

Low-element FPGA beamforming: A ZCU102 demonstration of directed ultrasonic inspection

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This paper presents the design and implementation of a compact FPGA-based (Field-Programmable Gate Array) controlled ultrasonic transducer system. Our aim was to achieve ultrasound beam steering using three elementary ultrasonic transducers. The transducers generated a steerable beam through ultrasound interference, which was controlled by adjusting the phase differences between them. The system's performance was demonstrated using a radar-style beamforming plot. Using elementary transmitters with an initial aperture angle of 50° - 130° , an effective aperture angle of 74° - 101° was achieved. The core of the device was implemented on a ZCU102 development panel, which had a considerable impact on the following development phase. Our proposed approach offers a compact and cost-effective solution for Non-Destructive Testing (NDT) systems; its applicability was demonstrated on a wood inspection example. Finally, potential directions for further development toward a fully functional device are discussed.

Keywords: beamforming, ZCU102, ultrasonic inspection, simulation

1 Introduction

Ultrasonic beamforming offers an efficient solution for Non-Destructive Testing (NDT) applications; however, compact, low-element-count FPGA-based (Field-Programmable Gate Array) systems have been less explored. In the case of wood inspection, currently applied methods often require 10-12 insertions and extraction points as in [1, 2], which may introduce contamination and cause minor damage to the material. In other implementations, sources [3-5] have a much larger number of elements (8-16), but the area of application does not allow for the use of inexpensive devices for this number. Therefore, it was only possible to use three sound generators so that even small trees could be examined. To overcome this limitation, a reflection-based approach requiring only a single insertion point was proposed. The envisioned device was expected to detect different types of rot and fungal decay with minimal impact while performing beamforming efficiently with a small number of ultrasonic transducers. Such a system could enable the assessment of decay severity and help avoid unnecessary felling by allowing the selective removal of damaged parts and providing the appropriate treatment to the tree. To achieve this goal, a device was designed to emit maximum acoustic power in a specified direction, based on a dedicated control algorithm. The orientation depends on the physical position of the device and the directivity is implemented in software; the hardware platform is based on FPGA to achieve high resolution.

The rest of this paper is structured as follows. Section 2 reviews the related work. Section 3 provides the theoretical background of both the generation and control of ultrasound, introduces the simulation, and describes the applied tool. Section 4 discusses the design and testing of the device, including both the design process and the measurements. Section 5 presents the results. Section 6 contains the discussion and outlines directions for future research. Section 7 concludes the paper.

2 Theoretical background

2.1 Ultrasound and the ultrasonic sound generator

The sound generator we applied, CTD40K1007R [6], used an inverse piezoelectric effect to generate ultrasound. The natural frequency of the transducer determined the frequency at which it operated at maximum efficiency, in this case 40 kHz.

For the tree inspection, we wanted to use echo signals. The phenomenon of sound reflecting on water – probably experienced by everyone – is very similar to our basic idea of measuring distance, which is the time of flight method, i.e., the measurement of the time between the sound's emission and receiving its reflection. Therefore, the time measurement we used was between sound emission and reflection. If the sound propagation velocity in the medium is known and time is measured with sufficient accuracy, the distance can be

determined using the trivial equation for uniform motion in a straight line:

$$v = \frac{s}{t} \quad (1)$$

In the case of a well-directed beam, both the distance and direction have to be determined and implemented accurately in software, as side beams caused by unfocused emission can result in detection outside the intended direction.

2.2 Principle of ultrasound guidance

The Huygens-Fresnel principle is the basis for exploiting wave interference to excite ultrasonic sound sources of elementary spherical characteristics in phase with one another to produce higher sound power output in one direction. We wanted to emphasize this effect. Therefore, we created an interference simulation to illustrate the operation when propagating in wood. Our aim was to realize the principle both in practice and in simulation using three elementary sound generators.

2.3 Sample application: Ultrasonic tree inspection simulation

The aim of the simulation was to detect unexpected effects and numerically validate our measurements. GNU Octave (version 10.1.0) simulation environment was used. Similar to a tomographic map [7], we examined only a single slice of wood, assuming a homogeneous material distribution. Although the simulation did not yet include material defects, the interference patterns measured in later experiments provided qualitative validation of the applicability of the idea.

The numerical time evolution of the wave field is described by explicit grid discretization. This can be described by the iteration formula shown as Eqn. (2). Starting from the two-dimensional acoustic wave equation presented in [8],

$$\frac{\partial^2 u}{\partial t^2} = a^2 \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

the simulation employs its spatially varying generalization,

$$\frac{\partial^2 u}{\partial t^2} = c(x, y)^2 \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (3)$$

where $c(x, y)$ denotes the local wave propagation speed of the medium (wood). The second spatial derivatives are approximated using the discrete Laplacian based on central differences, while the temporal second derivative is discretized with the classic three-level central difference scheme. This yields the update rule,

$$u_{i,j}^{n+1} = \frac{t^2 \Delta c_{i,j}^2}{\Delta x^2} \Delta u_{i,j}^n + 2u_{i,j}^n - u_{i,j}^{n-1} \quad (4)$$

where $u_{i,j}^n$ is the acoustic field amplitude at grid position (i, j) and time step n , $c_{i,j}$ is the spatially dependent wave speed (implemented as `c_map` in the code), while Δt and Δx denote the temporal and spatial step sizes, respectively. To account for the intrinsic energy dissipation present in real materials, a damping factor (damping wood) is incorporated into the whole scheme, causing the simulated waves to decay over time. Consequently, the implemented numerical model accurately reflects the behavior of attenuated acoustic wave propagation in an inhomogeneous medium.

Figure 1 shows the simulation results, i.e., the sound waves propagating in a tree from three elementary sources with the same phase and frequency. These sources were spaced at realistic distances from each other. The two images show how the interference was generated: the left hand side image shows the 100th frame, when the waves were still of high intensity and the image of the main beam was not yet visible; while the 2nd image shows the 500th frame, where the side beams were clearly visible and the intensity of the main beam, which in this case was the central wave front, was also clearly visible.

The simulation shows wave attenuation, which highlights a very important conclusion: it is not possible to consider an infinite tree size, and the wave's penetration depth severely limits the allowed tree diameter. The complete code, written in Octave, can be found in [9].

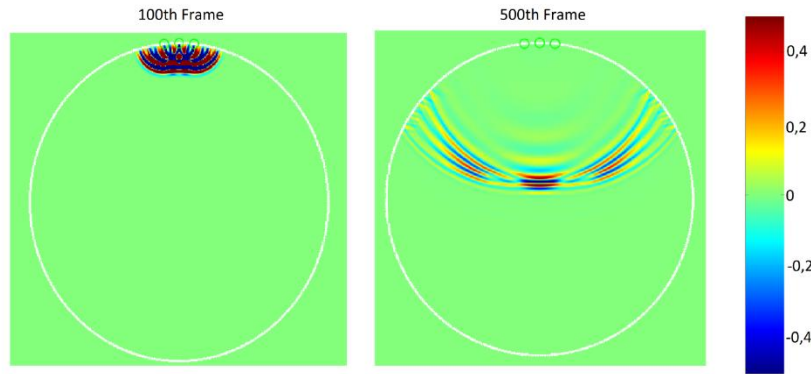


Fig. 1. Results of simulation

2.4 ZCU102 development tool

The device we used was evaluation kit ZCU102 [10]. The platform offered more capabilities than were necessary for our specific application than required by the program we implemented. Naturally, the aim of the application was to enable future extensions, but the present programs could also be of value to similar research.

The evaluation kit is based on XCZU9EG-2FFVB1156 [11] MPSoC (Multiprocessor System-on-Chip), which combined the advantages of FPGAs with the extensive support available for processors. Other major advantages of the XCZ for this project were the number of System Logic Cells, a very high number of logic cells (600,000), and the number of DSP (Digital Signal Processor) slices, which was also impressive at (2,520). In addition, the other parameters of the development board, such as the FMC connectors, which allowed the use of a number of high-speed analogue-to-digital converters, and the large built-in RAM storage, were also advantageous. The wide range of circuit implementations that could be used made development much easier.

These features are expected to play a significant role in the future, so we started work on this device in order to be able to use this powerful hardware at a later time. In its current state, my results can also be achieved with the Spartan6 device, but the powerful hardware presented here will play a major role in future work, from fast data processing to more accurate ADC.

3 Design and testing of the device

3.1 High-level design

Several design decisions were made that reduced costs compared to other possible alternative approaches. The communication between the PC and FPGA unit was handled by Raspberry PICO [12] development tool. The next design decision largely determined the number of signals output, as the control of the ultrasound wave was implemented by using three elementary transmitters, the generation of three phase shifted signals was necessary. The amount of phase shift was tuned by adjusting the number of pulses applied to the four paired outputs of the microcontroller. The phase shift could be as small as one clock pulse, which was set to 400 MHz on the FPGA. This means that the minimum phase shift was only 2.5 ns, which is sufficiently accurate for a 40 kHz signal with a 25 μ s. The code for this can be found in [9].

3.2 Amplifier

Once the 40 kHz three-line square-wave signals were generated and phase-shifted with 10k division resolution from a personal computer, only a few steps were necessary to create the directed ultrasound. The most important of these steps was the design of the MOSFET amplifier. The simplest possible MOSFET circuit was applied drawing 70 mA at 12 V from the three amplifier channels, which can be seen in Fig. 2.

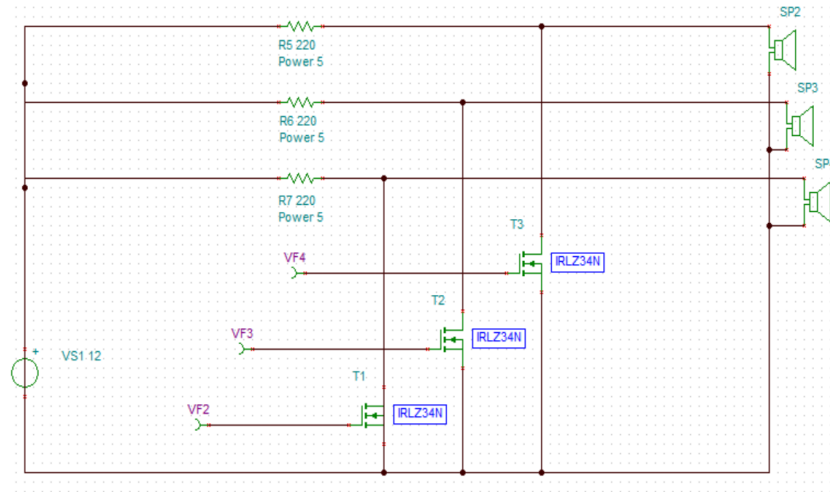


Fig. 2. Simple amplifier connection

3.3 Guided ultrasound testing system

On the transmitter side, the center-to-center distance between the closest ultrasonic transmitters was 10 mm. This distance is approximately equal to the wavelength, which predicts the formation of side lobes. To validate the directional ultrasound, the measurement setup shown in Fig. 3 was prepared with the ultrasound transducers mounted on a PCB (Printed Circuit Board). The setup of

the ultrasound transducers was fixed to test PCB, as shown in Fig. 3. Rotating this prototype PCB around its axis allowed us to measure the directional characteristics of the generated ultrasound of different orientations at discrete angular positions. This directional chart was similar to that of an antenna. If the components presented so far had been successfully designed, the angular characteristics could be varied by orientation (i.e., the applied phase shifts).

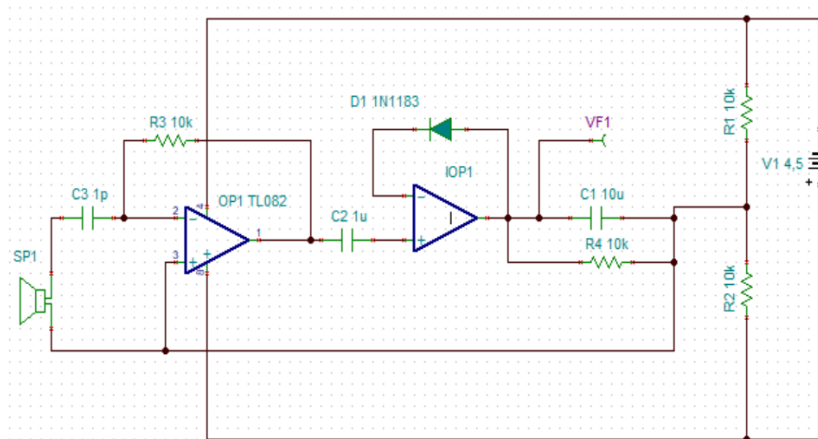


Fig. 3. Average power meter circuit

For rotating the transmitter array, a servo motor, type MS/SG90-180 [13] with a repeat accuracy of 1.6° , was controlled by PICO. In this way, we could ensure that a characteristic could be recorded for each direction. The power measurement was also performed by PICO using the built-in ADC (Analog to Digital Converter).

The core of the power meter unit was implemented using a TL082 integrated circuit (IC), which includes two operational amplifiers.

We implemented amplification with one of these amplifiers, while with the other, a superdiode was created that allowed only the positive half-period to pass through the signal line, charging a capacitor.

A discharge resistor was connected in parallel with the capacitor to ensure a fast response and avoid overheating due to the stored charge. The power supply was provided by a battery, which proved to be an excellent choice in many respects (stability, isolated, long enough lifetime, easy to handle, low noise level). However, the battery also acted as a sensitive measurement source, as it was susceptible to additional electrical noise, which increased measurement uncertainty. Point VF1 in Fig. 3 served as the measurement output; its values were converted by the 12-bit ADC of Raspberry PICO. We performed subsequent calibration, reducing the measurement results by a value corresponding to the noise

level. These rose for several reasons, but overall, they could be considered constant.

The code uploaded to Raspberry PICO is available in [9]. It was responsible for several functions, but the most important of these was providing the connection between the PC and FPGA. The control was obtained by counting the number of pulses emitted by the FPGA. In addition, compared to previous implementations, it controlled the motor. The components used to build the directed ultrasound generator and the testing system are shown in Tabs. 1 and 2, respectively.

Table 1. Components of the directed ultrasound generator

Type	Manufacturer	Function	Main features	Area of use	Ref.
Raspberry Pi Pico	Raspberry Pi Ltd.	Micro-controller	RP2040 dual-core ARM Cortex-M0+, 264KB SRAM, 2MB flash, 26 GPIO, 3.3 V	Interfacing FPGA-PC between measurement control, A/D conversion and motor control	[12]
ZCU102	AMD (Xilinx)	MPSoC development card	Zynq UltraScale+ MPSoC, ARM Cortex-A53, FPGA logic cells, DDR4 memory support	three 40 kHz signal generation with small step phase shift	[10]
IRLZ34N	Infineon	MosFET	Logic-level N-channel, 55 V, 30 A, low R _{ds(on)} , fast switching	Strengthening the FPGA signal	[17]
CTD40K1007R	Camdenbos	Speaker	10 mm diameter, 40 kHz resonant frequency, sensitivity –65 dB,	Production of ultrasound	[6]

Table 2. Components used for testing

Type	Manufacturer	Function	Main features	Area of use	Ref.
MS/SG90-180	TowerPro	Motor	Micro servo, 4.8-6 V, torque ~0.18 Nm, 180° rotation range	Rotating the sound generator vector	[13]
TL082	Texas Instruments	Operational amplifier	Dual JFET op-amp, wide bandwidth, low noise, ± 3 V to 18 V supply voltage	Analogue amplifier of a measuring circuit	[14]
1N4007	Micro Commercial Components	Diode	1000 V/1 A reverse voltage, material: Si	Rectification of the measured signal	[15]
3R12	VARTA	Dry cell block	4.5 V, flat cell	measuring circuit power supply	[16]

3.4 Guided ultrasound testing measurement

1. The test was performed using the following methodology: Setting the servo motor (MS/SG90-180) value to 0° .
2. Measuring the sound intensity 10 times at each orientation: the average of 10 measured values was used, as the setup was sensitive to external noise due to the amplifiers and the uncertainty caused by the ADC.
3. Serial port communication for sending the motor rotation to the PC.
4. Moving the motor by 5° and repeating the measurement cycle until the total rotation reached a given degree, which was 180° in our case.

As a series of measurements, we adjusted the maximum minimum value to the measurement series due to the decrease in the element, thus eliminating the phenomenon of battery drain.

We did not use the transformer (CTD40K1007T) because the TD40K1007R could operate properly in both modes.

Since the FPGA was capable of steering the ultrasound beam in up to 5000 directions per side, using a 5° angular resolution would have generated an enormous amount of data. Therefore, we tested only every 10th possible steering position, which also reduced the measurement time. Consequently, for 1000 cycles, only 37 measurements were necessary (considering the 180° maximum rotation). PuTTY software was used to open the port and save the received messages to a .log file. A Python code was created, which can be found in [9], that essentially opened Excel and, using the methodology for receiving messages from PICO, enabled the data to be easily converted into a polar diagram.



Fig. 4. Measurement set-up

Figure 4 shows how the measurement was carried out while trying to minimize disturbances from reflections. We used the pyramid acoustic foam (shown in the background) and tried to place all reflecting objects as far away as possible to avoid their interference in the measurement. The transmitter and receiver were spaced 33.5 cm apart.

4 Results

Two representative measurement results are shown in Fig. 5. On the left side of the figure, the 20th steering position is shown. Due to automated measuring, the minimum step size was 5 degrees. Hence, broken lines were used to connect the measured points for better visibility. The power distribution chart demonstrates that the main orientation was clearly visible. At the 20th orientation, it was not set to zero by the phase differences; therefore, a slight deviation from 90° was observed. The side beams were also clearly visible in Fig. 6, whose scaling is shown in dB, but they will be discussed in more detail later. The subplot on the right in Fig. 5 shows the orientation with the largest deflection. The two extreme large lobes covered a large area, but the area in front of the sensor had small sound power. Thus, it could be seen that this setup did not measure the area the transmitter was directed to, but rather the surroundings, which opens it up to innovative approaches.

The measurement result shown in Fig. 6 was taken in degrees to determine the precise beamwidth (or angular width) of the forward directivity lobe. Compared to the maximum level, the main beam is by 2 dB higher than the signal level at the attenuation points. The main lobe region was between 74° and 101° . However, due to the low measurement of sound power, the signal level could not reach the 3 dB difference. The SNR was 4.04 dB.

The results were plotted as normalized percentage values between the minimum and maximum measured powers and are displayed in a radial (polar) format.

This range was significantly narrower than the sphere-like radiation pattern of the stand-alone transmitter. The side lobe amplitudes started to increase as they approached 0° and 180° . This could be interpreted as the signal in which two new main beams would form after phase shifting above 180° . However, narrower but higher signal-level side beams were formed due to the distance between the transmitters. These could be reduced if the transmitters were placed closer together and their spacing was limited by their encapsulation. The highest power was observed (directly) in front of the device. Moreover, Fig. 5 shows that the first measurable beam-steering was achieved at approximately the 20th steering position (observed up to the 200th position).

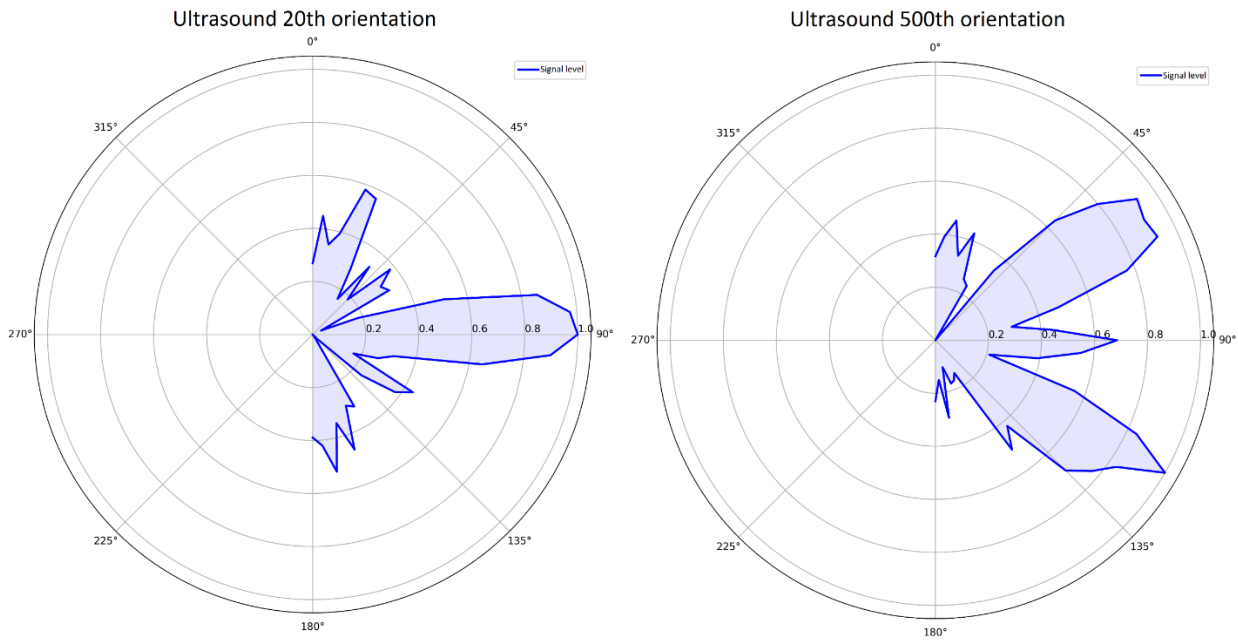


Fig. 5. 20 orientations towards 500 angular power distributions of two representative orientations (20th and 500th) with 5° angular resolution (the power values are normalized to the largest power)

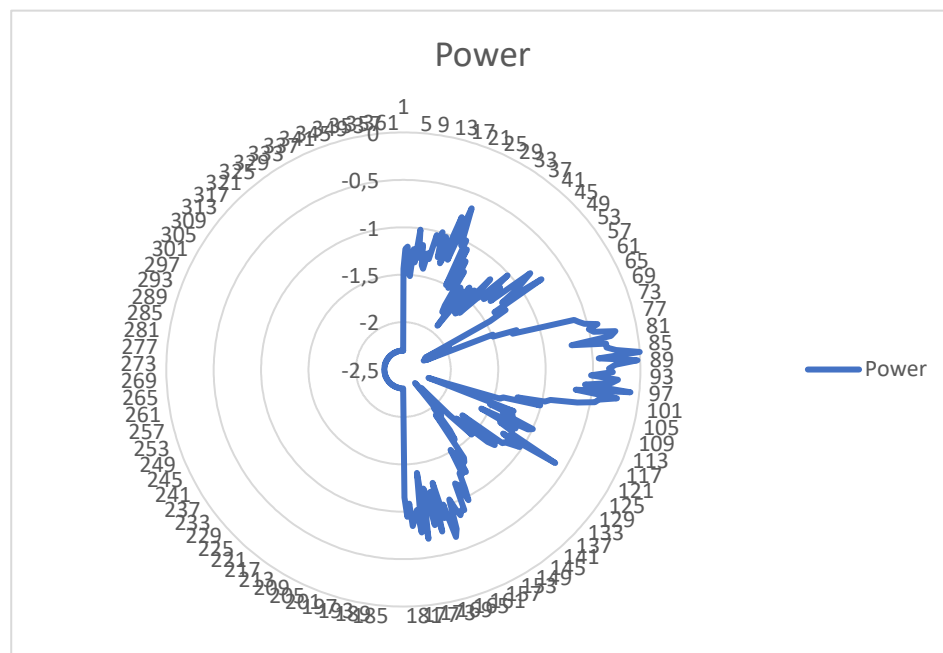


Fig. 6. Forward-directed transmitter detailed direction characteristics with 1° angular resolution

This confirmed that a very fine angular resolution of the directivity could be achieved, i.e., it was possible to select parameters that not only effectively steer the ultrasound beam in small steps but also effectively create directed characteristics.

We concluded that we had successfully put together a set of parameters capable of not only of steering the ultrasound with small step sizes, but also of successfully creating a directional characteristic. The prototype is functional. However, the wood sample experiments should be discussed in a subsequent paper, as the coupling of the waves into and out of the wood poses additional challenges.

5 Discussion and future research

An ultrasound steering and directing tool was created to control the ultrasound wave in 10,000 steps while keeping the system cost-efficient. The developed Verilog code can be easily ported to more cost-effective devices (e.g., Spartan 6 [18]), supporting other implementations and developments.

Future work will focus on transforming the prototype into a fully functional device that can exploit the multiple capabilities of the ZCU-102 development board, both in terms of signal processing and a more compact design. Additionally, there are plans to develop and perform tree testing measurements.

6 Conclusion

A directed ultrasound generator was designed and implemented using the development platform ZCU102. This, and the programs, can be easily transferred to other devices, as communication was handled by a micro-controller. However, in the future, even the ZCU-102 could perform both communication and signal processing.

Measurement supporting circuits were also successfully designed, and the resulting ultrasound wave characteristics were measured and analyzed.

The measurements demonstrated that a more controlled (steered and directed) beam was produced with our device, with extremely fine steering angular resolution. Furthermore, it was evident that extremely fine control was possible with the devices.

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