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Research and development of an ultrasound-based prosthetic interface

TDK

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1. Abstract

This research focuses on developing an ultrasound-based interface for prosthetic limbs to enhance their control and functionality. Traditional methods such as Electromyography (EMG) and Inertial Measurement Units (IMU) often struggle to capture the fine muscle movements needed for precise prosthetic control. This study explores the use of A-Mode ultrasound to overcome these limitations by providing a more detailed and reliable capture of muscle contractions in the forearm using morphological information.

The project, conducted within the Robotics Laboratory's prosthetic and exoskeletal research, begins with a literature review of existing ultrasound-based human-machine interfaces. The goal is to design a robust hardware-software system based on best practices and to perform experimental measurements.

The initial step involves understanding the biological basis of the forearm to determine the measurement targets. Following this, the process for receiving and processing A-mode ultrasound signals is researched in depth. Specific integrated circuits (ICs) are then selected for each function (wave generation, voltage level shifter, high voltage isolation, signal processing and quantization). After selecting the individual components, tests are conducted for fine-tuning parameters and adding necessary passive elements such as capacitors and resistors. In some cases there is also a need for the development of firmware drivers for some ICs. The final step will be the designing and assembling of a working printed circuit board.

2. Biological basis of the upper limb

Understanding the biological foundation of the forearm is crucial to this research. This chapter begins with an overview of the upper limb muscles, with a particular emphasis on the forearm muscles, which are essential for finger and hand movements. By comprehensively understanding these biological components, we can identify what measurements are necessary and how to capture them effectively.

The upper limb muscles can be grouped in four categories depending on where in the limb they are found[1].

- Shoulder muscles
- Arm muscles
- Forearm muscles
- Hand muscles

The forearm muscles are the point of interest for this project, as some of them are responsible for finger (flexion and extension) and hand (flexion and extension and abduction and adduction) movement. Figure 1 illustrate some of these movements. The forearm muscles can be further classified based on their depth and anatomical region:

- Superficial anterior region
- Superficial posterior region
- Deep anterior region
- Deep posterior region

For most of the cases, the superficial muscles are involved in the wrist movement and the deep muscles are responsible for the individual finger movements.

The primary function of the anterior muscles in hand movement is the flexion of the fingers and hand. The key muscles and their respective functions are:

- Flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP) are the responsible muscles for the flexion of the digits.
- The flexor pollicis longus (FPL) is responsible for the flexion of the thumb.
- Flexor carpi radialis (FCR) and the flexor carpi ulnaris (FCU) for the flexion of the hand and aiding in the abduction and adduction of the hand.

The posterior muscles are mainly responsible for the extension of the fingers and hand. And the key muscles are:

- The extensor digiti minimi (EDM), extensor digitorum communis (EDC) and extensor indicis proprius (EIP), responsible for the extension of the digits.
- The abductor pollicis longus (APL), extensor pollicis brevis (EPB) and extensor pollicis longus (EPL) muscle are responsible for the abduction and extension of the thumb.
- The extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB) and extensor carpi ulnaris (ECU) are responsible for the extension of the wrist and assists in the abduction and adduction of the wrist.

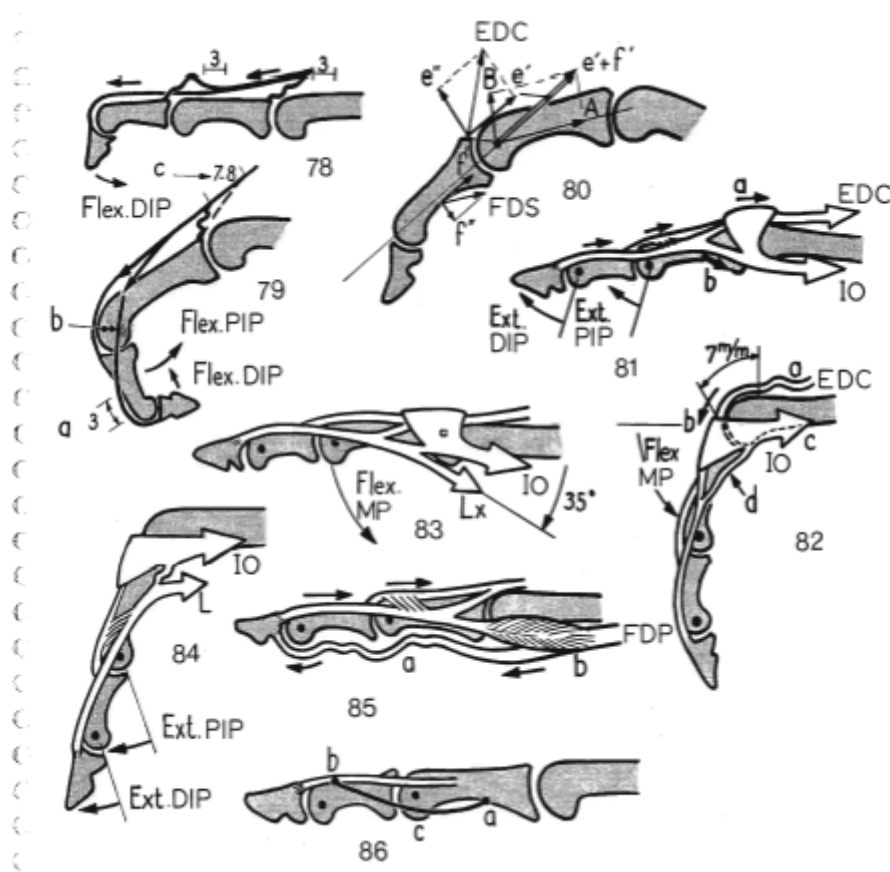


Figure 1: Examples of how the action of the extensor digitorum communis can impact the finger position[2]

3. Usual measurement methods for Prothesis control

3.1 EMG

Currently most prosthetic interfaces utilize surface electromyography (sEMG) as a control signal for the prosthesis [3]. The use of sEMG peaked the interest of researchers due to the fact that it can give a general understanding of the movement of the limb and can be easily and quickly processed. While this method is a really good solution for studying crude movements of the arm and hand, it lacks the refinement for adequately show the control of dexterous finger movements [4]. The reason for this is on the nature of the signal itself: sEMG is the superposition of multiple motor unit action potentials (MUAP) in a given area close to the skin. This superposition makes discerning the contribution of single muscles a difficult process. Furthermore, due to crosstalk and signal attenuation, the potential generated by deeper muscles, such as the ones responsible for some finger movement, cannot be properly measured or easily processed[5].

Increasing the number of sEMG channels (Figure 2 shows some examples of multi channel electrodes) can provide a better resolution to some degree, but even devices with more channels will not provide a robust solution for finger movement tracking. Another way to improve readings is by using intramuscular electrodes. These types of electrodes can provide better readings of the deep muscles, as they sit closer to the source of the signal. But as this practice is an invasive one and could generate pain and discomfort for the patient [6] it is not widely applied as a solution.

To translate EMG data into prosthetic limb commands some steps are necessary to ensure a proper actuation of the limb. After recording the signal usually the first step is filtering to reduce noise and motion artifacts[8]. For this step usually a band-pass filter with the range of 10-500 Hz and a notch filter at 50 or 60 Hz is used to remove the artifacts caused by the power lines[9]. Sometimes, after filtering, rectification and smoothing is used for extracting the overall shape of the signal. The next step is signal segmentation. As the measurements usually contain different poses, it is important to separate the signal into smaller parts related to each pose specifically. The last part before the prediction or classification algorithm is the feature extraction. Statistical data is calculated from the segmented signals to be used as input features for the underlying algorithm. These features can be: power spectrum density, mean absolute value, median frequency, waveform length, slope sign change[10] and kurtosis[11].

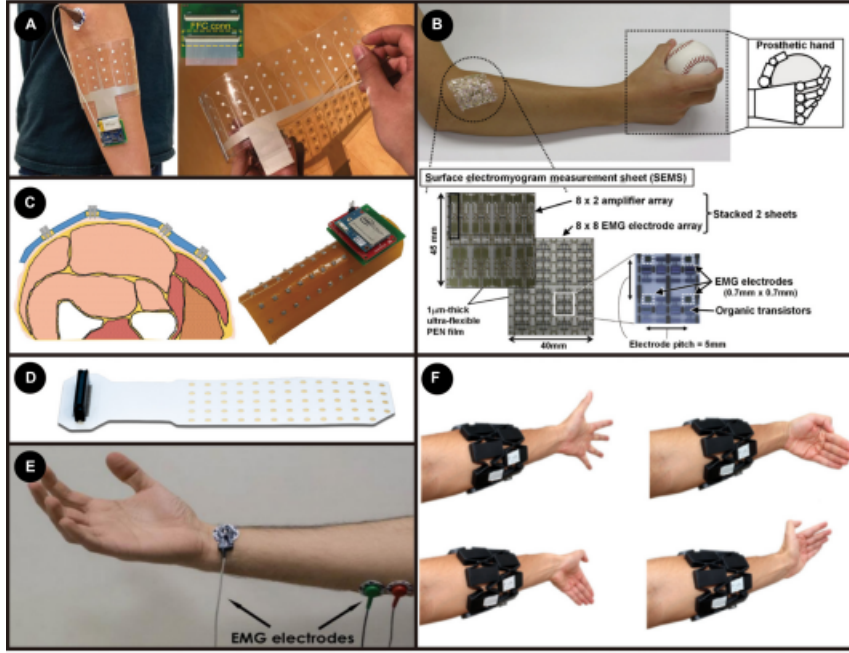


Figure 2: Examples of different sEMG arrays such as ultra-flexible high-density, Microneedle-Based High-Density Electrode Array and Bipolar electrode recording[7]

3.2 B-Mode Ultrasound

An accurate and non-invasive method for capturing muscle contraction information is B-mode ultrasound (US)[12]. This technique allows for real-time visualization of multiple muscle contractions in a cross-section of the limb. The resulting data can be used for prosthesis control using image processing algorithms to control the prosthesis. However, a significant drawback of this system is the processing time required to handle the ultrasound image data, which is considerably longer than processing a simple sEMG signal. Additionally, the equipment necessary for these measurements is typically larger than the standard electrodes used for EMG[13]. On Figure 3 there is an example of such an equipment.

Two common ways of processing B-mode US images are: comparing a sequence of images or extracting features from a single image [15]. When using the first method, there is an initial baseline image and a group of following images. From each of the following images the baseline is subtracted and the pixel-wise difference is aggregated over a time window to generate an activity pattern. This new simplified image is then used for the feature for the prediction algorithm[16][17]. When dealing with single images for the features, it is a common technique to identify a region of interest (ROI) in the image. This ROI is selected based on where finger-related movement may be spotted in the image[18]. These ROIs are then used for the feature selection part of the prediction algorithm.

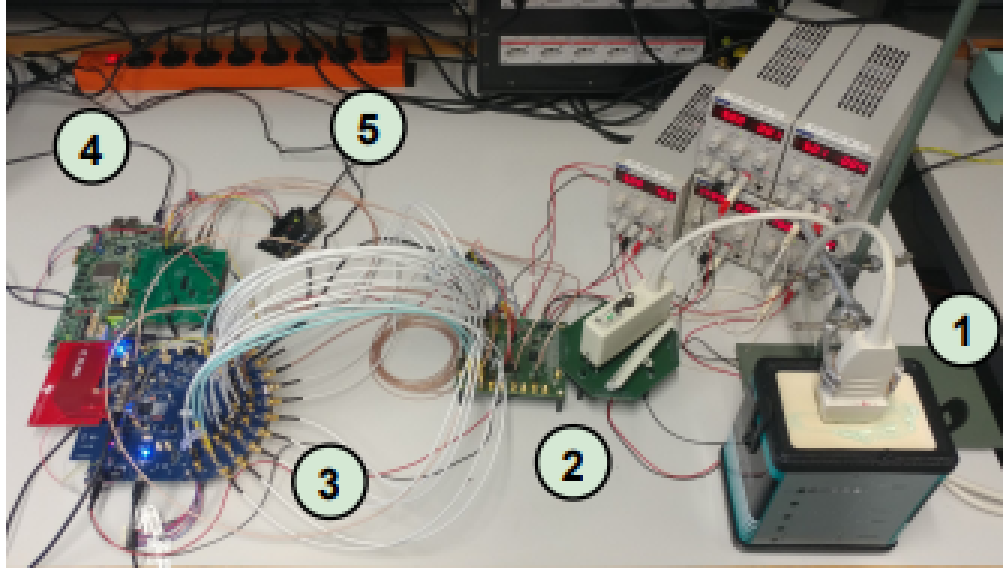


Figure 3: B-Mode interface prototype. 1: transducer, 2: Transmission chip, 3: Analog Front End (AFE), 4: field-programmable gate arrays, 5: WiFi microcontroller unit.[14]

3.3 IMU

The use of inertial measurement units (IMU) is one of the few control methods integrated into commercially available active prosthesis. IMUs are usually composed of three types of sensors: accelerometers, gyroscopes and magnetometers. data from these elements can be used to measure the change in joint angles (Figure 4 has an example of such an application). This could be a good solution for partially paralyzed patients, but for amputees or fully paralyzed people, it becomes less useful[3]. Another drawback of the use of IMUs is the drift due the integration error of the measured kinematics.

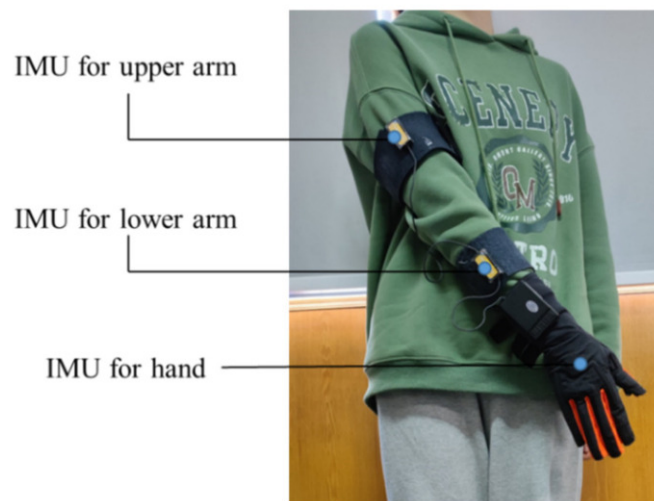


Figure 4: Example of an IMU being used for prosthetic control. In this experiment the IMU was used to acquire the action intention based on the motion of the upper limb[19]

The first step of IMU signal processing is to remove noise by filtering[19]. After the signal is filtered, it should be segmented for each specific action or pose to finally have its features extracted. IMU extracted features are usually separated into three categories: time-domain features, frequency-domain features and time-frequency domain features [20]. After the extraction there could be an optional step of feature selection, and finally comes the prediction algorithm.

3.4 A-Mode Ultrasound

In A-mode ultrasound measurement, a one-dimensional ultrasound transducer is used as an alternative to EMG and B-mode US for capturing muscle contractions with less computational complexity. This approach measures the echo intensity of different tissue boundaries along one line (exemplified in Figure 5). This signal can be interpreted as a single column from a B-mode ultrasound image. As it is a one-dimensional signal, it could be processed as quickly as the EMG signal or the IMU measurements. Although, this could make it a better method than B-mode US, the necessary setup for this type of measurement still requires a bit more work for a reliable output than the one from a IMU or sEMG measurement.

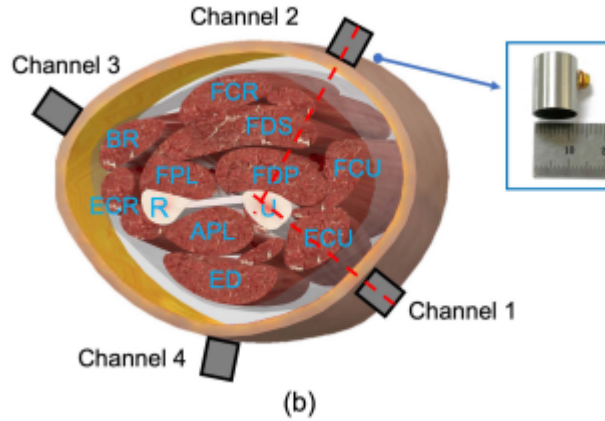


Figure 5: Illustration of A-mode ultrasound transducer positioning in the forearm of a patient[21]

When it comes to processing the signal provided by an A-mode system, the first step is amplification. Some interfaces and driver circuits manage this part before sending the data to the computer, still in the analog domain. where only raw data is provided, it is necessary to use a time gain compensation to correct the signal dampening due to tissue absorption and signal scattering[22]. After amplification, the signal is usually filtered by either a low-pass or band-pass filter to only keep frequency components around the central frequency of the transducer. To simplify the signal it is rectified and has its envelope extracted. Finally the resulting signal

is segmented and forwarded to feature extraction[13].

3.5 Comparison

Each of the previously explained methods offer distinct advantages and limitations in terms of signal acquisition, processing requirements, and precision. Table 1 below summarizes a comparison of these measurement methods, highlighting their key aspects, advantages, disadvantages, and typical applications. It aims to provide a clearer understanding of how each method works, and the trade-offs involved when selecting the most suitable technique for prosthetic control.

Aspect	EMG	B-mode Ultrasound	IMU	A-mode Ultrasound
Signal Dimension	1D	2D	1D	1D
Usual Application Case	Gross movement, simple control tasks	Fine movements, detailed muscle analysis	Gross limb movement, orientation	Fine control, quick hand/finger tasks
Advantages	Portable, widely available	High muscle morphology resolution	Good for larger movement tracking	Low computational overhead, compact design
Disadvantages	Limited depth resolution, crosstalk issues	High computational demand, bulky equipment	Drift prone, low precision for fine control	Limited spatial data
Usual Spatial Resolution	Surface muscles only	Multi-layer view	Limb-level accuracy, no depth	Multi-layer view

Table 1: Comparison of measurement methods for prosthetic control

4. Building blocks

The interface circuit necessary to drive A-mode US requires some well defined function blocks to work correctly (Figure 6). These blocks span from generating the control signal to properly receiving and processing the echo output. Currently, for most of these steps there are commercially available integrated circuits (ICs) that can fulfill each task as a whole.

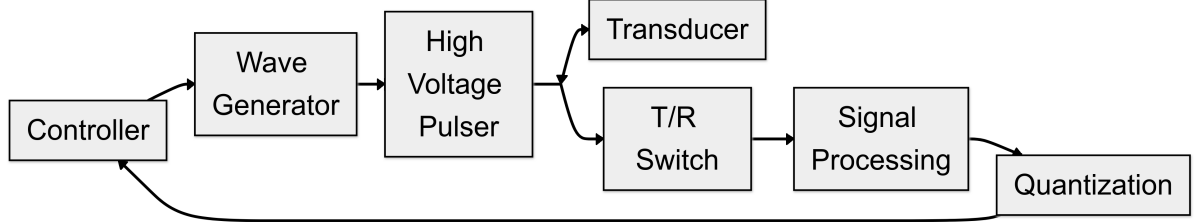


Figure 6: Block diagram of the functional blocks

Following is a deeper description of these building blocks:

- Controller

The controller should be a digital circuit responsible for issuing instructions to all the steps in the pipeline. The usual options for this step are microcontroller units (MCU), digital signal processors (DSP) and field-programmable gate arrays (FPGA). In case of a more complex logic and/or a greater throughput of units, an application-specific integrated circuit (ASIC) can also be considered for the task.

- Wave generator

The first step the controller should take in this pipeline is to generate a reference wave signal. This will be the signal responsible for shaping the output of the ultrasound transducer. For this application the reference wave signal is a square wave. The frequency of the wave should match the fundamental frequency of the transducer for an optimal measurement.

- High voltage pulser

When dealing with a microcontroller, the voltage levels are usually below the 10 V level. Realistically speaking that threshold is closer to 3 - 5 V. On the other hand the ultrasound transducer requires a higher voltage to operate reliably and penetrate the different layers of human tissue, usually from 50 to 100 V [23]. To achieve this voltage shift there are two main approaches: the first one is to build a simple transistor network capable of performing this task. The second one is to use a ready made integrated circuit for this function. As the ICs usually provide a simpler implementation with added security and controllability features, this was the chosen approach.

In some cases the transducer may also require a negative voltage level (bipolar), but for this application only the positive voltage (unipolar) was considered.

- T/R switch

Getting back to the voltage levels discrepancy, it is important to point out that even though the transducer requires a high voltage input, its output is in the range of millivolts. It is also important to note that, since the transducer is a half-duplex device, both the high voltage input and low voltage output share the same channel. This situation gives rise to an issue to be solved: receiving a low voltage signal from the same terminal where high voltage is being applied to. The solution for this is to employ a T/R switch. This device works by only allowing current to pass through it only when low voltage is applied. When a higher voltage (depending on bias and model, it can range from mV to around 5 V) is applied to the T/R switch its internal configuration will not allow the passage of current between its terminals.

- Signal processing

The first step in signal processing is amplification. When driving US signals plenty of amplification is needed. As stated before, the output of the transducer is in the mV range. Also, because of the physical characteristic of the measurements, there is a time dependent exponential attenuation in the signal. Due to this irregular low amplitude signal, two issues arise. First, with such a low amplitude, noise can become quite expressive in the signal. Second, ideally at the interface of two identical media the output signal should be the same regardless of how deep they are located in the limb. To solve the first issue a Low Noise Amplifier (LNA) is applied to the echo signal. This type of amplifier is necessary because the first step of amplification is the most important noise-wise[22], and by using this type as little noise as possible is added to the signal. To solve the second issue of the signal pipeline another type of amplifier is necessary: the Voltage Controlled Amplifier (VCA). This type of amplifier is also known as programmable gain amplifier or time compensation gain amplifier. As the name implies this type of amplifier will have a variable gain set to compensate the attenuation caused by absorption of the signal by the human tissue over time. After amplification it is needed to filter out the unwanted components. This step of the pipeline is a rather simple one. As the signal will be processed in the digital domain it needs an anti aliasing filter to guarantee a good analog to digital conversion. The cutoff frequency should be chosen based on the sampling rate of the ADC. Theoretically, to ensure a good attenuation of frequencies above the Nyquist frequency, the cutoff frequency should be defined as at least one half of the sampling frequency. In real life, to achieve better results, a rule of thumb of one fourth is used.

- Quantization

The last step in the pipeline is the quantization. This is the step in which the analog signal becomes a digital one. Here comes into consideration the required resolution for the application. As we move the signal to a discrete representation, only a finite amount of states can be represented. The number of bits chosen for this step will impact the size of the given voltage range mapped to a single state. Selecting more bits will decrease this range, allowing for more states, but will require more memory and processing time. Also tied to memory and processing time is the question of parallel channels. As stated, the device has to have 8 independent channels, but it is not necessary for all of them to fire simultaneously. Given the small time it takes for a full cycle of measurements, instead of recording simultaneously 8 channels at each step, the measurement protocol could be changed to, reading a different subset of the transducers at each step. Working with this format would provide a smaller throughput of data and decrease of costs, without heavily impacting the quality of the measurements. For the realization of this step an analog multiplexer should be used before the analog to digital conversion and an ADC should be used for each of the multiplexer outputs.

Besides the main signal path there are still some important electronics to be considered in the design of the whole project.

- Buffer

This is an optional, but recommended extra step of the signal pipeline. This would be a temporary place for the data after quantization. This step is only present to secure a reliable data transfer between the pipeline and the microcontroller. In case of a momentary higher workload for the microcontroller, it is important that no data get lost. To ensure this, a high speed FIFO memory is used as a buffer for the data. This guarantees that even when the microcontroller cannot read the data it will be stored safely[24].

5. IC Selection

- Signal generator

When selecting the signal generator the main parameter to be considered was its frequency. As there are multiple transducers with different frequencies, the ideal component should be able to drive as many transducers as possible. To achieve this, we could either select a higher frequency value and design a frequency divider network to drive the lower frequency ones or opt for a programmable source. The latter was chosen as it would allow for a more general and straightforward solution. Given these specifications the chosen IC was the LTC6903 from Linear Technology[25], allowing for frequencies up to 68 MHz.

- High speed buffer

An extra piece of the wave generator is the high speed buffer. As stated in the datasheet of the Programmable Oscillator, in some scenarios it is recommended to use a high speed buffer. The application of the High speed buffer is to provide a better signal accuracy when its output is under a higher load. This circuit will not only run with frequencies higher than 1 MHz (the turning point for extra care about the load) but it will also supply a signal for multiple logic inputs, which will provide a high capacitive load to the IC. Introducing a high speed buffer, which provides a low input capacitance, in-between the IC and this load will then lead to a better signal performance. The chosen IC for this task was the LMH6559 from Texas Instruments[26] which provides an input lower than 2.5 pF.

- High Voltage pulser

The main parameter considered for the selection of the voltage shifter was the high voltage threshold. As stated before, some transducers need up to 100 V as input to work properly. The second parameter was the number of channels. As the idea of the project is to build an 8 channel device, using an IC with multiple channels would be more advantageous than using multiples of the same IC. The chosen IC was the HV7355 from Microchip[27]. This component would allow voltages up to 150 V and it also possess 8 independent channels.

- T/R switch

Choosing the T/R switch was a matter of how much of a high voltage it could stand. The requirements were that it should withstand a voltage level of at least 100 V and that it should not allow voltages greater than 3 V across its terminals. The selected IC was the MD0105 from Microchip[28]. It can withstand voltages of 130 V and opens the circuit for voltages greater than 2 V. It also possesses 4 independent channels which promotes an

easier construction for the 8 channels device.

- Signal processing

The signal processing block was the most complex part of the selection process. As a requirement, it was necessary that both the LNA and the VCA were present in the IC. It should also have the VCA configurable via SPI during run time and with a quick response time so that the time compensation could closely follow the real attenuation. The chosen IC was the VCA5807 from Texas Instruments[29]. Which presents a VCA, LNA and a LPF for the anti aliasing. It contains 8 channels and the programming time for the VCA is within the allowed time limit: for every 1 cm of depth in the tissue, the signal will have a delay of $13 \mu s$ [30], so an attenuation of 6dB (the step size of the VCA) will happen every $7.8 \mu s$. The time at which the message to increase 6 dB using the VCA5807 needs to be sent can be calculated by equation 1.

$$SCLK_{period} \times \#bits = 50ns \times 24 = 1.2\mu s \quad (1)$$

- Multiplexer

For the multiplexer it was first necessary to decide how to divide the channels into subsets. The split was made to generate 4 sub-groups of 2 channels. This separation was not only interesting from a perspective of the ADCs but also of the T/R switches, as in this way only one channel would be active at a given time per switch, decreasing the load under which it would operate. Given these constraints, the selected MUX was the CDx4HCx4052 from Texas Instruments[31], an 8:2 analog multiplexer.

- ADC

For the ADC a minimum of 10 bit resolution and 40 MS/s were chosen as requirements. The resolution was chosen based on previous works done on this topic by Hettiarachchi[32]. The sampling rate was chosen as at least 4 times the higher transducer frequency to ensure signal fidelity during reconstruction. The chosen ADC was the ADC10065 from Texas Instruments[33]. It presents a 10 bit resolution and up to 65 MS/s of conversion rate.

- 1.2 Voltage reference

On the chosen ADC there is a pin which is responsible for providing a reference voltage for all the conversions. This pin could be either bypassed to ground with a capacitor or externally driven by a 1.2 V source. As the voltage in this pin can negatively impact the operation of the IC if it oscillates, there was a design choice of driving it with an external signal. The REF35120 from Texas Instruments[34],

which provides a 1.2 V output with an accuracy of $\pm 0.05\%$ and can be driven by 3.3 V.

- Buffer

The minimum requirement for the buffer is to be able to record at least one full measurement. It also needs a number of input bits that allows direct connection from the ADC output. The memory usage can be calculated equation 2, bearing in mind a depth of 4 cm:

$$samples = 2 \times \frac{depth}{ultrasound\ speed} \times sampling\ rate = 2 \times \frac{4 \times 10^{-2} m}{1540\ m/s} \times 40 \times 10^6\ S/s \approx 2078\ samples \quad (2)$$

As the memories are usually in powers of two, the memory configuration should be at least 4096x10. The chosen Memory IC was the SN74V245 from Texas Instruments[35]. It possess a parallel 18 bit input/output and can store up to 4096 words. Also, because this is a FIFO memory there is no need to handle indexing of the recorded samples, as they are read in the same order that they were recorded.

6. Test planning

For the design of the test setups, the datasheet of the respective ICs were used for a given example or test circuit. In most cases the search for a circuit template was successful and the tests could be conducted by using guidelines in the datasheet. In some cases some adaptations were required due to the environment setting. Besides testing if the individual IC works properly, some tests also aimed to check specific functionalities, like the SPI bus.

The first component to be tested was the square wave generator - LTC6903. For this component, it was also necessary to implement some drivers to control the output clock frequency besides the provided circuit (Figure 7). The aim of this test is to verify the effectiveness of the SPI communication and the waveform consistency over the possible configurations of the IC.

TYPICAL APPLICATION

A Microcontroller Controlling Its Clock

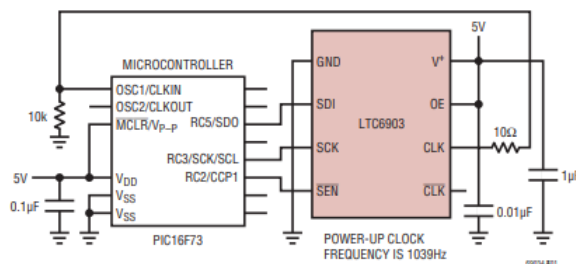


Figure 7: LTC6903 sample circuit[25]

Following the output of the square wave generator, there is the high speed buffer - LMH6559. For this component the aim of the tests was to confirm the consistency of the waveform in higher frequencies and to correctly design the bias network required at its input. The topology of the test circuit can be seen in Figure 8

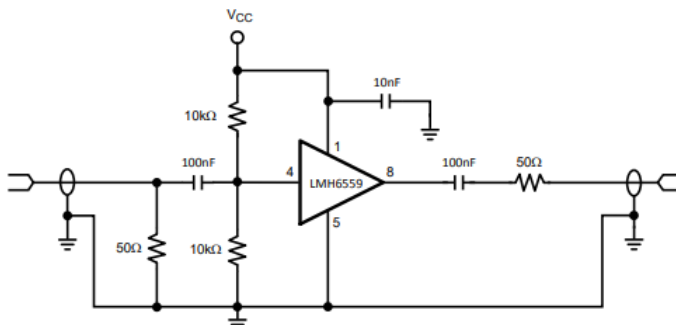


Figure 8: LMH6559 sample circuit[25]

The next step is the high voltage pulser - HV7355. This component also requires some control logic to be implemented. The aim of the tests was to check the control logic for

operating each channel, the power consumption regarding the number of active channels and the shift in the output voltage given the high state of the input signal. The example circuit for this application can be found in Figure 9

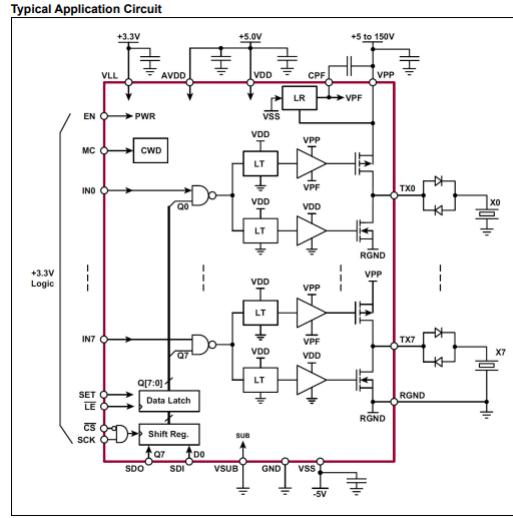


Figure 9: HV7355 sample circuit[27]

The first component after the transducer is the the T/R switch - MD0105. The testing for this IC is rather simpler as it does not require any control logic. The goal for these tests was to check the proper switching based on the voltage applied to the A terminal of each channel of the IC. Figure 10 has the schematic of the circuit used to test this part.

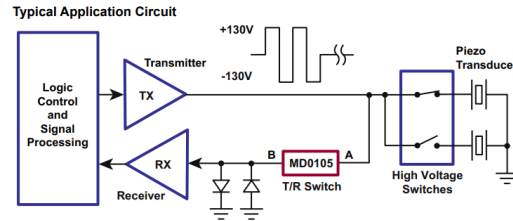


Figure 10: MD0105 sample circuit[28]

Following is the most complex section of the project: the voltage controlled amplifier - VCA5807. The VCA5807 requires an extensive assortment of extra capacitors and multiple power supply connections for its proper usage (as shown in Figure 11). The testing goal for this part was to verify the different amplifications applied over signals with different frequencies. It requires more control logic than any of the other components as well, given the assortment of different functions it provides.

The next component to be tested was the analog multiplexer - CDx4HCx4052. The test setup for this component is rather simple as well, requiring only addressing two channel selector pins to select the correct inputs of the multiplexer (similar to the schematic of Figure 12). The test setup should also verify the correct operation of each of the channels.

The final step was testing the FIFO buffer memory - SN74V245. This setup required a combination of fixed, hardwired connections for stable configuration along with writing control logic to correctly operate the component. The testing process, following the sample circuit in Figure 14, aims to provide insights into the behavior of the control flags as well as the read and write operations.

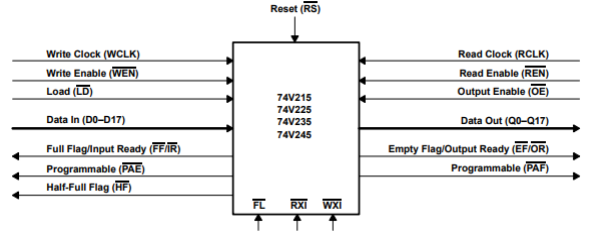


Figure 14: SN74V245 sample circuit[35]

7. Hardware Tasks

7.1 Adapter boards

All ICs for the project were acquired in surface mount device (SMD) packaging. This means that before any breadboard testing could start it was necessary to solder the components to adapter boards to act like a "breakout board". These adapter boards are simple printed circuit boards (PCB) with only the IC footprint on one side and some pads for the pin headers on the other side, making a one-to-one connection between the pads from the ICs and the pins of the board (Figure 15 depicts the adapter boards with the ICs). While some of the components had a small enough number of leads and could be easily soldered to the board using only a soldering iron, other components presented an overwhelming number of pins and/or a thermal pad that could only be properly attached to the board by using a hot air blower.

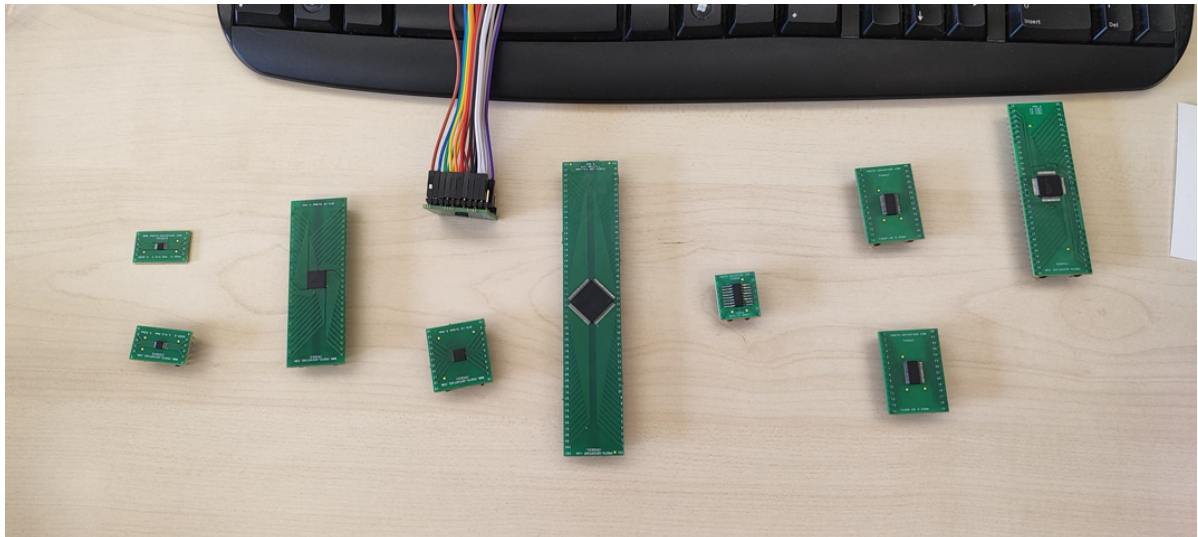


Figure 15: SMD components soldered to their respective adapter boards

7.2 Test setups

LTC6903

The testing setup for the LTC6903 consisted of connecting the IC to a microcontroller and a bypass capacitor. After that, the microcontroller would configure different frequency outputs through the SPI bus. The output signal was measured and could be verified to closely follow the reference frequency set through programming. One issue was that, at first, the waveform of higher frequencies ($f \approx 10^7$) was distorted in the oscilloscope. Further research revealed that this issue happened due to the capacitance of the scope's probe (Fig. 16). When using a lower capacitance probe the waveform became closer to the expected value (Fig. 17).

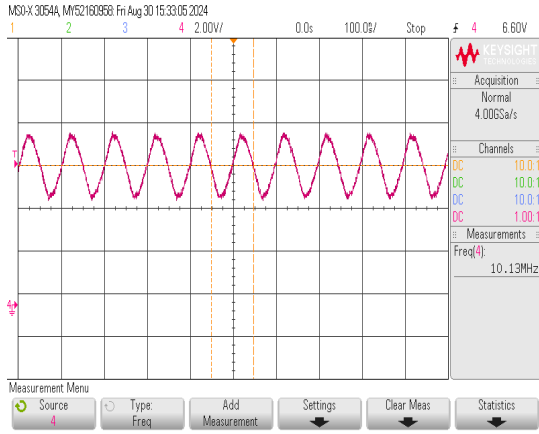


Figure 16: High capacitance probe (Keysight N2889A 1:1 (10MHz) 60 pF)

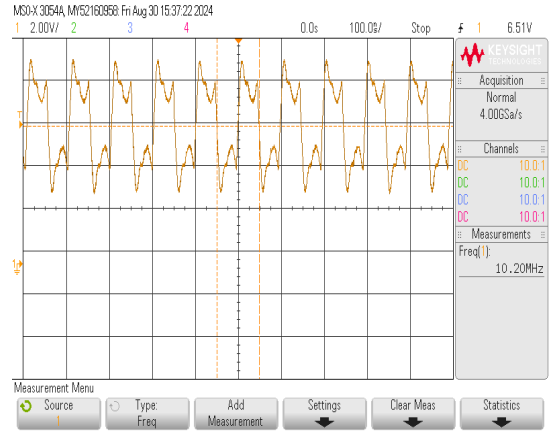


Figure 17: Low capacitance probe (Keysight N2890A 10:1 (500MHz) 11 pF)

LMH6559

The testing setup for the LMH6559 consisted of at first assembling the high-pass filter and voltage divider network for the proper conditioning of the buffer input signal. The filter is used to remove the DC component of the incoming signal. The voltage divider network is used to bias it around a central voltage. The values in the schematic would center the output signal around 0 V. This, however is not ideal for this application. As the high voltage pulser is expecting signals in the 3.3 V range, it was necessary to change the bias point to a higher level around 1.65 V.

HV7355

For testing the high voltage pulser the control pins were connected to a microcontroller, the channels inputs where connected to the square wave generator and the VPP pins connected to multiple bench power supplies in series. The frequency of the input signal and the voltage supply of the VPP pins were gradually increased to observe its behavior. For some reason which requires more research we were not able to drive the high voltage pulser in frequencies higher than 5 MHz or with voltages higher than 40 V (Fig. 19). When a constant input was provided the VPP could easily reach over 80 V (Fig. 18)though.

MD0105

For the T/R switch the testing setup consisted of adding a pair of back-to-back diodes to the receiving side of the switch and applying a sinusoidal voltage around 4.5 V to each channel. When probing the output of the IC, we could verify that the magnitude of the output voltage would follow the input voltage and stabilize at around 880 mV (Fig. 20), the expected forward voltage of the diode, not allowing higher voltage signals to pass through it.

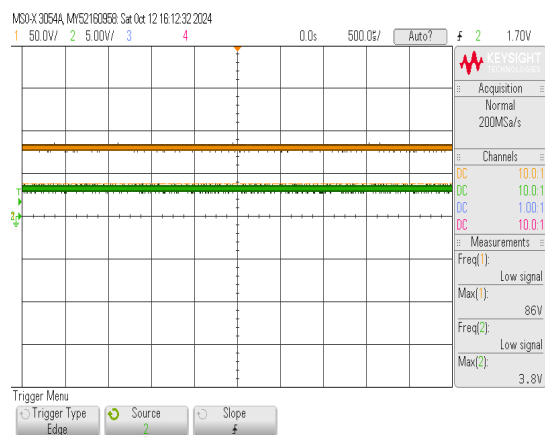


Figure 18: High voltage pulser working with 80 V @ DC input (low voltage input in green and high voltage output in yellow)

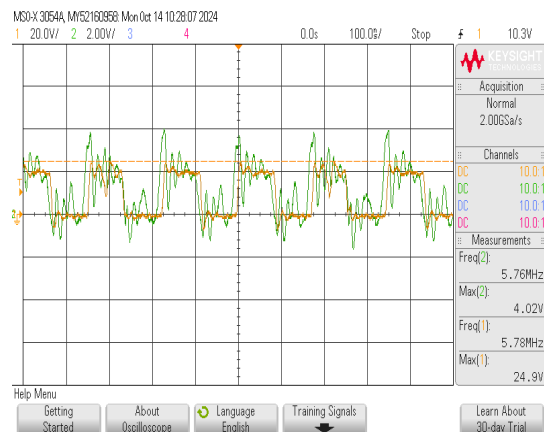


Figure 19: High voltage pulser failing to work with 25 V @ 5.8 MHz (low voltage input in green and high voltage output in yellow)

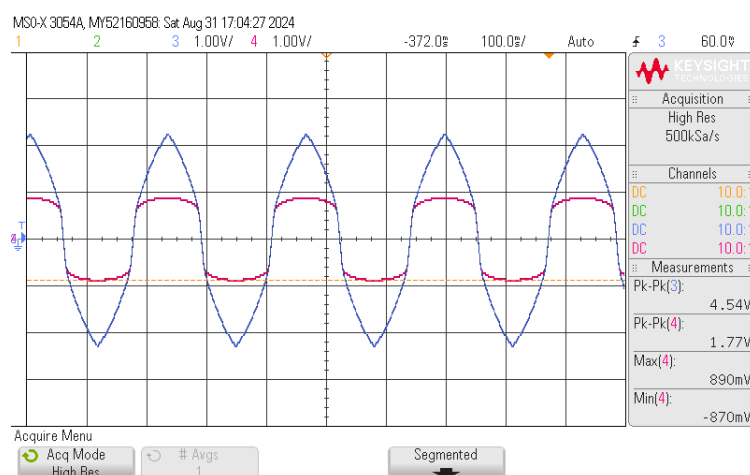


Figure 20: MD0105 output (Purple line) over a 4.5 V sinusoidal input (Blue line)

VCA5807

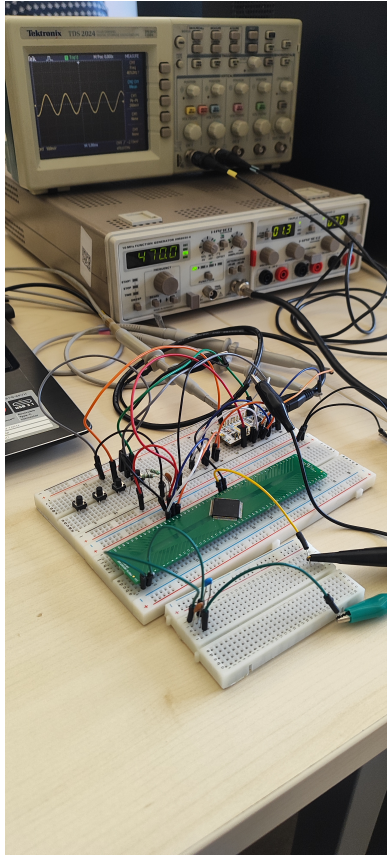


Figure 21: VCA5807 initial test setup

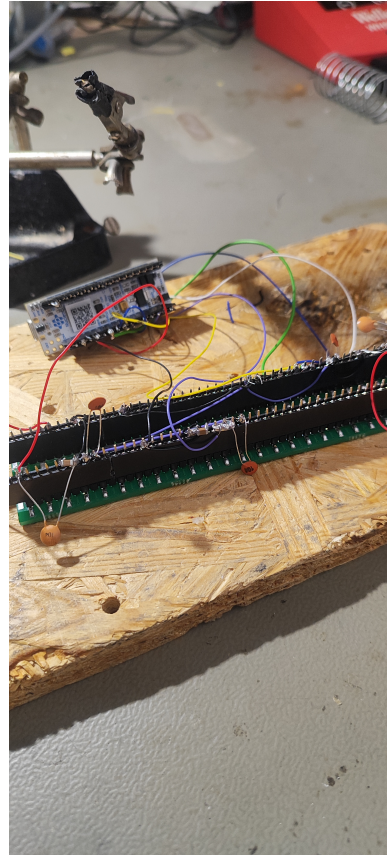


Figure 22: VCA5807 final test setup

The next test setup is the VCA5807. The testing for this component was rather lengthy and complex. Initially the testing was conducted in a breadboard environment. This setting was not ideal as it turned out there were separated avss and avdd networks inside the IC, and each separated network required its own power inputs. Also many capacitors were necessary for the proper operation of the circuit. Following this failed attempt (Fig. 21) the connections and components were soldered directly into the pins (Fig. 22) to guarantee that no bad connection was present. With this new configuration, better results were achieved and some amplification could be detected in the amplifier's output, as shown by Figure 23.

CDx4HCx4052

The test setup for the analog multiplexer consisted of using the microcontroller to select the different channels, a power supply to source a different voltage to each channel and the oscilloscope to measure the output. The inputs between the A part and B part were wired in reverse to provide a better contrast for the measurement. As it did not require extra passive components it could easily be mounted in a breadboard environment (Fig. 24). During the tests, the IC successfully transmitted different voltage levels across its terminals, according to

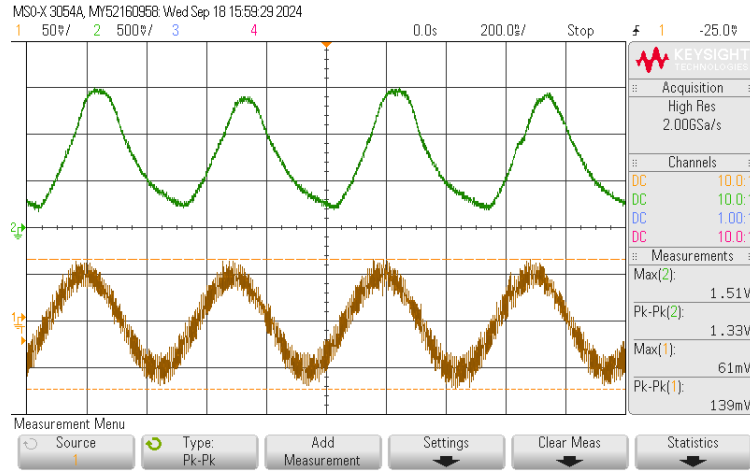


Figure 23: VCA5807 test measurement(input is in yellow and output in green). The input channel has 50 mV/div and the output channel has 500 mV/div

the selected channel as shown in Figure 25. The channel 1 of the oscilloscope had the A output of the IC and the channel 2 had the B part.

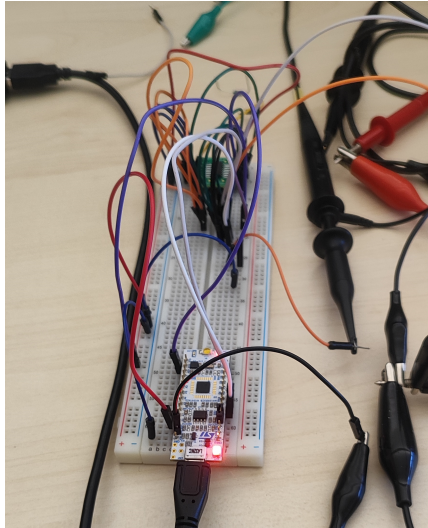


Figure 24: CDx4HCx4052 test setup

ADC10065

Testing this ADC at first consisted of following the sample circuit in the schematics. The first measurements had a big discrepancy from the expected values calculated by the usual formula (eq 3).

$$V_{in} = \frac{ADC_{code} \times ADC_{ref}}{2^{resolution} - 1} \quad (3)$$

The biggest issue was that this formula assumes the range of the ADC to be from 0 V to the voltage reference. Looking at the data sheet for the component it is possible to realize that this is not the case here. The voltage range of this ADC is dependable on the type of input (single

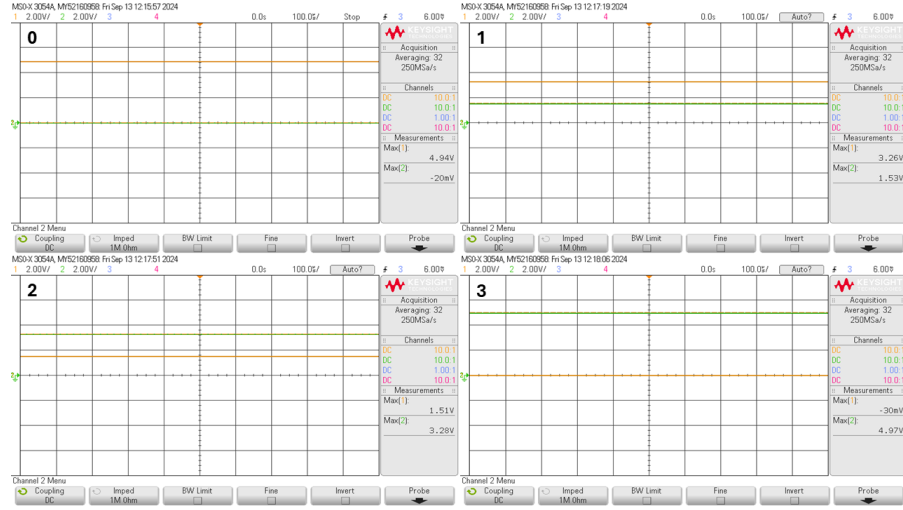


Figure 25: CDx4HCx4052 test measurements. The measurement point is the same for each one of the scopes, the only difference is the selected channel, as denoted in the upper left part of image. the selected channel, from the upper left image in clockwise direction, is channel 0, channel 1, channel 3 and channel 2.

ended or differential) and the selected input range (1.0, 1.5 or 2.0 V). For the topology selected for this application, the voltages should be between 0.45 V and 2.45 V. The general formula used to calculate the voltage based on the output code was then derived to be eq 5, where the maximum and minimum voltages can be calculated based on the input range selection and the V_{cm} parameter of the IC. The application of this new formula made the relationship between the provided codes and input voltage converge to similar value. The reading although closer to expected were still too inconstant. When examining the internal reference voltage it had some noticeable swings (Figure 26), which would explain the variance in the values of the conversion. Following the suggestion of the datasheet, an external voltage reference was used. This provided with more stable measurements as shown in Figure 27

$$StepSize = \frac{V_{max} - V_{min}}{2^{resolution}} \quad (4)$$

$$V_{in} = ADC_{code} \times StepSize + V_{min} \quad (5)$$

SN74V245

The testing of the FIFO Buffer was mostly software related. At first to test the writing and reading functionality there was a testing code (code snippet: 2) that would write all 10-bit number to check if all of the used data pins were working fine. This also helped to check the behavior of the empty flag, as it was an indicator that the values were indeed being written to the IC. To check the functionality of the flags (empty, Programmable almost-empty, half-full, Programmable almost-full and full flags) helper functions were developed to write as many words

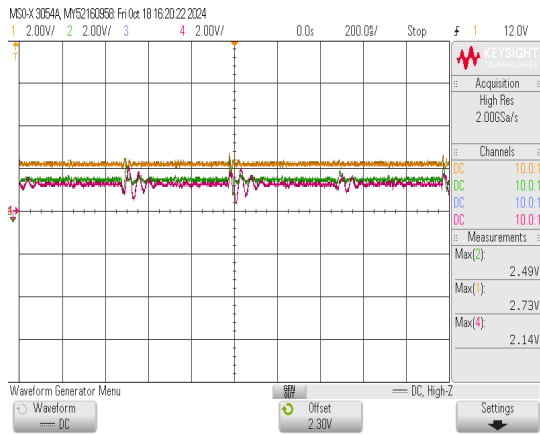


Figure 26: ADC10065 test measurement (in yellow is the voltage input, in green the common voltage and in purple the reference voltage)

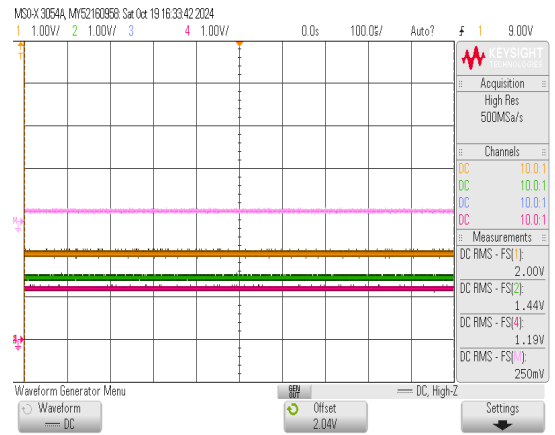


Figure 27: ADC10065 test measurement with external 1.2 V source (in yellow is the voltage input, in green the common voltage and in purple the reference voltage)

as necessary inside the memory. The programmable flags were also tested against new arbitrary values.

```
#define TEST_SIZE 1024
uint32_t write_buffer[TEST_SIZE];
uint32_t read_buffer[TEST_SIZE];
for (uint32_t i = 0; i < TEST_SIZE; i++) {
    write_buffer[i] = i;
}
// Reset the buffer
SN_Reset(&sn74v245);
// Write the numbers to the buffer
SN_Write_N_Data(&sn74v245, TEST_SIZE, write_buffer);
// Read the numbers back from the buffer
SN_Read_N_Data(&sn74v245, TEST_SIZE, read_buffer);
uint8_t test_passed = 1;
for (uint16_t i = 0; i < TEST_SIZE-1; i++) {
    if (write_buffer[i] != read_buffer[i]) {
        test_passed = 0;
        break;
    }
}
```

1. Code snippet: Test code for the SN74V245

8. Firmware Tasks

To drive the ICs requiring control logic, an STM32 microcontroller was used. The MCU would send SPI messages to configure specific behaviors of the components as needed. Everytime after powering on the MCU would initialize the other components of the interface. This initialization process would first happen to the VCA5807 then the LTC6903 and finally to the HV7355. Figure 28 shows the SPI bus during the initialization of the MCU. In simpler cases, it would only toggle logic inputs on certain components to enable and/or select the correct operation mode. Additionally, the MCU was essential for reading data from the buffer. Besides writing SPI wrappers and control logic for the different inputs of the multitude of ICs, there was also a need to create functions to help debug the system. For most of the components it was not possible to poll for its current state, and for the ones that could provide this information, it was usually in a binary stream instead of a human readable format. To circumvent that, structs for each component that hold a state were implemented. Based on the content of those structs a function to properly describe it in a human readable way was developed. The two components with most logic required to be implemented were the square wave generator and the voltage controlled amplifier.

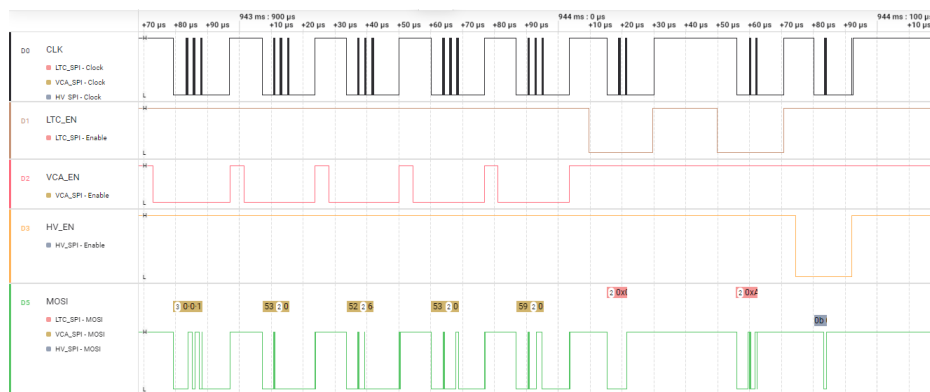


Figure 28: SPI bus during the initialization of the interface. The first row has the clock signal. The second row the VCA5807 serial enable pin. In the third row the chip select for the LTC6903. In the fourth row the HV7355 serial enable pin

The next addition to the code was a way to control the IC during runtime. As it presents a high complexity, it became challenging to check every different way it could operate using only buttons and simple flux control structures. To circumvent this issue an UART communication was also set so it would be possible to send real time commands to the IC via a serial terminal. This allowed for different scenarios and settings to be tested without requiring the microcontroller to be restarted. Even though this functionality will not be necessary for the

final product, it will greatly increase the speed of development.

8.1 LTC6903 Driver

For driving this wave generator seven functions, besides the one used for the description, were created. Two for calculating the parameters (DAC and OCT) needed for a given frequency, two for configuring the output state, one for handling the SPI functionality, two to wrap the other functions under high level function. According to the timing characteristics information in the data sheet, a delay of at least 20 ns between the serial port enable (SEN) being toggled low and the first clock pulse is required for a successful operation. Such small time interval could not be set through code, but upon further inspection, the microcontroller itself takes a millisecond long interval between those operations naturally, given the time it takes to move between instructions.

```
uint8_t LTC_get_oct(int freq);
int LTC_get_dac(int freq, uint8_t oct);
void LTC_EN(LTC6903* ltc6903, uint8_t value);
void LTC_set_config(LTC6903* ltc6903, uint8_t value);
void LTC_SPI_config(LTC6903* ltc6903);
void LTC_set_frequency(LTC6903* ltc6903, int freq);
void LTC_Init(LTC6903* ltc6903);
void LTC_Describe(LTC6903* ltc6903, char* description);
```

2. Code snippet: LTC related functions

8.2 VCA5807 Driver

Driving the VCA presented a greater challenge than expected. First due to its complexity, many more functions were needed for basic usage of the component. Secondly, as most of the time the settings bits for a specific function would share the same register as other functions, it was required to keep track of the current configuration before sending the SPI message to avoid rewriting all the information in the register. To achieve this we could either read each register before each write operation and change only the desired bits or keep track of each and every change done to the IC in the memory. As the reading process would add more complexity and time delay to the whole writing routine, keeping tracking of the current state of the IC in the memory was chosen. The code snippet 3 shows how the struct developed to keep track of the IC was implemented. The struct for the other ICs followed a similar pattern, but with elements relevant for each application.

```
typedef struct
{
```

```
uint16_t r51;  
uint16_t r52;  
uint16_t r53;  
uint16_t r54;  
uint16_t r55;  
uint16_t r56;  
uint16_t r57;  
uint16_t r58;  
uint16_t r59;  
}VCA5807;
```

3. Code snippet: VCA5807 struct definition

9. System-level test on the connected analog stages and current results

With the conclusion of the individual tests, it was time to test the whole system. As there was no computer software developed yet, to handle the data transfer and display it properly, this first global test was realized with only the analog part of the system and the results were displayed in a oscilloscope. At this time we chose to use a lower voltage from the transducer excitation due to the already complex arrangement of wires and cables. For this measurement the protocol used was to generate 5 pulses with 2 MHz and repeat it 5 times.

On the hardware side, the components were connected as described by Figure 6 and the transducer was placed in the bottom of a bowl with water. Figure 29 contains the results of the measurement. Channel 1 was probed from the input of the High voltage pulser and channel 2 from its output. Channels 3 and 4 were probed from the input and output of the voltage controlled amplifier respectively. On the end of the measurement for channel 4 it is visible the the response of the transducer to the received echos. Comparing channels 3 and 4 it is clear the impact of the VCA in amplifying the the response, as there is no visible output due to its low voltage.

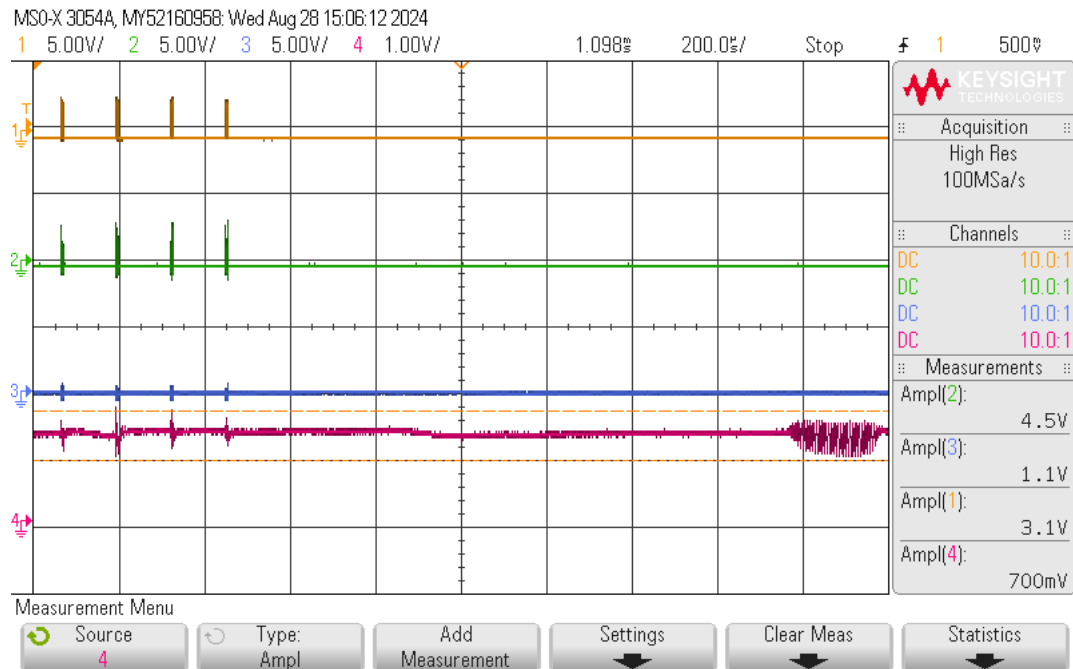


Figure 29: Transducer response in the water. In yellow is the input of the high voltage pulser and in green its output. In blue is the input of the VCA5807 and in purple its output.

10. Comparison with other solutions

Recent research has explored various approaches to using ultrasound and other sensing technologies for prosthetic control and monitoring of internal structures, focusing on wearability, signal resolution, and response speed. Some of the studies in the field develop their own solution for driving the ultrasound transducer, while others use commercially available interfaces for this task and focus more on the data processing. Although the main focus of this study is to develop an interface for sensing finger movement and controlling a prosthetic hand, the use of such an interface is not limited to only this application. Similar hardware has been successfully used for vascular assessment [36][37][38] and monitoring[39], predicting the prosthesis walking kinematics[40] and muscle fatigue assessment[41].

Hettiarachchi et al.[32] introduced in 2015 a new system for radial muscle activity detection. This was a modularized system with 4 main units. They used 8 5MHz sequentially excited transducers to inspect the forearm of the patient. This system was developed with the goal of being used for multi degree of freedom device usage.

Yang et al. in 2018[13] used a commercially available interface for his research. This interface was used to drive 4 A mode transducers with a 5 MHz center frequency. This system would excite the transducer with a single 40 volts pulse and repeat this pulse 10 times a second. The process of transmission and reception was done sequentially for one transducer at a time. In 2021[42] they developed a new system for the driving of ultrasound transducers. For this experiment the target was using the information from the sensors to control a virtual hand. The new system was based around the DSP dsPIC33. This change allowed the use of eight channels and the increase the voltage to 100V.

Yin et al.[21] developed an interface with similar components as the one developed by Yang et al. The new interface instead of being used for virtual hand control, was used to hand gesture classification. There are two main differences between the interfaces: the number of channels, and the controller unit. In this new work the number of channels was reduced by half from the previous version, as its goal was to develop a miniaturized version. The processing unit in this study was a STM MCU instead of a DSP.

Vostrikov et al. [43] used WULPUS[39] as the base for their interface. This study also aimed to classify hand gestures using A-mode ultrasound. This application of the WULPUS probe uses 24 5 MHz transducers as 6 individual channels. As it is with most hand gesture recognition applications, only one channel was active at a time. Just like the normal version, the transducers were excited with 15 volts and the ADC resolution is of 12 bits.

There is also the EUT3160M8, a commercial 8-channel US pulser and receiver in the US lab of the Faculty. This device is being used as a baseline for the development of this interface.

Currently due to some connection issues between this device and the host computer there are no worth while comparisons between the partial results of this work.

Table 2 shows a summary of the comparisons among those interfaces and EUT3160M8

Characteristic	Current Work	Hettiarachchi et al.[32]	Yang et al.[13]	Yang et al.[42]	Yin et al.[21]	Vostrikov et al.[43]	EUT3160M8
# Channels	8	8	4	8	4	6	8
Voltage Level at the transducer (V)	130	180	-40	100	100	15	25–400
Transducer Frequency (MHz)	1–4	5	5	5	1	2.25	up to 30
Bit Resolution	10	10	?	10	12*	12	8 or 12
Pulses/Measurement	Configurable	Configurable	1	2	2	Configurable	Configurable
Parallel Channels	2	1	1	1	1	1	1
Sampling Rate (MHz)	20	40	100	40	36*	8	160

* Estimated value based on microcontroller datasheet.

Table 2: Comparison of interface specifications

11. Future work

The development of this ultrasound-based prosthetic interface provides a promising foundation for advancing control accuracy and real-time responsiveness in prosthetic devices. To build upon the current achievements and enhance the functionality of this system, several essential steps and long-term goals have been outlined for future work.

11.1 Immediate Next Steps

In the near term, I aim to implement the following:

PCB Design for the Full System: A crucial step toward creating a functional, compact, and efficient device is the development of a dedicated printed circuit board (PCB) for the entire system. The PCB will integrate all selected components, ensuring that the hardware setup is streamlined and optimized for consistent performance and reliability in real-world applications. The first version of the PCB shall use the components with their adapter boards and following versions will have them directly soldered on the board.

Dataset Acquisition for Real Forearm Measurements: Acquiring a diverse and representative dataset of forearm muscle contractions is essential to calibrate and test the system. Using the completed prototype, I plan to record data from real muscle contractions in a forearm, capturing variations in muscle morphology under different movements. This dataset will help train the system's algorithms and establish robust mappings between muscle activity and corresponding prosthetic commands.

Computer Interface Development for Data Transmission and Configuration: To facilitate data processing, storage, and real-time control adjustments, I will develop a computer interface for the system. This interface will allow for seamless data transmission and configuration, enabling remote access to the system settings and data visualization. Additionally, the interface will enhance usability for future researchers.

Prediction Algorithm Development for Prosthetic Limb Control: The development of a prediction algorithm will enable the system to translate forearm muscle contractions into precise, real-time commands for prosthetic limb control. This algorithm will likely employ machine learning techniques trained on the acquired dataset to predict intended movements accurately, ensuring responsive and intuitive prosthetic operation.

11.2 Long-Term Goals

For future iterations of the system, I plan to explore the following improvements and research directions:

FPGA Implementation for Enhanced Performance: Replacing the current MCU with an FPGA could significantly improve the system's performance, particularly in terms of processing speed and responsiveness. An FPGA's parallel processing capabilities are well-suited to handle the real-time demands of ultrasound data processing and will contribute to lower latency in movement prediction and control.

11.3 Additional Research Directions

With a fully functional system, several research avenues can be explored to further refine and optimize the interface's performance and applicability:

Characterization of Ultrasound Transducer Response Across Frequencies: Conducting a frequency sweep with the ultrasound transducer and analyzing its output will help characterize the ideal operating frequency for the device. By evaluating the transducer's response at various input frequencies, I aim to identify the optimal frequency range that maximizes signal clarity and resolution, which will improve the accuracy of muscle contraction detection. This research would also allow the system to self calibrate, allowing the use of any transducer without the need of manually setting the frequency beforehand.

Analysis of Output Signal Based on Measurement Protocol Variations: Different measurement protocols, such as variations in pulse count and input frequency, could impact the output signal's quality and stability. I plan to investigate how these parameters affect signal integrity, with the goal of determining an optimal measurement configuration that provides the most accurate data for prosthetic control.

12. Summary

The project aims to enhance the control of prosthetic limbs using A-mode ultrasound-based interfaces. The detailed exploration covered the biological basis of the forearm, selection of integrated circuits (ICs), testing, and firmware development. The ultimate goal is to design and assemble a functional printed circuit board (PCB) for capturing morphological data about muscle movements with precision. Following is the current situation of this research project, focusing in the status of each of the components of the interface.

Currently all components were tested. For most of them (LTC6903, LMH6559, MD0105, CDx4HCx4052, ADC10065 and SN74V245) successful results were achieved and the component is ready to be added to the end product. The VCA5807 presents good enough results for now, but further development is needed for its readiness for the final product. The HV7355 Is current the biggest challenge as it presents an unexpected behavior. The results using only the analog part of the circuit under a lower voltage showed the feasibility of the project and it indicated that this work is following in the correct direction with the development of the interface.

The acceptance of a paper[44] with partial results from this work to a flagship conference of The IEEE Circuits and Systems Society (CASS) indicates that this work is currently relevant and may result in relevant results. With the fully developed interface we hope for a new publication amounting the complete results of this work.

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