher than the manufacturing tolerances of the array. The difference between specified and actual heights are likely to be as high as 2mm due to the uncertainty associated with the height of the piezo diaphragm within the transducer body.

The trapping force limits the velocities and reduces the stable range so increasing the trapping force improves functionality. The current stable range means that the 128 digital positions translates to a separation for neighbouring points of approximately 1 mm. From the musicians perspective, this makes it difficult to distinguish neighbouring points. This and the lag when moving long distances reduces the quality of the information provided as a display. While this project may not be an ideal tool for musicians, it can still be effective as a non technical controller for industries that don't demand such high velocities. The system could be extended as a control in chemical and assembly applications [6][7][8].

III.A. Increasing the Velocity

Methods of increasing velocity include:-

1. Reduce reflections.
2. Increase the supply voltage.
3. Improve the calibration.
4. Make acceleration constant rather than velocity.

The main source of reflections according to Asier [30] is the surface of the opposing board and that adding "felt or other padding material to the frame and does not seem to affect it that much". The supply voltage used was 9 volts as recommended in the Instructable [27], The transducers can be driven up to 40V and the (MIC4127 SOIC8) drivers to 20 V [31]. 18V was briefly tested and greater object vibration was observed.

Asier [30] advises "18 Volts is a bit too much". Asier has been using 12V for a long time and advises against voltages higher than this for extended periods of time without cooling. Improving the calibration is likely to increase the trapping force and to make it more consistent over the region. The optimal height for object location is 11 cm [29]. Choosing a variable step size to keep object acceleration constant would allow higher velocities but is likely to cause instability without improved calibration.

IV. Conclusion

Overall, the project met its requirements by building a dynamic acoustic levitator display with a field that can be controlled and manipulated using a MIDI controller. Tools were developed that allow the user to manipulate the field in three dimensions by mapping dials and keys with the Ableton DAW. However, the focal point is only moved at 40 mm/s over a stable range of ± 6.5 cm in each axis which limits the system as a musical display. This limitation is dependent on the trapping force which could be improved to create a lower latency display. The project still provides a good baseline for how an acoustic levitator could be used as a musician's tool and can be integrated into other industries that do not require such high velocities.

V. Recommendations for Future Work

The musician tools developed could be expanded upon to provide additional functionality and to find ways to display the MIDI information in a better way. Perhaps through the use of polyphonic control and multiple focal points.

Calibrating the transducer offsets to include the build errors would be an improvement. The method could be:-

1. Use a transducer in each corner of the board as a microphone or use an ultrasonic receiver (MA40S4S, Murata) in each corner of the board.
2. Use a comparator to detect zero crossing of these 4 signals to change the state of a digital signal. Do the same with the reference wave.
3. Connect the comparator outputs to 5 digital input pins on the ESP32.
4. Measure phase offset by generating an interrupt from the reference signal that starts a microsecond timer on the ESP32 and generate further interrupts on each of the signals associated with the four corner microphones to read the timer.
5. In an automated software controlled process in the ESP32, turn on one transducer at a time and measure the phase at the ultrasonic receiver on each corner of the opposing board.
6. Calculate the optimum location data and phase offsets for each transducer and use these. Asier[30] advised they are considering "implementing the Navigator Equations to get exact positioning".

Adding felt beneath the transducers should reduce reflections from the base boards and adding cooling to the drivers [31] would allow the drivers to be driven at up to 20V continuously. Modifications that could be made to the board design include relocating the high voltage pin for a large physical separation from the low voltage pins to reduce the risk of connecting the low and high voltage circuits, extending two sides of the board so that there is enough space between the speakers and the board edge to support the board on the frame and providing a socket so that the ESP32 boards can plug directly into the base board as is done with the FPGA.

Additionally adding another two boards would improve the trapping force significantly and remove the instability in the vertical Y axis, however, this would reduce the field of view of the display. Additionally developing a method to position the boards in each axis with less than a millimeter precision would further increase the acoustic trapping force.

VI. Acknowledgements

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VII. Appendix

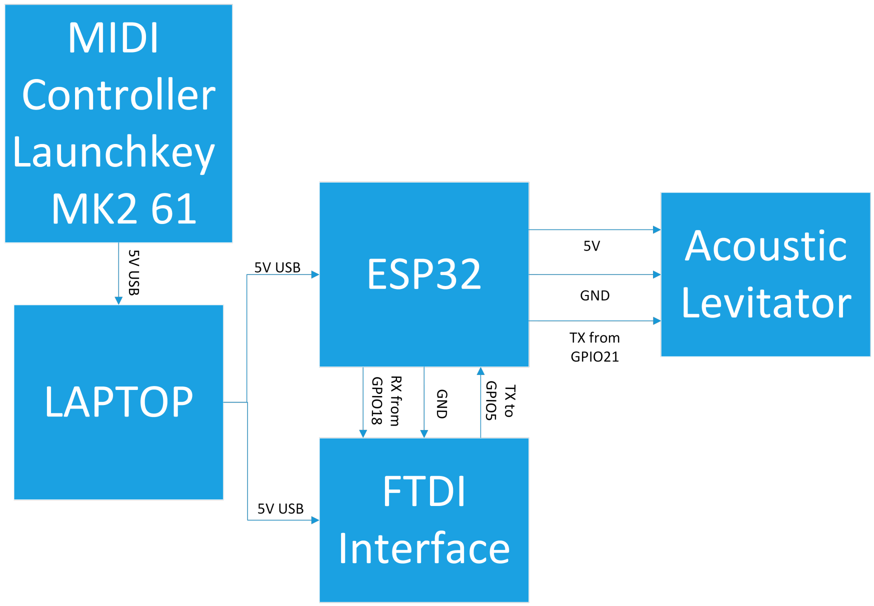

Figure 6. System Wiring Diagram

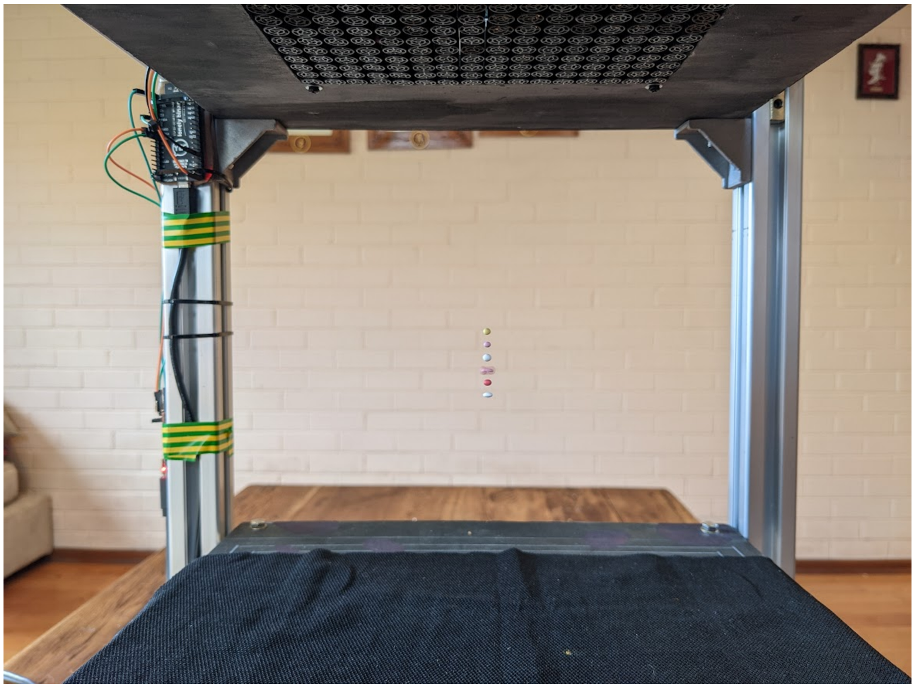

Figure 7. Levitator floating several objects at the side lobes of the acoustic field

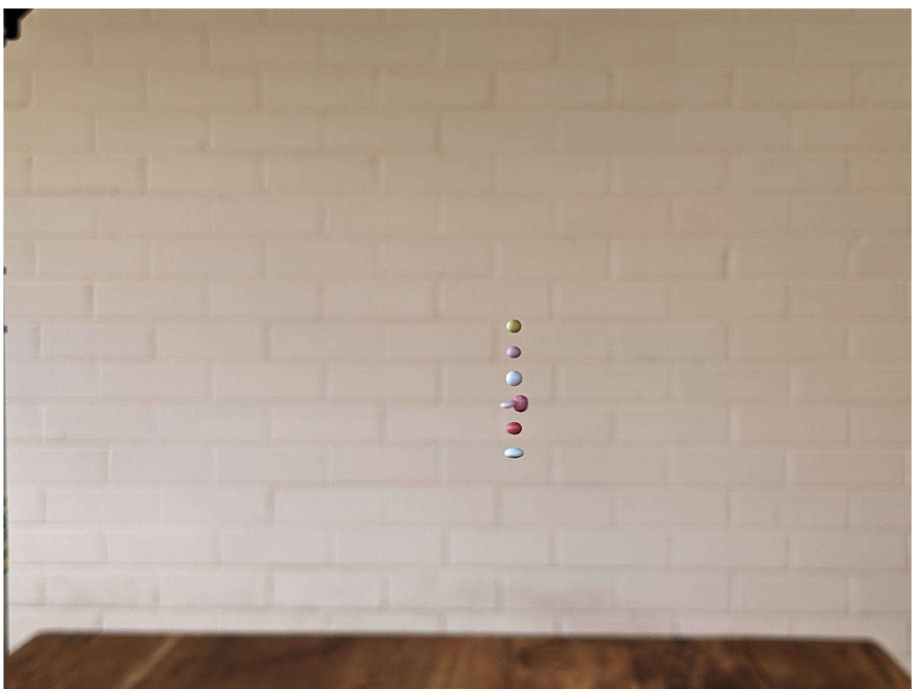

Figure 8. Close up view of the levitator floating several objects at the side lobes of the acoustic field for a single focal point

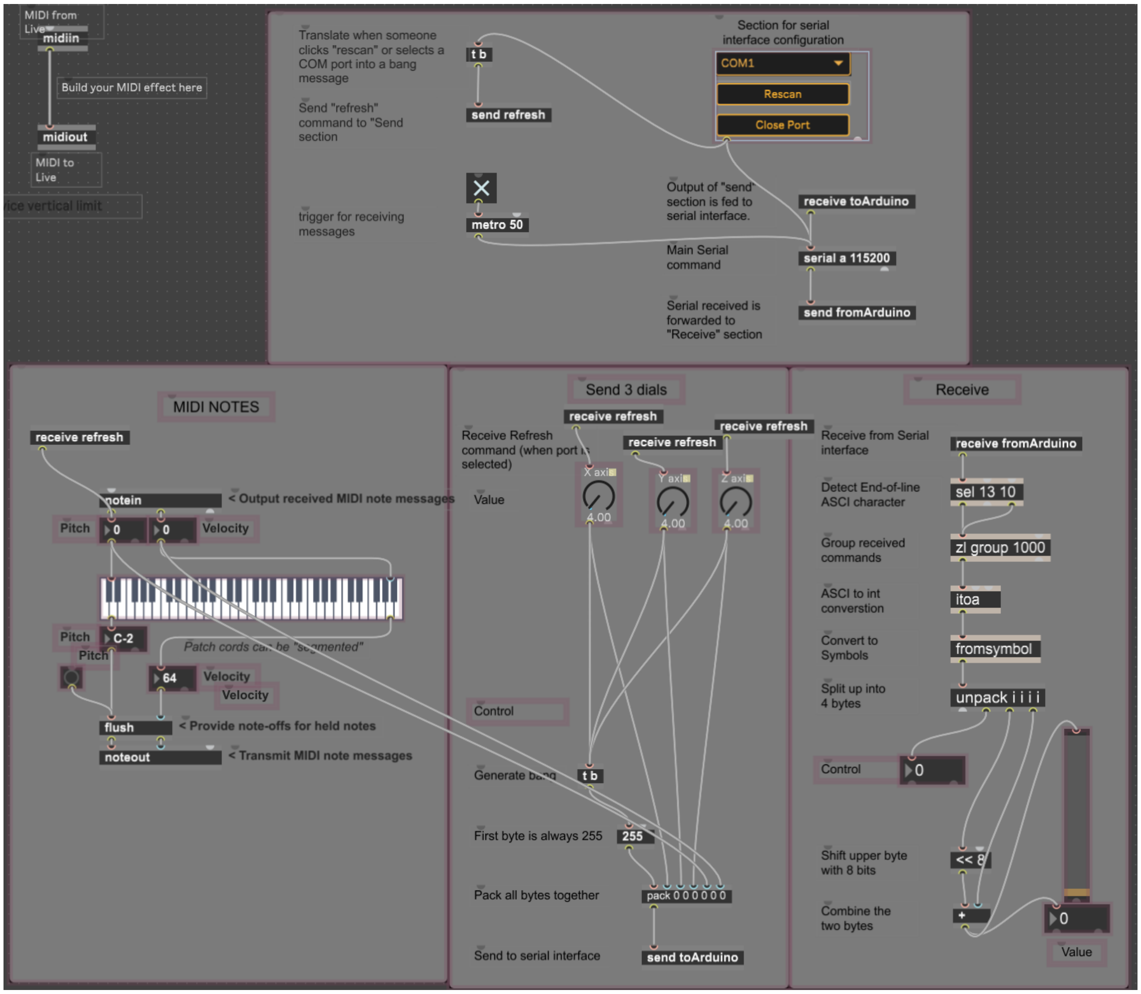

Figure 9. MAX for Live plugin showing the flow block code for how Ableton sends the MIDI information through the FTDI serial connection