Review of current ultrasound hardware considerations, designs, and processing opportunities

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Abstract

Ultrasound is one of the most widely used imaging tools for non-destructive testing (NDT) and non-invasive diagnostic medicine. Since its beginnings in the 1970s, ultrasound has been an active field of research, with innovations such as new sensors, signal processing, and hardware development.

However, within the realm of open-source methodology, the field remains under-researched in terms of experimental hardware. An open, highly flexible and cost-efficient platform is still needed for many medical and biological applications to support the efforts of the researchers, makers and device developers and to accelerate ultrasound research and development.

The aim of this review is to identify literature that is relevant for understanding, designing and operating a simple single-channel ultrasound device, and to make this body of knowledge accessible to both makers and hobbyist designers.

We try to capture design and use considerations from older designs, new ones, but also with high-end, and multi-channel systems, used in medical and NDT applications, starting with a review of the context, following on the review of existing architectures and buildings blocks, then on digital options available to support and complement the hardware aspects.

**Key words:** ultrasound hardware open-source frugal device imaging single-element modular design

## 1 Context

### 1.1 Why ultrasound is interesting

Ultrasound has been a developing field for medical imaging and non-destructive testing and exploration (NDT/NDE) that has bloomed the 1950s, even with precusor portable devices such as with the Sonovisor [Zeiss, 1962].

Although ultrasound is today a relatively mature technology, it remains an active field of study, and there are aspects that have yet to be further explored, such as compressed sensing [Kruizinga et  al., 2017, Liebgott et  al., 2012], which have the potential to revolutionize ultrasound imaging on three figure price tag devices.

With this in mind, it makes sense to build an affordable and extensible platform for ultrasound research that leverages advances in low-cost computing in order to offload functions which previously required dedicated hardware.

Ultrasound imaging has numerous advantages over other widely-used imaging modalities, such as computer tomography (CT) or magnetic resonance tomography (MRI), particularly because it is deemed safe and affordable. As a result of these characteristics [Kurjak and Breyer, 1986], it has become an important tool in medical care. The World Health Organisation [WHO, 1985] recognises and stresses the advantages of using ultrasound in medically under-served regions such as low- and middle-income countries where other technology is simply not affordable or the infrastructure non-existent. High-end systems, such as those used in clinics, are mounted on trolleys so they can be easily moved to the patient’s bedside). Smaller “game-changing” systems referred to as hand-held devices can have the dimensions of a laptop computer or even a smartphone, these have been the subject of recent research in the field of medical ultrasound imaging [Kjeken et  al., 2011].

### 1.2 Ultrasound Imaging Modes

In general, with the exception of Doppler imaging, ultrasound imaging is based on the "pulse-echo" principle, which relies on the dual receiver-transmitter function of a piezoelectric transducer. The two main modes commonly found in ultrasound equipment are as follows:

***A-Mode***, or amplitude mode, is used to display the direct amplitude of echoes received as a function of time and creates one-dimensional images.

***B-Mode***: In B-Mode ultrasound, the most common form of ultrasound imaging, a 2D image is produced. It displays the envelope of the recorded symbols, typically in grey-value representation on a 2D map where every value is assigned a different shade of grey. The higher the intensity of the echo, the brighter the reflection interface in the reconstructed image. This is the widely known sonogram used to examine babies in utero.

Other modes, such as M-Mode, C-Mode, and Doppler combine or extend the previously discussed modes for other uses. These are beyond the scope of simple imaging methods.

***Tomography***: though less common than the previously discussed uses, ultrasound can be used in tomography for imaging soft tissue [Zhang, 2015, Duric et  al., 2007, Wen et  al., 2019, Ashfaq and Ermert, 2004], in this application, a transducer or array of transducers is used to measure acoustic impedance at different angles and an image is reconstructed using back-projection or related finite element techniques. The same acoustic impedance methods used in tomography have also been used to recreate images with high temporal and spatial resolution in recent research on plane wave acoustic imaging[Rabut et  al., 2019], as well as translational work from geophysics in acoustic full-wave inversion[Warner et  al., 2013]. Witte and Tanter have also pioneered acoustoelectric imaging systems which are able to combine the acoustic image with a current-source density image, suggesting promising novel applications in electrophysiology[Berthon et  al., 2017, Qin et  al., 2017]. New computing techniques have also the opened door to better imaging [Guasch et  al., 2020, Rymarczyk et  al., 2019].

### 1.3 Existing Applications

***Overall imaging***: Although it is relatively simple and does not enable 2D imaging, A-mode enables measurements for examinations such as para-nasal sinuses, trans-skull fluid detection, sinus pathology, skeletal muscle detection in the wrist extension [noa, b], measurement of the carotid artery lumen diameter [Hu et  al., 2011, Zhang et  al., 2017, Shomaji et  al., 2019], bone porosity [Wahab et  al., 2016, Fontes-Pereira et  al., 2018, Gräsel et  al., 2017] and ophthalmology assessments [Carotenuto et  al., 2004].

***Vascular measurements*** present a combination of ultrasound imaging and photoplethysmography, they are used to measure the diameter and the blood pulse speed traveling through the radial artery [Worthing, 2016], which then can be used to track changes in blood pressure at various points on the human body. Artery stiffness measurements [Joseph et  al., 2015a, Joseph et  al., 2015b, Seo, 2018]. Other ***body monitoring*** uses can include monitoring bone density [Wahab et  al., 2016, Fontes-Pereira et  al., 2018], muscle assessment [Brausch et  al., 2019] and quantifying neuromuscular disease progression [Zhang, 2015], both using A-mode and B-mode imaging, or even tissue assessment [Keyes, 2017]. ***Body composition assessment*** is another application of A-mode imaging [Wagner et  al., 2016, Martins, 2017]. The measurement of ***bladder volumes*** is also a standard medical use [Kuru et  al., 2019]. Another use can be providing ***biofeedback***, it has been shown that ultrasound also enables the tracking of finger movements [Sikdar et  al., 2014] and follow-up of biofeedback in stroke reeducation [Sosnowska et  al., 2019]. Ultrasound has also been used in ***tracking body movements***, for example, tracking obstructive sleep apnea (OSA) [Weng et  al., 2015], breathing patterns [Shahshahani et  al., 2018], and heart muscle behavior [Nguyen et  al., 2019].

Other interesting uses include the development of ***ultrasound capsules***, typically swallowable devices, which enable endoscopy imaging with high frequency ultrasound by fitting the hardware into a 10mm diameter by 30 mm long capsule [Cox et  al., 2017, Wang et  al., 2017]. Capsules promise further development and their architecture can be a source of inspiration [Lee et  al., 2014a, Memon et  al., 2016, Lay et  al., 2016, Lay et  al., 2018].  ***Wearable devices*** are also gaining momentum due to the miniaturisation trend in components and sensors [Basak et  al., 2013]. This is also seen in ***neuromodulation*** [Pashaei et  al., 2020], where, interestingly, ultrasound can be used both to power devices and communicate with them [Johnson et  al., 2018, Seo et  al., 2016, Santagati et  al., 2020], and even to stream video [Kou et  al., 2020].

Ultrasound can also be used for ***nondestructive testing (NDT)*** or nondestructive examination (NDE) [Duncan, 1990, noa, a], for quality or integrity control of mechanical elements. [FRITSCH, ] presents a very interesting design for single-element FPGA-based NDE design, migrating traditionally analog functions, like filtering and envelope extraction, to the digital domain developed by others [Triger et  al., 2008, Shrisha et  al., 2018, Rodrí guez-Olivares et  al., 2018].

### 1.4 Why commercial medical ultrasound is not easily accessible

Accessible ultrasound technologies remain are generally limited to researchers. Commercial medical systems are expensive, bulky, and inaccessible to non-medical staff, and are mostly not adapted for research. Some pieces of equipment are adapted for research, these are relatively more flexible, but the focus is on developing designs for complex sensors, which keeps costs high. The system architecture of a modern ultrasound system is quite complex and is typically beyond the scope of a maker. The high cost of the commercially-available ultrasound equipment is a result of complex system architecture, expensive sensors, and the costly certification process necessary to put a product on the market. However, cost is not the main criteria for researchers [Chagas, 2018]: software and hardware are issued under patents and licenses, preventing researchers from adapting these tools to specific requirements.

Older equipment is available at lower cost but has drastically limited capabilities. In contrast, ultrasound equipment designed for single-element systems from the 1970s-80s was significantly less complex. To gain an understanding and appreciation of electronics and mechanical design, old mechanical probes can easily be procured, it is also possible to do this with veterinary single-element designs found today. Other designs have been proposed by researchers over the two last decades, and these will be reviewed below.

### 1.5 Open-source medical hardware

Open-hardware lowers barriers to product research [Pandey and Vora, 2019], having a full design under an open-source license provides access for all researchers to contribute to and improve a design. This in turn creates the potential for rapid spread of the design, customisation for specific uses, and ad-hoc modification. The existence of an open design means that a higher number of contributors can inspect and improve it. Open source hardware can be a disruptive tool on the medical device market. Shorter development cycles, even for hardware, with open source permit rapid iterations of a product, for which the economic impacts can be significant [Pearce, 2015, Pearce, 2016, Moritz et  al., 2019, Winter et  al., 2019].

Because they are medical hardware and devices, it is essential to ensure that these tools have the functions they are designed to have: quality and medical certification are critical. As such, certification of open-hardware designs is a challenge that needs to be tackled, starting, for example, from a CE marking perspective. Alternatively, it funding certification through crowd-funding approaches has been proposed [De  Maria et  al., 2018]. According to the WHO, 70–90 percent of all medical devices donated to the developing world do not function as intended, and 20 percent are not used due to poor documentation and inadequate training on the use of the device [Niezen et  al., 2016]. Since their hardware and software architecture are not public knowledge, it is impossible for users to access and repair them. Using open-source products, this problem could be avoided, in contrast, support could be provided online detailing how to repair these systems [Gibney, 2016].

## 2 Designing the system architecture

The following section provides an overview of the available open-source hardware and existing hardware architectures for ultrasound devices, based on an earlier similar review [Jonveaux, 2017] or with more complex designs [Roman, 2019].

### 2.1 Sourcing information

Apart from the projects aimed at developing open-source ultrasound hardware described in this paper [Roman, 2019, Jonveaux, 2019], several sources can be consulted to inform the design stage.

For example, teardowns of medical devices available online provide information about the state of the art in terms of hardware architecture. However, investigations of this kind are relatively infrequent, as this activity requires that researchers have both specific skills and interest in dismantling expensive equipment.

Alternatively, refurbished equipment representing technologies from the 80s and 90s, such as mechanical probes, can be an affordable source of sensors, in addition to providing ideas that are useful from a design perspective.

Chip makers can be considered actors in the diffusion of knowledge and know-how [Brunner and Com, 2002, Xu et  al., 2010], as they are major producers of concept and design notes. Chip makers also provide guidance on designs [Chu, ], but integrating these components can be challenging. For example, datasheets may be incomplete or erroneous. To support the use of their circuits, chip makers have also proposed evaluation kits – but these may be overly complex for a simple hobbyist, in addition to being somewhat expensive.

Equipment suppliers provide researchers with similar equipment, making it possible to better understand the required functionalities. They include:

• Verasonics [Peyton et  al., 2017, George et  al., 2018, Kang et  al., 2017, Hager et  al., 2017b]

• Lecoeur Electronique [LeCoeur, , Tortoli et  al., 2009, Zhang et  al., 2018, Al-Aufi et  al., 2019]

• Ultratek [Veenstra, , Pérez-Sánchez et  al., 2020, Chen et  al., 2016, Wang et  al., 2019b]

• Optel [Scholle and Sinapius, 2018, Ratajski and Trajer, 2017, Nowak and Markowski, 2020, Karjalainen et  al., 2012],

• Eurosonic [Jin et  al., 2017, Mostavi et  al., 2017, Ranachowski et  al., 2020, Vadalma, 2020],

• Biosono [Biosono, ]

• or the Fraunhofer Institute [Zimmermann, 2019, Zimmermann, 2018b, Zimmermann, 2018a]

Other suppliers have made smaller contributions to the literature [Ozdemir, 2018], such as Socomate [Gil-Alba et  al., 2019], MATEC TB-1000 [KieŃczyński et  al., 2017] JSR Ultrasonics [Cramer et  al., 2015], or high speed Dr Hillger’s USPC [HILLGER, 2016].

### 2.2 Functional blocks

The functions required in an ultrasound system (shown in Figure 1) are relatively standard and are well described in the literature [Ali, 2008].

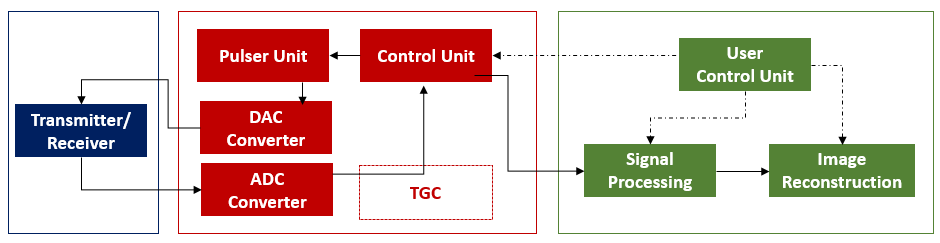


Figure 1: Block diagram of a single-element ultrasound system showing the functions needed for a simple ultrasound device

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These blocks are used to create the pulse-echo pattern that ultimately creates an ultrasound image.

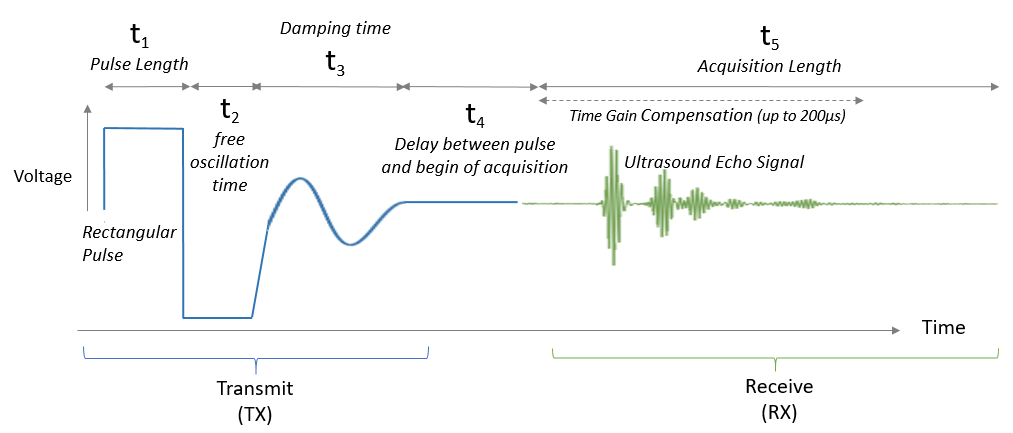


Figure 2: Pulse Train of a pulse echo device. Transmit (blue) and Receive (green) path

### 2.3 Earlier works on a simple hardware architecture for ultrasound systems

The first research setup appears to date back to 1993 [Jensen et  al., 1993], in which a Bruel & Kjaer, BK Type 1846 was modified to accept research equipment. Since early 2000, apart from the design of medical probes, several groups of researchers have worked to design research-friendly equipment. Most of these designs are for multi-channel devices [Boni et  al., 2016, Boni et  al., 2012, Boni et  al., 2018, Qiu et  al., 2012, Lévesque, 2011], but other authors have considered single-element designs, such as [Carotenuto et  al., 2005] and [Richard et  al., 2008]. An interesting modular design was proposed in [Wall, 2010] which has a motherboard connected to the device. More recently, [Taylor et  al., 2017] also used a beagle bone device. [Jonveaux, 2017] proposed an Arduino-like approach to functional blocks, balanced by SNR and cost impacts, which may have inspired further designs [GoŃabek et  al., 2019].

### 2.4 State of the art and review of the ultrasound hardware designs

#### 2.4.1 General state of the art review

A summary of the literature with respect to ultrasound system design, based on a systematic review of components used, is presented in the table below. High-end systems were considered in this review, as it is possible to exploit aspects of their design approach for use on simpler platforms.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Reference** | **Elements** | **Voltage** | **Msps** | **Res** | **AFE-TGC** | **Year** |
| [Ahn et  al., 2015] | 16 | 70V | 40 | 10 | AFE5808 | 2015 |
| [Assef et  al., 2014] | 128 | 100 Vpp | 50 | 12 | AFE5805 | 2014 |
| [Assef et  al., 2012] | 128 | 100 Vpp | 50 | 12 | AFE5805 | 2012 |
| [Assef et  al., 2015] | NA | 100 Vpp | 40 | 12 | AFE5805 | 2015 |
| [Batbayar et  al., 2018] | 4x32 | NA | 80 | 10 | NA | 2018 |
| [Bharath et  al., 2018] | 8 | 105V | 50 | 16 | AFE5809 | 2018 |
| [Bharath et  al., 2016] | 8 | +-50V | 40 | 12 | AFE5808 | 2016 |
| [Bharath et  al., 2015a] | NA | NA | NA |  | NA | 2015 |
| [Chang-hong Hu et  al., 2008] | 1 | 15V | 120 | 12 |  | 2008 |
| [Chatar and George, 2016] | 16 | NA | 150 | 14 | NA | 2016 |
| [Cheung et  al., 2012] | 128 | NA | 80 | 10 | AD9272 | 2012 |
| [Dusa et  al., 2014] | 8 | 100 Vpp | 65 | 12 | AFE5809 | 2014 |
| [FRITSCH, ] | 1 | 50-400V | 80 |  | NA | NA |
| [Govindan et  al., 2015] | 8 | NA | 250 | 8 | VCA8500 | 2015 |
| [Hager et  al., 2017b] | 64 | 100Vpp | 32,5 | 12 | AFE5851 | 2017 |
| [Hewener et  al., 2012] | 128 | +-75V | 80 |  | AD9273 | 2012 |
| [Ibrahim et  al., 2018] | 64 | 12 V | 20 | 12 | NA | 2018 |
| [Jonveaux, 2017] | Single | 100Vpp | 22 | 9 | AD8331 | 2018 |
| [Kim et  al., 2017] | 128 (32 ch) | +-80 V | 50 | 12 | NA | 2017 |
| [Kruizinga et  al., 2017] | Single | 100 Vpp | 200 | 12 | NA | 2017 |
| [Kushi and Suresh  Babu, 2017] | Single | NA | 100 | 14 | NA | 2017 |
| [Lee et  al., 2014b] | 16 | NA | 40 |  | AFE5808 | 2014 |
| [Li et  al., 2014] | Single | 80 V | 40 | 12 | AD9276 | 2014 |
| [Matera et  al., 2018] | 8 | 6V | 75 | 14 | AFE5809 | 2018 |
| [Nguyen et  al., 2019] | 2 | 18V | 40 | 10 |  | 2019 |
| [Pashaei et  al., 2020] | 8 | 10V | 80 | 12 | AD9276 | 2020 |
| [Peyton et  al., 2018] | 32 | NA | 20 |  | Custom | 2018 |
| [Qiu et  al., 2018] | Single | +48V | 160 |  | AD8331 | 2018 |
| [Qiu et  al., 2020] | 1 | 60V | 250 | 12 | TC6320 | 2020 |
| [Ricci et  al., 2006] | 1 | 100 V | 64 | 14 | MAX4107 | 2006 |
| [Roman et  al., 2018] | 64 | +-50V | 80 | 12 | AD9276 | 2018 |
| [Vasudevan et  al., 2014] | Single | 100 Vpp | 250 | 12 | VCA8500 | 2014 |
| [Wall, 2010] | NA | 12 V | 65 |  | NA | 2010 |
| [Weng et  al., 2015] | 16 | 100V | 150 | 10 | Max2077 | 2015 |
| [Zhang et  al., 2019a] | 64 | 100V | 80 | 14 |  | 2019 |
| [Zhang et  al., 2017] | 8 | 70V | 250 | 16 | QT1138 | 2017 |

Table 1: Review of ultrasound hardware designs, detailing speed of acquisitions (Msps), Resolution (Res.) and features where applicable

#### 2.4.2 Analog Front-End (AFE)

It appears that most research designs use all-integrated analog front-ends (AFEs), which allow for a simpler design, at the cost of integrating several functions into NDA-covered chips, which can make a design more expensive and less open. Different chips families were identified during this review. *AD927X* systems usually have 8 channels, with a 12-bit ADC from 10 MSPS to 80 MSPS, full LNA, VGA, and AAF, widely used [Hewener et  al., 2012, Di  Ianni et  al., 2016, Raj et  al., 2018, Cheung et  al., 2012, Alqasemi et  al., 2012, Batbayar et  al., 2018, Techavipoo et  al., 2012]. More design considerations were researched by [Di  Ianni et  al., 2016]. The *AFE58XX* family has 8- to 32-channel AFEs from 50-65MSPS, with LNA, VCAT, PGA, LPF, ADC, and possibly Continuous Wave (CW) Mixer [Assef et  al., 2015, Assef et  al., 2012, Assef et  al., 2014, Assef et  al., 2016, Bharath et  al., 2015b, Bharath et  al., 2016, Lee et  al., 2014b, Hager et  al., 2017a, Bharath et  al., 2018, Kidav et  al., 2019]. Finally, the *MAX2082 and MAX2077* have 8 channels, including the HV pulser and TR-Switch, but offer no digitization capability [Hewener et  al., 2019, Weng et  al., 2015].

These AFEs all include several channels, which is not necessary for a single-element design. However, AFEs may be useful in multi-channel designs in order to improve space and cost efficiency.

#### 2.4.3 Managing several channels

Even if not strictly required for single-element pulse-echo devices, multiplexers or high-voltage switches can be used to address several transducers from a single transmit-receive electronics channel. Options to connect several transducers are numerous, such as the HV2605, HV2201, MAX14866 [Enwia et  al., 2019, Pashaei et  al., 2020, Enwia, 2020], or HV20220 [Li et  al., 2014] chips. Switches can also be integrated at the pulser level [Worthing, 2016, Hidayat et  al., 2020] or on the receiving path, with a LM96530 [Gwirc et  al., 2019, Vasudevan et  al., 2014, Roman et  al., 2018], for example.

Beamformers, were another option commonly observed in research setups for arrays, mostly based on the LM965XX family [Gwirc et  al., 2019, Yu, 2012, Roman et  al., 2018, Bharath et  al., 2015b, Roman et  al., 2018]. However, by nature, beamformers would be of lesser importance in single-element designs.

#### 2.4.4 Mechanical sweeping

When designing a single-element sensor to produce a 2D image, a system capable of sweeping the space to be imaged is required. Several types of actuators were identified in the review. In general, and to minimize hardware costs, a single piezoelectric element, mechanically sweeps across the target scene with the corresponding channel acquisition circuit [Saijo, ]. This sweeping principle has been used in multiple experimental setups, including [Chang et  al., 2009], and was used in older mechanical probes, which are based on either continuous rotation (Kretztechnik AR3 4/5B/A, ATL 724A, ... ) of the transducer to accommodate plane sweeping, sometimes with multiple transducers to allow for multiple images per rotation or with mechanical sweeps (Interspec Apogee, Diasonics probes, Kretztechnik AW14/5B/A, HP 21412A, ... ). This was initially more common in intra-cavity probes, due to space constraints.

For cardiac scans of small animals, heartbeat and target size require in excess of 100 frames per second (fps) with a spatial resolution of 100um or less. Lei et al. [Lei, ] achieved an interesting 30-50MHz real-time ultrasound single-element device that scans at 130 fps using a 22-degree arc at 65Hz, the unit’s pulse-echo system is controlled by the motor position. Imaging transducers are also relatively smaller in size, which makes them mechanical the solution of choice when arrays are too large. However, this implies strong positioning control and precision motors, requiring, for example, optical encoder and piezoelectric motors [Carotenuto et  al., 2004], which allow for 256 view lines to build a single frame at a rate of 15 frames per second. Other uses of piezoelectric actuators include the use of bimorphs [Bezanson et  al., 2011], which can increase the benchmark of 130fps for electromagnetic motors. Still, the weight borne by the actuator has to be limited [Brown et  al., 2013, Huang and Zou, 2015], a constraint also satisfied by MEMs [Choi et  al., 2020].

In laboratory designs, where real-time imaging is not an issue, XYZ positioning may also be used [Svilainis et  al., 2014, Wang and Saniie, 2019, Xu et  al., 2019], using 3D-printed elements [Bottenus et  al., 2016], for example, demonstrated that a three-axis translation stage allowed for precise position and orientation control of the transducer. [Qiu et  al., 2011] uses a transducer on a linear motor stage to allow 8 mm/s linear imaging scans. This approach was used in other experiments [Govindan et  al., 2015, Soto-Cajiga et  al., 2012], [Heuvel et  al., 2017], for example, use a motor as the positioning system in their design, which allows the system’s single transducer to sweep across the target scene. [Smith et  al., 2015] also uses a single transducer element in combination with a mechanical actuator, a compromise with significant production cost savings (over 95%) while the image quality is reduced. In particular, this system explores the possibility of using a lower noise voice coil motor (VCM), which is interesting for maintaining a high signal-to-noise ratio of the echo data, and the accurate positional encoder allows the ultrasound image to be constructed at the end of each scanning cycle.

Alternative displacements methods can be used, for example, using accelerometers to determine the angular position of the transducer [Sobhani et  al., 2016] or allowing for precise image reconstruction with an Arduino and Raspberry Pi setup [Herickhoff et  al., 2019], which can also be used in ultrasound training simulators [Farsoni et  al., 2017]. In the case of skin imaging, another example is to use optical trackers like those used in computer mice [Zhang et  al., 2019b, Poulsen et  al., 2005, Herickhoff et  al., 2018].

#### 2.4.5 High-voltage tools

High-voltage components were also reviewed, however, the topic of efficient high-voltage sources is not considered in most publications, apart from [Xiao et  al., 2013]. High-voltage design for ultrasound has been a particular point of interest. The ideal requirements for a good high-voltage design would involve developing a unit with a small footprint, low consumption, and settable levels between 0 to 90V – ideally with another source for 0 to -90V for bipolar pulses – which would usually function with a current supply of 25-30mA. Early designs [Brown and Lockwood, 2002] achieved 350V pulses with $50 but finding a working design is still a challenge today. In addition, only few researchers are sharing their designs [Tang and Clement, 2014], even considering existing detailed datasheets provided by manufacturers [Granata et  al., 2020]. Devices such as the LM96550 were not considered in this review because of their relative important physical size. In the open-source literature, designs used of an expensive RECOM device, providing a 0 - 120V range, or a NMT0572SC, providing 24, 48 and 72V rails, as well as the LT3494 with a rail up to 39V. Other alternatives were considered, namely the *MAX668* (which operates from O to 150V), *MAX1856* (between -80V and -24V), an *MIC3172* design, using an *HV9150* to reach up to 200V, or a *MAX15031* of up to 80V. The *DRV8662* family, including the DRV2700, also has been used to provide rails for up to 105V. Older devices were seen using integrated devices, such as the PICO 5SM250S DC-DC. Clipping devices (MD0100 [Li et  al., 2014, Sharma, 2015], MMBD4148/MMBD3004 [Chu, ]) allow clipping of the signal on the receive path to protect it.

Electrical impedance matching [Rathod, 2019] can also be used to improve the level of energy transmitted to the transducer, especially with low-cost VNAs, like the 40$ NanoVNA, usable in MHz-range transducers), which has allowed for some interesting developments [Garcia-Rodriguez et  al., 2010, Wei et  al., 2020] and can be used for improving the overall signal-to-noise ratio.

#### 2.4.6 Materials choice

In most mechanical designs, an acoustic window is needed to seal the scanner head from the external medium while minimizing signal loss. The first mechanical scanners used water-baths as an intermediate between the transducers and the subject [Schueler et  al., 1984]. A material regularly used for this is TPX (polymethylpentene), which is used for example on ahand-held high-frequency ultrasound scanners [Erickson et  al., 2001]. TPX is also used as for acoustic windows in the bimorph design [Brown et  al., 2013], in which the 45MHz element is located inside a 3D printed probe, allowing for scans at 100Hz. Alternatively, [Qiu et  al., 2020] uses an acoustic window made from polydimethylsiloxane (PDMS) to minimize reflection and attenuation during the ultrasound transmission.

Acoustically interesting materials can also be used. For example, polyimide can be used in phantoms [Xu et  al., 2008, Lei Sun et  al., 2008], as well as sealant silicones [Lorenzo et  al., 2009] that mimic soft tissues. Agar and gelatin are used on temporary phantoms [Vogt and Ermert, 2005, Chun et  al., 2015], where graphite powder reproduces tissue scattering. Alternatively, for good device-patient coupling, polyvinyl alcohol or polyurethane, in additon to polyvinylidene fluoride (PVDF), can be considered [Sikdar et  al., 2014].

3D-printed parts are generally a very useful supplement to finalise a scanner device. Apart from a holder mechanism to house the transducer, they can be used to provide the casing and cover to shield the device. Functional parts, like aberration masks in the case of compressed sensing applications can also be produced using 3D printing [Kruizinga et  al., 2017].

### 2.5 Minimal specifications

In order to understand the minimal set of specifications for an ultrasound B-mode scanner, [Kurjak and Breyer, 1986] laid out the basic specifications for a general purpose ultrasound scanner. It is deemed necessary to:

• produce B-mode images, which translates as a device having linear- and convex- type scan-heads

• image at least 3.5MHz – extendable to 5MHz.

• images should be displayed on a reconstructed 512 x 512 image, on 4 bits.

• images should go to a depth of 18cm, meaning 240us of acquisition, in line with a 512 pixel-deep image considering a single-element resolution.

• viewing angle of 40 degrees or more, which indicates that 128 lines per image should be sufficient.

• image should be refreshed at 5 to 10fps.

In terms of ADC selection, image of human tissues requires at least 50dB of SNR [Attarzadeh et  al., 2017] translating with a 9-bit ADC. A target of 10 fps leads to 780us between lines (and less than 700ksps), which is in line with the requirements, and manageable by modern information transfer buses.

## 3 Downstream hardware, to signal processing

### 3.1 Bandwidth reduction

Many microcontrollers lack sufficient bandwidth to digitize and process the full ultrasound signal at radio frequencies. Therefore, microcontroller-based systems typically use an envelope detector in hardware prior to digitization of the signal, so that the signal bandwidth is reduced to that of the amplitude-modulating information. However, this approach causes a loss of phase information from the signal, which is needed to perform Doppler mode imaging. Additionally, envelope detectors in hardware typically have a fixed cutoff frequency, which prevents them from being adaptable to different transducer frequencies.

A useful technique demonstrated by [Peyton et  al., 2018] is the use of quadrature sampling to preserve both amplitude and phase information and frequency downconversion to reduce the bandwidth requirement for data transmission, storage, and processing to that of the ultrasound modulation bandwidth, which can be significantly narrower than the maximum frequency of the signal. Because frequency downconversion and quadrature sampling are used in software defined radios (SDRs) [Hager, 2019, Hager and Benini, 2019] to capture the modulated information on a radio frequency (RF) carrier, SDR hardware can serve as a drop-in replacement for quadrature sampling hardware, as in the "rtl-ultrasound" open-source project [Meng, 2019].

Alternatively, demodulation techniques would allow shifting signals from higher frequencies to lower, allowing slower acquisition techniques and leaner hardware.

### 3.2 Using FPGAs - digital hardware processing of radio frequency signals

Real-time information can be transmitted to a computation platform using DMA-optimized microcontroller designs [Kidav et  al., 2019], but the progress in field-programmable gate arrays (FPGAs), digital signal processors(DSPs), and systems-on-chip (SoCs). Along with the development of integrated AFEs, they have accelerated the creation and availability of high-end programmable research platforms to explore signal-processing methods [Roman et  al., 2018]. In some designs, an additional micro-controller is set up between the FPGA and the USB and provides configuration on the fly, allowing access to the computation platform to set up the pulse-echo sequence parameters [Raj et  al., 2017, Raj et  al., 2016]. In any case, this interface has been shown to easily stream data to a host with a bandwidth of 2.4MHz [Pashaei et  al., 2018, Schneider et  al., 2010].

FPGAs improve the potential for developing ultrasound imaging systems with small form factors and creating high-performance devices with reduced power consumption [Dusa et  al., 2014]. It can be noted that configurable hardware makes the system resilient to future changes: designs can be adjusted without reprinting the circuit board [Zhang, 2012, Qiu et  al., 2010, Ibrahim et  al., 2017]. In terms of open-source, FPGA use has been supported by the development of new open-source toolchains [Shah et  al., 2019] opening a tool that has been relatively closed to a wider public [Saiz-Vela et  al., 2020] and promoting its spread.

From an open-source perspective, the Lattice HX FPGA family was one of the first families to get an open toolchain. However, more integrated chips, such as the Lattice UP5K, can be used to benefit from DSP blocks as well as from integrated 1Mb RAM, lowering the complexity and cost of the materials and routing.

FPGA also allow more flexible connection between systems. Many high-end designs are based on peripheral component interconnect express (PCIe) due to high bandwidth requirements[Zimmermann, 2018a, Lewandowski et  al., 2012, Kidav et  al., 2019], but the complexity of PCIe is an obstacle to low-cost designs. In [Jonveaux, 2019], Raspberry Pi’s 40-pin header was used as a simple, standardized interface for developing extension boards. In theory, SPI buses can also be fast enough to transfer downsampled signals, and i2s bus could be adapted to envelope signals.

### 3.3 Signal processing options for improving single-element ultrasound imaging

Now that we have covered the hardware aspects of the research, we now aim t provide the reader with resources describing an improved non-array imaging method, separate from the three basic components of the signal processing path, i.e., envelope detection, signal compression and scan conversion [Basoglu et  al., 1998].

***General filtering*** has been commonly used early in the processing pipeline, often close to the ADC via DSPs and FPGAs, to remove unwanted noise from RF signals while preserving the bandwidth of interest [Assef et  al., 2019b, Levesque and Sawan, 2009].

***Envelope detection*** is a reference aspect of the signal processing path, transforming an RF signal into a human-readable image, for example using a Hilbert transform. Different envelope-detection methods and algorithms have been explored in DSPs and FPGAs [Chang et  al., 2007, Assef et  al., 2019a, Assef et  al., 2018].

***Amplitude compression*** is another points of interest: radio frequency signals are significantly large, and transfer rates between hardware and software can easily become the limiting factor. In this sense, having upstream compression would alleviate these bottlenecks [Soto-Cajiga et  al., 2012, Akkala et  al., 2014b]. Alternatives [Akkala et  al., 2014a, Boonleelakul et  al., 2013] include to adjust high dynamic ranges (12 bits and more) to the 8 bits of LCDs and CRTs, but also using the ITU-T G.711 standard (or the a-law) used in sound compression.

***Scan conversion*** is another point of interest in single-sensor designs. In the case of mechanical sweeping of an imaging area or volume, it is often necessary to geometrically reconstruct a geometrically the image from the RF signals. Several algorithms have been developed to tackle this issue [Ophir and Maklad, 1979], with a focus on real-time scan conversion [Csány et  al., 2019].

***Deconvolution***. If a point source object is scanned with an ultrasound transducer, it will be not be represented as a sharp point but as a blurred smear. The magnitude of blur in relation to the actual dimension of the point source is a measure of the resolution of the system. To record this behaviour, a point-spread function (PSF) is measured, i.e., the "impulse response" of the system. Knowing a system’s PSF makes improving the image resolution an inverse problem [Jensen et  al., 1993, Dalitz et  al., 2015]. It establishes the possibility of recursively reconstructing the true position of the point source through the inverse convolution (deconvolution). Applying deconvolution filters to an image in order to inverse the optical distortions, and hence reduce the blurring, is a critical step to enhance image quality in medical imaging [Dalitz et  al., 2015].

***Synthetic Aperture Focusing (SAF)*** : it can be noted that single-element sensors (often focused as a given depth) have good characteristics to image around this region of depth. However, outside of this fixed depth, the resolution quickly degrades - which can can be alleviated by using synthetic aperture focusing [Andresen et  al., 2011, Assef et  al., 2015, LI et  al., 2018, Lewandowski et  al., 2012, Zhang et  al., 2016]. Other Synthetic Aperture techniques (SAFT) have been widely discussed, for example in [Romero-Laorden et  al., 2013, Jeon et  al., 2019] or earlier on [Burckhardt et  al., 1974] .

***MSAS/MFFS*** : Monostatic Synthetic Aperture Scanner (MSAS) and Monostatic Fixed Focus Scanner (MFFS) are approaching worth citing in the review of data processing, as developed by [Bottenus et  al., 2015, Ylitalo and Ermert, 1994, Heuvel et  al., 2017, Nikolov et  al., 2008].

***Time reversal focusing*** would allow a low-profile acoustic imaging device with only one transmit/receive element [Etaix et  al., 2012]. Provided the medium is reciprocal and the channel’s impulse response is known, the latter can be re-emitted in time-reversed order. Mathematically, this results in the response auto-convolution [Etaix et  al., 2012]. Knowing that the auto-convolution has a peak in the origin, focusing is effectively achieved. The time reversal result is equivalent to matched filtering – energy maximization at the desired location in space and time [Robin et  al., 2017]. In practice, this opens the door to compressed sensing imaging.

***Compressed sensing (CS)*** : traditional 2-D and 3D ultrasound require the use of complex sensors, with matching hardware such as cabling. There are available, still costly - but such sensors require more hardware and become ultimately more complex and expensive to produce. It appears that classical sampling is challenged by the signal processing "compressed sensing" field [Liutkus et  al., 2014]: many signals have a sparse representation - a finite sparse signal can be reconstructed from a small set of linear, non-adaptive measurements [Hua et  al., 2011]. This allows for reconstruction of a signal with fewer samples than dictated by the Nyquist-Shannon sampling theorem, thereby enabling "sub-Nyquist" sampling. Starting with time reversal applications [Montaldo et  al., 2004, Montaldo et  al., 2005] or [Sarvazyan et  al., 2009], compressing measurements before sensing enable new clinical applications, with for example analogue compression techniques, where positioning a plastic coding mask in front of the aperture [Fedjajevs, 2016] or simply for the purpose of envelope extraction [Kim et  al., 2020]. One can therefore encode individual voxels through a ’chaotic’ intermediary [Luong et  al., 2016], and allows to design simple ultrasound imaging equipment that can provide 3D imaging using a single-element ultrasound sensor. This opens doors to simpler hardware - and new applications [Kruizinga et  al., 2017]. Different works have been dedicated to creating the phase encoding masks [van  der Meulen et  al., 2017] or even using random interference to improve image resolution [Ni and Lee, 2020].

***Barker codes*** is a way as well to work on improving imaging from the creation of the signal itself. It has been shown for example that it is possible to improve lateral resolution with excitation 5-bit barker codes [Fujita and Hasegawa, 2017, Chun et  al., 2015, Kim et  al., 2018] also presents a Binary cLuster (BL) code for improved compression ratio compared to the exponential Golomb code.

***Machine learning*** (ML) presents opportunities from an early stage for ultrasound imaging : promising steps have been taken in this direction in terms of both image quality improvement [Wang et  al., 2019a, Hewener et  al., 2019] and support for image interpretation [Divya  Krishna et  al., 2016], even in A-mode [Brausch and Hewener, 2019]. An open-source MT tool to interpret Doppler signals [Dhutia et  al., 2017] has also been developed. ML also applies to texture imaging, as earlier proposed by reviewing "Average Higuchi Dimension of RF Time series" [Moradi et  al., 2006], or in to-non imaging techniques, such as mixing monitoring [Bowler et  al., 2020].

## 4 Conclusion

State-of-the-art ultrasound hardware design and implementation were described in this article. Though there is a lack of available open hardware on the market, there seems to be sufficient information available to assemble a proof-of-concept system that offers a safe, cheap and portable alternative to other imaging technologies.

The number of multi-channel designs appears to have grown due to the increased availability of electronic components and AFE integration of additional analog channels, these systems also have improved functionality. However, these designs also require rapid logic control, which is not possible from an open-source perspective, however, this may change in the coming years. In addition, compressed sensing allows for drastic improvements in image quality while reducing the number of sensors and the corresponding hardware required.

From an academic perspective, there is significant evidence in the literature demonstrating the utility of open-source design. Moreover, researchers have identified ultrasound as a safe, low-cost solution in medically under-served regions and markets with rising health costs. There is also increased interest in terms of private-sector research and development, as indicated by the abundance of recent works and new projects indicating the innovative aspects of the topic. This would also support the development of multi-modalities devices – systems that combine ultrasound with electrical, MRI, optical and tomography imaging modalities – especially in light of the recent piezoelectric OLEDs [Yu et  al., 2020] or non-contact laser ultrasound [Zhang et  al., 2019c], a development that that has the potential to drastically change the ultrasound hardware paradigm. In particular, it appears feasible to reproduce the methodology for a [single-element device](http://un0rick.cc) to develop an open-hardware MRI device, as requirements appear relatively similar.

In general, open source ultrasound hardware research [Roman, 2019] has begun, and it is our hope that this article will encourage other researchers and makers to share their work. Joining forces with industrial players such as Shenzen, along with quality experts and medical staff to build fully open-source devices is clearly something that is possible for the production of veterinary or NDT devices.

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References

[noa, a] Integration of the Remote Ultrasound Nondestructive Evaluation (NDE) Procedures into Engineering Programs.

[noa, b] Wrist and Finger Gesture Recognition With Single-Element Ultrasound Signals: A Comparison With Single-Channel Surface Electromyogram - IEEE Journals & Magazine.

[Ahn et  al., 2015] Ahn, S., Kang, J., Kim, P., Lee, G., Jeong, E., Jung, W., Park, M., and Song, T. k. (2015). Smartphone-based portable ultrasound imaging system: Prototype implementation and evaluation. In *2015 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4.

[Akkala et  al., 2014a] Akkala, V., Bharath, R., Rajalakshmi, P., and Kumar, P. (2014a). Compression techniques for IoT enabled handheld ultrasound imaging system. In *2014 IEEE Conference on Biomedical Engineering and Sciences (IECBES)*, pages 648–652.

[Akkala et  al., 2014b] Akkala, V., Rajalakshmi, P., Kumar, P., and Desai, U. B. (2014b). FPGA based ultrasound backend system with image enhancement technique. In *5th ISSNIP-IEEE Biosignals and Biorobotics Conference (2014): Biosignals and Robotics for Better and Safer Living (BRC)*, pages 1–5.

[Al-Aufi et  al., 2019] Al-Aufi, Y. A., Hewakandamby, B. N., Dimitrakis, G., Holmes, M., Hasan, A., and Watson, N. J. (2019). Thin film thickness measurements in two phase annular flows using ultrasonic pulse echo techniques. *Flow Measurement and Instrumentation*, 66:67–78.

[Ali, 2008] Ali, M. (2008). Signal processing overview of ultrasound systems for medical imaging.

[Alqasemi et  al., 2012] Alqasemi, U., Li, H., Aguirre, A., and Zhu, Q. (2012). FPGA-Based Reconfigurable Processor for Ultrafast Interlaced Ultrasound and Photoacoustic Imaging. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 59(7):1344–1353.

[Andresen et  al., 2011] Andresen, H., Nikolov, S. I., and Jensen, J. A. (2011). Synthetic aperture focusing for a single-element transducer undergoing helical motion. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 58(5):935–943.

[Ashfaq and Ermert, 2004] Ashfaq, M. and Ermert, H. (2004). A new approach towards ultrasonic transmission tomography with a standard ultrasound system. In *IEEE Ultrasonics Symposium, 2004*, volume 3, pages 1848–1851 Vol.3. ISSN: 1051-0117.

[Assef et  al., 2019a] Assef, A. A., de Oliveira, J., Maia, J. M., and Costa, E. T. (2019a). FPGA Implementation and Evaluation of an Approximate Hilbert Transform-Based Envelope Detector for Ultrasound Imaging Using the DSP Builder Development Tool. In *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 2813–2816. ISSN: 1557-170X.

[Assef et  al., 2018] Assef, A. A., Ferreira, B. M., Maia, J. M., and Costa, E. T. (2018). Modeling and FPGA-based implementation of an efficient and simple envelope detector using a Hilbert Transform FIR filter for ultrasound imaging applications. *Research on Biomedical Engineering*, 34(1):87–92.

[Assef et  al., 2015] Assef, A. A., Maia, J. M., and Costa, E. T. (2015). A flexible multichannel FPGA and PC-Based ultrasound system for medical imaging research: initial phantom experiments. *Research on Biomedical Engineering*, 31(3):277–281.

[Assef et  al., 2016] Assef, A. A., Maia, J. M., and Costa, E. T. (2016). Initial experiments of a 128-channel FPGA and PC-based ultrasound imaging system for teaching and research activities. In *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 5172–5175.

[Assef et  al., 2014] Assef, A. A., Maia, J. M., Costa, E. T., and Nantes, V. L. d. S. (2014). A compact and reconfigurable 8-channel Ultrasound Evaluation System for experimental research. In *2014 IEEE International Ultrasonics Symposium*, pages 1607–1610.

[Assef et  al., 2012] Assef, A. A., Maia, J. M., Schneider, F. K., Costa, E. T., and Button, V. L. S. N. (2012). Design of a 128-channel FPGA-based ultrasound imaging beamformer for research activities. pages 635–638. IEEE.

[Assef et  al., 2019b] Assef, A. A., Oliveira, J. d., Scherbaty, L., Maia, J. M., Zimbico, A., Ferreira, B. M., and Costa, E. T. (2019b). Modeling of a Simple and Efficient Cascaded FPGA-Based Digital Band-Pass FIR Filter for Raw Ultrasound Data. *XXVI Brazilian Congress on Biomedical Engineering*, pages 501–505.

[Attarzadeh et  al., 2017] Attarzadeh, H., Xu, Y., and Ytterdal, T. (2017). A Low-Power High-Dynamic-Range Receiver System for In-Probe 3-D Ultrasonic Imaging. *IEEE Transactions on Biomedical Circuits and Systems*, 11(5):1053–1064.

[Basak et  al., 2013] Basak, A., Ranganathan, V., and Bhunia, S. (2013). A wearable ultrasonic assembly for point-of-care autonomous diagnostics of malignant growth. pages 128–131.

[Basoglu et  al., 1998] Basoglu, C., Managuli, R., York, G., and Kim, Y. (1998). Computing requirements of modern medical diagnostic ultrasound machines. *Parallel Computing*, 24(9):1407–1431.

[Batbayar et  al., 2018] Batbayar, E., Ham, W., Tumenjargal, E., and Song, C. (2018). A Hardware Design of Capture Multichannel Ultrasound Raw Signal for Photoacoustic Medical Image. *제어로봇시스템학회 국내학술대회 논문집*, pages 257–259.

[Berthon et  al., 2017] Berthon, B., Pierre-Marc, D., Mickael, T., and Mathieu Pernot, J. P. (2017). An Integrated and highly sensitive Ultrafast Acoustoelectric Imaging System for biomedical applications. *Bioscience Reports*.

[Bezanson et  al., 2011] Bezanson, A. B., Adamson, R., and Brown, J. A. (2011). A low-cost high frame-rate piezoelectric scanning mechanism for high-frequency ultrasound systems. In *2011 IEEE International Ultrasonics Symposium*, pages 458–461.

[Bharath et  al., 2015a] Bharath, R., Chandrashekar, D., Akkala, V., Krishna, D., Ponduri, H., Rajalakshmi, P., and Desai, U. B. (2015a). Portable ultrasound scanner for remote diagnosis. In *2015 17th International Conference on E-health Networking, Application Services (HealthCom)*, pages 211–216.

[Bharath et  al., 2015b] Bharath, R., Kumar, P., Dusa, C., Akkala, V., Puli, S., Ponduri, H., Krishna, K. D., Rajalakshmi, P., Merchant, S. N., Mateen, M. A., and Desai, U. B. (2015b). FPGA-Based Portable Ultrasound Scanning System with Automatic Kidney Detection. *Journal of Imaging*, 1(1):193–219.

[Bharath et  al., 2018] Bharath, R., Kumar, P., Reddy, D. S., and Rajalakshmi, P. (2018). Compact and Programmable Ultrasound Front-End Processing Module for Research Activities. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 921–924, Honolulu, HI. IEEE.

[Bharath et  al., 2016] Bharath, R., Reddy, D. S., Kumar, P., and Rajalakshmi, P. (2016). Novel architecture for wireless transducer based ultrasound imaging system. In *2016 IEEE EMBS Conference on Biomedical Engineering and Sciences (IECBES)*, pages 432–436.

[Biosono, ] Biosono. SonoLab Echo I hardware.

[Boni et  al., 2016] Boni, E., Bassi, L., Dallai, A., Guidi, F., Meacci, V., Ramalli, A., Ricci, S., and Tortoli, P. (2016). ULA-OP 256: A 256-Channel Open Scanner for Development and Real-Time Implementation of New Ultrasound Methods. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 63(10):1488–1495.

[Boni et  al., 2012] Boni, E., Bassi, L., Dallai, A., Guidi, F., Ramalli, A., Ricci, S., Housden, J., and Tortoli, P. (2012). A reconfigurable and programmable FPGA-based system for nonstandard ultrasound methods. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 59(7):1378–1385.

[Boni et  al., 2018] Boni, E., Yu, A. C. H., Freear, S., Jensen, J. A., and Tortoli, P. (2018). Ultrasound Open Platforms for Next-Generation Imaging Technique Development. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 65(7):1078–1092.

[Boonleelakul et  al., 2013] Boonleelakul, W., Techavipoo, U., Worasawate, D., Keinprasit, R., Pinunsottikul, P., Sugino, N., and Thajchayapong, P. (2013). Compression of ultrasound RF data using quantization and decimation. In *The 6th 2013 Biomedical Engineering International Conference*, pages 1–4.

[Bottenus et  al., 2015] Bottenus, N., Jakovljevic, M., Boctor, E., and E. Trahey, G. (2015). Implementation of swept synthetic aperture imaging. *Progress in Biomedical Optics and Imaging - Proceedings of SPIE*, 9419.

[Bottenus et  al., 2016] Bottenus, N., Long, W., Zhang, H. K., Jakovljevic, M., Bradway, D. P., Boctor, E. M., and Trahey, G. E. (2016). Feasibility of Swept Synthetic Aperture Ultrasound Imaging. *IEEE Transactions on Medical Imaging*, 35(7):1676–1685.

[Bowler et  al., 2020] Bowler, A. L., Bakalis, S., and Watson, N. J. (2020). Monitoring Mixing Processes Using Ultrasonic Sensors and Machine Learning. *Sensors*, 20(7):1813.

[Brausch and Hewener, 2019] Brausch, L. and Hewener, H. (2019). Classifying muscle states with ultrasonic single element transducer data using machine learning strategies. page 022001, Bruges, Belgium.

[Brausch et  al., 2019] Brausch, L., Hewener, H., and Lukowicz, P. (2019). Towards a wearable low-cost ultrasound device for classification of muscle activity and muscle fatigue. In *Proceedings of the 23rd International Symposium on Wearable Computers - ISWC ’19*, pages 20–22, London, United Kingdom. ACM Press.

[Brown et  al., 2013] Brown, J. A., Leadbetter, J., Leung, M., Bezanson, A., and Adamson, R. (2013). A low cost open source high frame-rate high-frequency imaging system. In *2013 IEEE International Ultrasonics Symposium (IUS)*, pages 549–552.

[Brown and Lockwood, 2002] Brown, J. A. and Lockwood, G. R. (2002). Low-cost, high-performance pulse generator for ultrasound imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 49(6):848–851.

[Brunner and Com, 2002] Brunner, E. and Com, E. (2002). How ultrasound system considerations influence front-end component choice.

[Burckhardt et  al., 1974] Burckhardt, C. E., Grandchamp, P. A., and Hoffmann, H. (1974). An Experimental 2 MHz Synthetic Aperture Sonar System Intended for Medical Use. *IEEE Transactions on Sonics and Ultrasonics*, 21(1):1–6.

[Carotenuto et  al., 2004] Carotenuto, R., Caliano, G., and Caronti, A. (2004). Very fast scanning probe for ophthalmic echography using an ultrasound motor. In *IEEE Ultrasonics Symposium, 2004*, volume 2, pages 1310–1313 Vol.2.

[Carotenuto et  al., 2005] Carotenuto, R., Caliano, G., Caronti, A., Savoia, A., and Pappalardo, M. (2005). Fast scanning probe for ophthalmic echography using an ultrasound motor. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 52(11):2039–2046.

[Chagas, 2018] Chagas, A. M. (2018). Haves and have nots must find a better way: The case for open scientific hardware. *PLOS Biology*, 16(9):e3000014.

[Chang et  al., 2007] Chang, J., Yen, J., and Shung, K. (2007). A Novel Envelope Detector for High-Frame Rate, High-Frequency Ultrasound Imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 54(9):1792–1801.

[Chang et  al., 2009] Chang, J. H., Sun, L., Yen, J. T., and Shung, K. K. (2009). Low-Cost, High-Speed Back-End Processing System for High-Frequency Ultrasound B-Mode Imaging. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 56(7):1490–1497.

[Chang-hong Hu et  al., 2008] Chang-hong Hu, Qifa Zhou, and Shung, K. (2008). Design and implementation of high frequency ultrasound pulsed-wave Doppler using FPGA. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 55(9):2109–2111.

[Chatar and George, 2016] Chatar, K. and George, M. L. (2016). Analysis of Existing Designs for FPGA-Based Ultrasound Imaging Systems. *International Journal of Signal Processing, Image Processing and Pattern Recognition*, 9(7):13–24.

[Chen et  al., 2016] Chen, C.-K., Fang, J., Wan, Y.-L., and Tsui, P.-H. (2016). Ultrasound characterization of the mastoid for detecting middle ear effusion: A preliminary clinical validation. *Scientific Reports*, 6(1):27777. Number: 1 Publisher: Nature Publishing Group.

[Cheung et  al., 2012] Cheung, C. C. P., Yu, A. C. H., Salimi, N., Yiu, B. Y. S., Tsang, I. K. H., Kerby, B., Azar, R. Z., and Dickie, K. (2012). Multi-channel pre-beamformed data acquisition system for research on advanced ultrasound imaging methods. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 59(2):243–253.

[Choi et  al., 2020] Choi, S., Kim, J. Y., Lim, H. G., Baik, J. W., Kim, H. H., and Kim, C. (2020). Versatile Single-Element Ultrasound Imaging Platform using a Water-Proofed MEMS Scanner for Animals and Humans. *Scientific Reports*, 10(1):6544.

[Chu, ] Chu, C. Designing An Ultrasound Pulser with MD1812/MD1813 Composite Drivers.

[Chun et  al., 2015] Chun, G.-C., Chiang, H.-J., Lin, K.-H., Li, C.-M., Chen, P.-J., and Chen, T. (2015). Ultrasound Elasticity Imaging System with Chirp-Coded Excitation for Assessing Biomechanical Properties of Elasticity Phantom. *Materials*, 8(12):8392–8413. Number: 12 Publisher: Multidisciplinary Digital Publishing Institute.

[Cox et  al., 2017] Cox, B. F., Stewart, F., Lay, H., Cummins, G., Newton, I. P., Desmulliez, M. P. Y., Steele, R. J. C., Näthke, I., and Cochran, S. (2017). Ultrasound capsule endoscopy: sounding out the future. *Annals of Translational Medicine*, 5(9):201.

[Cramer et  al., 2015] Cramer, K. E., Perey, D. F., and Yost, W. T. (2015). Ultrasonic inspection to quantify failure pathologies of crimped electrical connections. *AIP Conference Proceedings*, 1650(1):1820–1825. Publisher: American Institute of Physics.

[Csány et  al., 2019] Csány, G., Szalai, K., and Gyöngy, M. (2019). A real-time data-based scan conversion method for single element ultrasound transducers. *Ultrasonics*, 93:26–36.

[Dalitz et  al., 2015] Dalitz, C., Pohle-Frohlich, R., and Michalk, T. (2015). Point spread functions and deconvolution of ultrasonic images. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 62(3):531–544.

[De  Maria et  al., 2018] De Maria, C., Di Pietro, L., Lantada, A. D., Madete, J., Makobore, P. N., Mridha, M., Ravizza, A., Torop, J., and Ahluwalia, A. (2018). Safe innovation: On medical device legislation in Europe and Africa. *Health Policy and Technology*, 7(2):156–165. Publisher: Elsevier.

[Dhutia et  al., 2017] Dhutia, N. M., Zolgharni, M., Mielewczik, M., Negoita, M., Sacchi, S., Manoharan, K., Francis, D. P., and Cole, G. D. (2017). Open-source, vendor-independent, automated multi-beat tissue Doppler echocardiography analysis. *The International Journal of Cardiovascular Imaging*, 33(8):1135–1148.

[Di  Ianni et  al., 2016] Di Ianni, T., Hemmsen, M. C., Llimos Muntal, P., Jorgensen, I. H. H., and Jensen, J. A. (2016). System-Level Design of an Integrated Receiver Front End for a Wireless Ultrasound Probe. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 63(11):1935–1946.

[Divya  Krishna et  al., 2016] Divya Krishna, K., Akkala, V., Bharath, R., Rajalakshmi, P., Mohammed, A. M., Merchant, S. N., and Desai, U. B. (2016). Computer Aided Abnormality Detection for Kidney on FPGA Based IoT Enabled Portable Ultrasound Imaging System. *IRBM*, 37(4):189–197.

[Duncan, 1990] Duncan, M. G. (1990). Real-time analysis signal processor for ultrasonic nondestructive testing. *IEEE Transactions on Instrumentation and Measurement*, 39(6):1024–1029.

[Duric et  al., 2007] Duric, N., Littrup, P., Poulo, L., Babkin, A., Pevzner, R., Holsapple, E., Rama, O., and Glide, C. (2007). Detection of breast cancer with ultrasound tomography: first results with the Computed Ultrasound Risk Evaluation (CURE) prototype. *Medical Physics*, 34(2):773–785.

[Dusa et  al., 2014] Dusa, C., Rajalakshmi, P., Puli, S., Desai, U. B., and Merchant, S. N. (2014). Low complex, programmable FPGA based 8-channel ultrasound transmitter for medical imaging researches. In *2014 IEEE 16th International Conference on e-Health Networking, Applications and Services (Healthcom)*, pages 252–256.

[Enwia, 2020] Enwia, G. (2020). *OPEN-SOURCE MINIATURIZED TEST-BENCH DESIGN FOR APPLICATIONS IN WEARABLE AUTONOMOUS ULTRASOUND IMAGING*. PhD thesis, CASE WESTERN RESERVE UNIVERSITY.

[Enwia et  al., 2019] Enwia, G., Pashaei, V., Bayat, M., Roman, A., and Mandal, S. (2019). An Open-Source Ultrasound Imaging System with Wearable Active Probes. In *2019 IEEE National Aerospace and Electronics Conference (NAECON)*, pages 503–506. ISSN: 2379-2027.

[Erickson et  al., 2001] Erickson, S., Kruse, D., and Ferrara, K. (2001). A hand-held, high frequency ultrasound scanner. In *2001 IEEE Ultrasonics Symposium. Proceedings. An International Symposium (Cat. No.01CH37263)*, volume 2, pages 1465–1468 vol.2.

[Etaix et  al., 2012] Etaix, N., Fink, M., and Ing, R. K. (2012). Acoustic imaging device with one transducer. *The Journal of the Acoustical Society of America*, 131(5):EL395–EL399.

[Farsoni et  al., 2017] Farsoni, S., Bonfè, M., and Astolfi, L. (2017). A low-cost high-fidelity ultrasound simulator with the inertial tracking of the probe pose. *Control Engineering Practice*, 59:183–193.

[Fedjajevs, 2016] Fedjajevs (2016). *Ultrasound Imaging Using a Single Element Transducer*. PhD thesis, tudelft.

[Fontes-Pereira et  al., 2018] Fontes-Pereira, A., Rosa, P., Barboza, T., Matusin, D., Freire, A. S., Braz, B. F., Machado, C. B., von Krüger, M. A., Souza, S. A. L. d., Santelli, R. E., and Pereira, W. C. d. A. (2018). Monitoring bone changes due to calcium, magnesium, and phosphorus loss in rat femurs using Quantitative Ultrasound. *Scientific Reports*, 8(1):1–9.

[FRITSCH, ] FRITSCH, C. A Full Featured Ultrasound NDE System in a Standard FPGA.

[Fujita and Hasegawa, 2017] Fujita, H. and Hasegawa, H. (2017). Effect of frequency characteristic of excitation pulse on lateral spatial resolution in coded ultrasound imaging. *Japanese Journal of Applied Physics*, 56(7S1):07JF16.

[Garcia-Rodriguez et  al., 2010] Garcia-Rodriguez, M., Garcia-Alvarez, J., Yañez, Y., Garcia-Hernandez, M., Salazar, J., Turo, A., and Chavez, J. (2010). Low cost matching network for ultrasonic transducers. *Physics Procedia*, 3(1):1025–1031.

[George et  al., 2018] George, S. S., Huang, M. C., and Ignjatovic, Z. (2018). Portable ultrasound imaging system with super-resolution capabilities. *Ultrasonics*.

[Gibney, 2016] Gibney, E. (2016). ‘Open-hardware’ pioneers push for low-cost lab kit. *Nature*, 531(7593):147–148.

[Gil-Alba et  al., 2019] Gil-Alba, R., Alonso, L., Navarro, C., and García-Castillo, S. K. (2019). Morphological study of damage evolution in woven-laminates subjected to high-velocity impact. *Mechanics of Advanced Materials and Structures*, 26(24):2023–2029.

[Govindan et  al., 2015] Govindan, P., Vasudevan, V., Gonnot, T., and Saniie, J. (2015). Reconfigurable Ultrasonic Testing System Development Using Programmable Analog Front-End and Reconfigurable System-on-Chip Hardware. *Circuits and Systems*, 06(07):161.

[GoŃabek et  al., 2019] Gołąbek, M., Rymarczyk, T., and Adamkiewicz, P. (2019). Construction of Ultrasonic Reflection Tomograph for Analysis of Technological Processes. In *2019 Applications of Electromagnetics in Modern Engineering and Medicine (PTZE)*, pages 47–51.

[Granata et  al., 2020] Granata, E., Vishwa, A., and Shen, J. (2020). Designing Bipolar High Voltage SEPIC Supply for Ultrasound Smart Probe. page 15.

[Gräsel et  al., 2017] Gräsel, M., Glüer, C. C., and Barkmann, R. (2017). Characterization of a new ultrasound device designed for measuring cortical porosity at the human tibia: A phantom study. *Ultrasonics*, 76:183–191.

[Guasch et  al., 2020] Guasch, L., Calderón Agudo, O., Tang, M.-X., Nachev, P., and Warner, M. (2020). Full-waveform inversion imaging of the human brain. *npj Digital Medicine*, 3(1):1–12.

[Gwirc et  al., 2019] Gwirc, S. N., Márquez, M. A., Mariño, N., Pascoli, H., and Fernández, N. (2019). Desarrollo de Módulo Emisor/Receptor Ultrasónico Multicanal. Accepted: 2019-10-24T15:56:08Z Publisher: Universidad Nacional de La Matanza. Departamento de Ingeniería e Investigaciones Tecnológicas.

[Hager, 2019] Hager, P. A. (2019). *Design of Fully-Digital Medical Ultrasound Imaging Systems*. PhD thesis, Zurich.

[Hager and Benini, 2019] Hager, P. A. and Benini, L. (2019). LightProbe: A Digital Ultrasound Probe for Software-Defined Ultrafast Imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 66(4):747–760.

[Hager et  al., 2017a] Hager, P. A., Risser, C., Weber, P. K., and Benini, L. (2017a). LightProbe: A 64-channel programmable ultrasound transducer head with an integrated front-end and a 26.4 Gb/s optical link. In *2017 IEEE International Symposium on Circuits and Systems (ISCAS)*, pages 1–4.

[Hager et  al., 2017b] Hager, P. A., Speicher, D., Degel, C., and Benini, L. (2017b). UltraLight: An ultrafast imaging platform based on a digital 64-channel ultrasound probe. pages 1–5. IEEE.

[Herickhoff et  al., 2019] Herickhoff, C., Lin, J., and Dahl, J. (2019). Low-cost Sensor-enabled Freehand 3D Ultrasound. In *2019 IEEE International Ultrasonics Symposium (IUS)*, pages 498–501. ISSN: 1948-5727.

[Herickhoff et  al., 2018] Herickhoff, C. D., Morgan, M. R., Broder, J. S., and Dahl, J. J. (2018). Low-cost Volumetric Ultrasound by Augmentation of 2D Systems: Design and Prototype. *Ultrasonic Imaging*, 40(1):35–48.

[Heuvel et  al., 2017] Heuvel, T. L. A. v. d., Graham, D. J., Smith, K. J., Korte, C. L. d., and Neasham, J. A. (2017). Development of a Low-Cost Medical Ultrasound Scanner Using a Monostatic Synthetic Aperture. *IEEE Transactions on Biomedical Circuits and Systems*, 11(4):849–857.

[Hewener et  al., 2019] Hewener, H., Risser, C., Brausch, L., Rohrer, T., and Tretbar, S. (2019). A mobile ultrasound system for majority detection. In *2019 IEEE International Ultrasonics Symposium (IUS)*, pages 502–505. ISSN: 1948-5719.

[Hewener et  al., 2012] Hewener, H. J., Welsch, H. J., Fonfara, H., Motzki, F., and Tretbar, S. H. (2012). Highly scalable and flexible FPGA based platform for advanced ultrasound research. In *2012 IEEE International Ultrasonics Symposium*, pages 2075–2080.

[Hidayat et  al., 2020] Hidayat, D., Syafei, N. S., Emiliano, Rohadi, N., Setianto, and Wibawa, B. M. (2020). Determination of generated ultrasonic wave characteristics by a bipolar square burst excitation. *Journal of Physics: Conference Series*, 1568:012007.

[HILLGER, 2016] HILLGER, W. (2016). High Frequency Ultrasonic Systems with Frequency Ranges of 35 to 200 MHz.

[Hu et  al., 2011] Hu, T., Zhao, X., and Xia, L. (2011). Design of a protable ultrasonic system based on USB used in carotid artery measurement. In *2011 4th International Conference on Biomedical Engineering and Informatics (BMEI)*, volume 2, pages 1068–1071. ISSN: 1948-2922.

[Hua et  al., 2011] Hua, S., Yuchi, M., and Ding, M. (2011). Compressed Sensing for RF Signal Reconstruction in B-model Ultrasound Imaging. In *2011 International Conference on Intelligent Computation and Bio-Medical Instrumentation*, pages 19–22.

[Huang and Zou, 2015] Huang, C.-H. and Zou, J. (2015). A novel two-axis micromechanical scanning transducer using water-immersible electromagnetic actuators for handheld 3D ultrasound imaging. *Sensors and Actuators A: Physical*, 236:281–288.

[Ibrahim et  al., 2017] Ibrahim, A., Simon, W., Doy, D., Pignat, E., Angiolini, F., Arditi, M., Thiran, J. P., and Micheli, G. D. (2017). Single-FPGA complete 3D and 2D medical ultrasound imager. In *2017 Conference on Design and Architectures for Signal and Image Processing (DASIP)*, pages 1–6.

[Ibrahim et  al., 2018] Ibrahim, A., Zhang, S., Angiolini, F., Arditi, M., Kimura, S., Goto, S., Thiran, J., and Micheli, G. D. (2018). Towards Ultrasound Everywhere: A Portable 3D Digital Back-End Capable of Zone and Compound Imaging. *IEEE Transactions on Biomedical Circuits and Systems*, pages 1–14.

[Jensen et  al., 1993] Jensen, J. A., Mathorne, J., Gravesen, T., and Stage, B. (1993). Deconvolution of in-Vivo Ultrasound B-Mode Images , Deconvolution of in-Vivo Ultrasound B-Mode Images. *Ultrasonic Imaging*, 15(2):122–133.

[Jeon et  al., 2019] Jeon, S., Park, J., Managuli, R., and Kim, C. (2019). A Novel 2-D Synthetic Aperture Focusing Technique for Acoustic-Resolution Photoacoustic Microscopy. *IEEE Transactions on Medical Imaging*, 38(1):250–260.

[Jin et  al., 2017] Jin, B. C., Li, X., Jain, A., González, C., LLorca, J., and Nutt, S. (2017). Optimization of microstructures and mechanical properties of composite oriented strand board from reused prepreg. *Composite Structures*, 174:389–398.

[Johnson et  al., 2018] Johnson, B. C., Shen, K., Piech, D., Ghanbari, M. M., Li, K. Y., Neely, R., Carmena, J. M., Maharbiz, M. M., and Muller, R. (2018). StimDust: A 6.5mm3, wireless ultrasonic peripheral nerve stimulator with 82% peak chip efficiency. In *2018 IEEE Custom Integrated Circuits Conference (CICC)*, pages 1–4. ISSN: 2152-3630.

[Jonveaux, 2017] Jonveaux, L. (2017). Arduino-like development kit for single-element ultrasound imaging. *Journal of Open Hardware*, 1(1).

[Jonveaux, 2019] Jonveaux, L. (2019). un0rick : open-source fpga board for single element ultrasound imaging.

[Joseph et  al., 2015a] Joseph, J., Radhakrishnan, R., Kusmakar, S., Thrivikraman, A. S., and Sivaprakasam, M. (2015a). Technical Validation of ARTSENS–An Image Free Device for Evaluation of Vascular Stiffness. *IEEE Journal of Translational Engineering in Health and Medicine*, 3:1–13.

[Joseph et  al., 2015b] Joseph, J., Thrivikraman, A. S., Radhakrishnan, R., and Sivaprakasam, M. (2015b). ARTSENSTouch - A portable device for evaluation of carotid artery stiffness. In *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 3755–3758.

[Kang et  al., 2017] Kang, J., Kim, Y., Lee, W., and Yoo, Y. (2017). A New Dynamic Complex Baseband Pulse Compression Method for Chirp-Coded Excitation in Medical Ultrasound Imaging. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 64(11):1698–1710.

[Karjalainen et  al., 2012] Karjalainen, J. P., Riekkinen, O., Töyräs, J., Hakulinen, M., Kröger, H., Rikkonen, T., Salovaara, K., and Jurvelin, J. S. (2012). Multi-site bone ultrasound measurements in elderly women with and without previous hip fractures. *Osteoporosis International*, 23(4):1287–1295.

[Keyes, 2017] Keyes, S. R. (2017). *Electrical system for interfacing with muscle for use in prosthetic devices*. Thesis, Massachusetts Institute of Technology.

[Kidav et  al., 2019] Kidav, J. U., Sivamangai, N. M., Pillai, M. P., and Raja M, S. (2019). Architecture and FPGA prototype of cycle stealing DMA array signal processor for ultrasound sector imaging systems. *Microprocessors and Microsystems*, 64:53–72.

[KieŃczyński et  al., 2017] Kiełczyński, P., Ptasznik, S., Szalewski, M., Balcerzak, A., Wieja, K., and Rostocki, A. J. (2017). Thermophysical properties of rapeseed oil methyl esters (RME) at high pressures and various temperatures evaluated by ultrasonic methods. *Biomass and Bioenergy*, 107:113–121.

[Kim et  al., 2018] Kim, J. H., Yeo, S., Kim, J. W., Kim, K., Song, T.-K., Yoon, C., and Sung, J. (2018). Real-Time Lossless Compression Algorithm for Ultrasound Data Using BL Universal Code. *Sensors*, 18(10):3314.

[Kim et  al., 2017] Kim, J. H., Yeo, S., Kim, M., Kye, S., Lee, Y., and Song, T. k. (2017). A smart-phone based portable ultrasound imaging system for point-of-care applications. In *2017 10th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics (CISP-BMEI)*, pages 1–5.

[Kim et  al., 2020] Kim, Y., Park, J., and Kim, H. (2020). Signal-Processing Framework for Ultrasound Compressed Sensing Data: Envelope Detection and Spectral Analysis. *Applied Sciences*, 10(19):6956.

[Kjeken et  al., 2011] Kjeken, I., Smedslund, G., Moe, R. H., Slatkowsky-Christensen, B., Uhlig, T., and Hagen, K. B. (2011). Systematic review of design and effects of splints and exercise programs in hand osteoarthritis. *Arthritis Care & Research*, 63(6):834–848.

[Kou et  al., 2020] Kou, Z., Miller, R. J., Singer, A. C., and Oelze, M. L. (2020). Real-time video streaming in vivo using ultrasound as the communication channel. *arXiv:2009.13683 [eess]*. arXiv: 2009.13683.

[Kruizinga et  al., 2017] Kruizinga, P., Meulen, P. v. d., Fedjajevs, A., Mastik, F., Springeling, G., Jong, N. d., Bosch, J. G., and Leus, G. (2017). Compressive 3D ultrasound imaging using a single sensor. *Science Advances*, 3(12):e1701423.

[Kurjak and Breyer, 1986] Kurjak, A. and Breyer, B. (1986). The use of ultrasound in developing countries. *Ultrasound in Medicine & Biology*, 12(8):611–621.

[Kuru et  al., 2019] Kuru, K., Ansell, D., Jones, M., Goede, C. D., and Leather, P. (2019). Feasibility study of intelligent autonomous determination of the bladder voiding need to treat bedwetting using ultrasound and smartphone ML techniques. *Medical & Biological Engineering & Computing*, 57(5):1079–1097.

[Kushi and Suresh  Babu, 2017] Kushi, A. and Suresh Babu, P. (2017). Ultrasonic Signal Processing Using FPGA. pages 82–87.

[Lay et  al., 2018] Lay, H., Cummins, G., Cox, B. F., Qiu, Y., Turcanu, M. V., McPhillips, R., Connor, C., Gregson, R., Clutton, E., Desmulliez, M. P. Y., and Cochran, S. (2018). In-Vivo Evaluation of Microultrasound and Thermometric Capsule Endoscopes. *IEEE Transactions on Biomedical Engineering*, pages 1–1.

[Lay et  al., 2016] Lay, H. S., Qiu, Y., Al-Rawhani, M., Beeley, J., Poltarjonoks, R., Seetohul, V., Cumming, D., Cochran, S., Cummins, G., Desmulliez, M. P. Y., Wallace, M., Trolier-McKinstry, S., McPhillips, R., Cox, B. F., and Demore, C. E. M. (2016). Progress towards a multi-modal capsule endoscopy device featuring microultrasound imaging. In *2016 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4. ISSN: 1948-5727.

[LeCoeur, ] LeCoeur. Bluetooth single channel ultrasonic device - Android systems.

[Lee et  al., 2014a] Lee, J. H., Traverso, G., Schoellhammer, C. M., Blankschtein, D., Langer, R., Thomenius, K. E., Boning, D. S., and Anthony, B. W. (2014a). Towards wireless capsule endoscopic ultrasound (WCEU). In *2014 IEEE International Ultrasonics Symposium*, pages 734–737, Chicago, IL, USA. IEEE.

[Lee et  al., 2014b] Lee, Y., Kang, J., Yeo, S., Lee, J., Kim, G. D., Yoo, Y., and Song, T. K. (2014b). A new smart probe system for a tablet PC-based point-of-care ultrasound imaging system: Feasibility study. In *2014 IEEE International Ultrasonics Symposium*, pages 1611–1614.

[Lei, ] Lei, S. A High-Frame Rate High-Frequency Ultrasonic System for Cardiac Imaging in Mice - IEEE Journals & Magazine.

[Lei Sun et  al., 2008] Lei Sun, Xiaochen Xu, Richard, W., Feng, C., Johnson, J., and Shung, K. (2008). A High-Frame Rate Duplex Ultrasound Biomicroscopy for Small Animal Imaging *In vivo*. *IEEE Transactions on Biomedical Engineering*, 55(8):2039–2049.

[Levesque and Sawan, 2009] Levesque, P. and Sawan, M. (2009). Real-Time Hand-Held Ultrasound Medical-Imaging Device Based on a New Digital Quadrature Demodulation Processor. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 56(8):1654–1665.

[Lewandowski et  al., 2012] Lewandowski, M., Sielewicz, K., and Walczak, M. (2012). A low-cost 32-channel module with high-speed digital interfaces for portable ultrasound systems. In *2012 IEEE International Ultrasonics Symposium*, pages 1–4, Dresden, Germany. IEEE.

[LI et  al., 2018] LI, H., LUO, L., GAO, X., and LI, J. (2018). Initial Architecture Design of Ultrasound Synthetic Aperture Imaging Based on FPGA. In *2018 IEEE Far East NDT New Technology Application Forum (FENDT)*, pages 60–64.

[Li et  al., 2014] Li, H., Zhou, Y., Wang, L., and Wen, X. (2014). A New Implementation of A-Mode Ultrasound Pulser-Receiver System. In *Modelling and Simulation 2014 5th International Conference on Intelligent Systems*, pages 187–190.

[Liebgott et  al., 2012] Liebgott, H., Basarab, A., Kouame, D., Bernard, O., and Friboulet, D. (2012). Compressive sensing in medical ultrasound. In *2012 IEEE International Ultrasonics Symposium*, pages 1–6. ISSN: 1051-0117.

[Liutkus et  al., 2014] Liutkus, A., Martina, D., Popoff, S., Chardon, G., Katz, O., Lerosey, G., Gigan, S., Daudet, L., and Carron, I. (2014). Imaging With Nature: Compressive Imaging Using a Multiply Scattering Medium. *Scientific Reports*, 4:5552.

[Lorenzo et  al., 2009] Lorenzo, D. D., Momi, E. D., Beretta, E., Cerveri, P., Perona, F., and Ferrigno, G. (2009). Experimental validation of A-mode ultrasound acquisition system for computer assisted orthopaedic surgery. In *Medical Imaging 2009: Ultrasonic Imaging and Signal Processing*, volume 7265, page 726502. International Society for Optics and Photonics.

[Luong et  al., 2016] Luong, T.-D., Hies, T., and Ohl, C.-D. (2016). A compact time reversal emitter-receiver based on a leaky random cavity. *Scientific Reports*, 6:36096.

[Lévesque, 2011] Lévesque, P. (2011). *Architecture d’un processeur dédié aux traitements de signaux ultrasoniques en temps réel en vue d’une intégration sur puce*. phd.

[Martins, 2017] Martins, Y. W. (2017). A-scan ultrassônico aplicado na identificação da camada adiposa.

[Matera et  al., 2018] Matera, R., Meacci, V., Rossi, S., Russo, D., Ricci, S., and Lootcns, D. (2018). Smart Ultrasound Sensor for Non-Destructive Tests. In *2018 New Generation of CAS (NGCAS)*, pages 29–32.

[Memon et  al., 2016] Memon, F., Touma, G., Wang, J., Baltsavias, S., Moini, A., Chang, C., Rasmussen, M. F., Nikoozadeh, A., Choe, J. W., Olcott, E., Jeffrey, R. B., Arbabian, A., and Khuri-Yakub, B. T. (2016). Capsule ultrasound device: Further developments. In *2016 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4, Tours, France. IEEE.

[Meng, 2019] Meng, W. (2019). rtl-ultrasound: Ultrasound imaging with RTL-SDR.

[Montaldo et  al., 2004] Montaldo, G., Palacio, D., Tanter, M., and Fink, M. (2004). Time reversal kaleidoscope: A smart transducer for three-dimensional ultrasonic imaging. *Applied Physics Letters*, 84(19):3879–3881.

[Montaldo et  al., 2005] Montaldo, G., Palacio, D., Tanter, M., and Fink, M. (2005). Building three-dimensional images using a time-reversal chaotic cavity. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 52(9):1489–1497.

[Moradi et  al., 2006] Moradi, M., Abolmaesumi, P., Isotalo, P. A., Siemens, D. R., Sauerbrei, E. E., and Mousavi, P. (2006). Detection of Prostate Cancer from RF Ultrasound Echo Signals Using Fractal Analysis. In *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*, pages 2400–2403. ISSN: 1557-170X.

[Moritz et  al., 2019] Moritz, M., Redlich, T., Günyar, S., Winter, L., and Wulfsberg, J. P. (2019). On the Economic Value of Open Source Hardware – Case Study of an Open Source Magnetic Resonance Imaging Scanner. *Journal of Open Hardware*, 3(1):2.

[Mostavi et  al., 2017] Mostavi, A., Tehrani, N., Kamali, N., Ozevin, D., Chi, S. W., and Indacochea, J. E. (2017). The application of water coupled nonlinear ultrasonics to quantify the dislocation density in aluminum 1100. *AIP Conference Proceedings*, 1806(1):060003.

[Nguyen et  al., 2019] Nguyen, T. T., Espinoza, A. W., Hyler, S., Remme, E. W., D’hooge, J., and Hoff, L. (2019). Estimating Regional Myocardial Contraction Using Miniature Transducers on the Epicardium. *Ultrasound in Medicine & Biology*, 45(11):2958–2969.

[Ni and Lee, 2020] Ni, P. and Lee, H.-N. (2020). High-Resolution Ultrasound Imaging Using Random Interference. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, pages 1–1.

[Niezen et  al., 2016] Niezen, G., Eslambolchilar, P., and Thimbleby, H. (2016). Open-source hardware for medical devices. *BMJ Innovations*, 2(2):78–83.

[Nikolov et  al., 2008] Nikolov, S., Jensen, J., and Tomov, B. (2008). Fast parametric beamformer for synthetic aperture imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 55(8):1755–1767.

[Nowak and Markowski, 2020] Nowak, K. W. and Markowski, M. (2020). Evaluation of selected properties of a gelatinized potato starch colloid by an ultrasonic method. *Measurement*, 158:107717.

[Ophir and Maklad, 1979] Ophir, J. and Maklad, N. (1979). Digital scan converters in diagnostic ultrasound imaging. *Proceedings of the IEEE*, 67(4):654–664.

[Ozdemir, 2018] Ozdemir, A. (2018). A Remote Tone Burst Pulser Design for Automated Ultrasonic Scanning Systems.

[Pandey and Vora, 2019] Pandey, G. and Vora, A. (2019). Open Electronics for Medical Devices: State-of-Art and Unique Advantages. *Electronics*, 8(11):1256.

[Pashaei et  al., 2020] Pashaei, V., Dehghanzadeh, P., Enwia, G., Bayat, M., Majerus, S. J. A., and Mandal, S. (2020). Flexible Body-Conformal Ultrasound Patches for Image-Guided Neuromodulation. *IEEE Transactions on Biomedical Circuits and Systems*, 14(2):305–318. Conference Name: IEEE Transactions on Biomedical Circuits and Systems.

[Pashaei et  al., 2018] Pashaei, V., Roman, A., and Mandal, S. (2018). Live Demonstration: An Open-Source Test-Bench for Autonomous Ultrasound Imaging. pages 1–1.

[Pearce, 2015] Pearce, J. M. (2015). Quantifying the value of open source hardware development. *Modern Economy*, 6:1–11.

[Pearce, 2016] Pearce, J. M. (2016). Return on investment for open source scientific hardware development. *Science and Public Policy*, 43(2):192–195.

[Peyton et  al., 2017] Peyton, G., Boutelle, M., and M. Drakakis, E. (2017). Front-End Receiver Architecture for Miniaturised Ultrasound Imaging.

[Peyton et  al., 2018] Peyton, G., Boutelle, M. G., and Drakakis, E. M. (2018). Comparison of synthetic aperture architectures for miniaturised ultrasound imaging front-ends. *BioMedical Engineering OnLine*, 17:83.

[Poulsen et  al., 2005] Poulsen, C., Pedersen, P., and Szabo, T. (2005). An optical registration method for 3D ultrasound freehand scanning. In *Proceedings - IEEE Ultrasonics Symposium*, volume 2, pages 1236–1240.

[Pérez-Sánchez et  al., 2020] Pérez-Sánchez, A., Segura, J. A., Rubio-Gonzalez, C., Baldenegro-Pérez, L. A., and Soto-Cajiga, J. A. (2020). Numerical design and analysis of a langevin power ultrasonic transducer for acoustic cavitation generation. *Sensors and Actuators A: Physical*, 311:112035.

[Qin et  al., 2017] Qin, Y., Ingram, P., Xu, Z., O’Donnell, M., and Witte, R. (2017). Performance of a transcranial ultrasound array designed for 4D acoustoelectric brain imaging in humans. *IEEE International Ultrasonics Symposium, IUS*, pages 1–4.

[Qiu et  al., 2018] Qiu, W., Xia, J., Shi, Y., Mu, P., Wang, X., Gao, M., Wang, C., Xiao, Y., Yang, G., Liu, J., Sun, L., and Zheng, H. (2018). A Delayed-Excitation Data Acquisition Method for High-Frequency Ultrasound Imaging. *IEEE transactions on bio-medical engineering*, 65(1):15–20.

[Qiu et  al., 2012] Qiu, W., Yu, Y., Chabok, H. R., Liu, C., Zhou, Q., Shung, K. K., Zheng, H., and Sun, L. (2012). A flexible annular array imaging platform for micro-ultrasound. In *2012 IEEE International Ultrasonics Symposium*, pages 2172–2175.

[Qiu et  al., 2010] Qiu, W., Yu, Y., and Sun, L. (2010). A programmable, cost-effective, real-time high frequency ultrasound imaging board based on high-speed FPGA. *Proceedings - IEEE Ultrasonics Symposium*, pages 1976–1979.

[Qiu et  al., 2011] Qiu, W., Yu, Y., Tsang, F. K., and Sun, L. (2011). A programmable and compact open platform for ultrasound bio-microscope. In *2011 IEEE International Ultrasonics Symposium*, pages 1048–1051.

[Qiu et  al., 2020] Qiu, Y., Huang, Y., Zhang, Z., Cox, B. F., Liu, R., Hong, J., Mu, P., Lay, H. S., Cummins, G., Desmulliez, M. P. Y., Clutton, E., Zheng, H., Qiu, W., and Cochran, S. (2020). Ultrasound Capsule Endoscopy With a Mechanically Scanning Micro-ultrasound: A Porcine Study. *Ultrasound in Medicine & Biology*, 46(3):796–804.

[Rabut et  al., 2019] Rabut, C., Correia, M., Finel, V., Pezet, S., Pernot, M., Deffieux, T., and Tanter, M. (2019). 4D functional ultrasound imaging of whole-brain activity in rodents. *Nature Methods*, 16(10):994–997.

[Raj et  al., 2016] Raj, J., Smk, R., and Anand, S. (2016). *8051 microcontroller to FPGA and ADC interface design for high speed parallel processing systems – Application in ultrasound scanners*, volume 19.

[Raj et  al., 2018] Raj, J. J. R., Rahman, S., and Anand, S. (2018). Programmable FPGA-based 32-channel transmitter for high frame rate ultrasound channel excitation applications. *International Journal of Instrumentation Technology*, 2(1):18–33.

[Raj et  al., 2017] Raj, J. R., Rahman, S. M. K., and Anand, S. (2017). Microcontroller USB interfacing with MATLAB GUI for low cost medical ultrasound scanners. *Collection of Engineering Science and Technology, an International Journal*.

[Ranachowski et  al., 2020] Ranachowski, Z., Ranachowski, P., Dębowski, T., Brodecki, A., Kopec, M., Roskosz, M., Fryczowski, K., Szymków, M., Krawczyk, E., and Schabowicz, K. (2020). Mechanical and Non-Destructive Testing of Plasterboards Subjected to a Hydration Process. *Materials*, 13(10):2405.

[Ratajski and Trajer, 2017] Ratajski, A. and Trajer, J. (2017). Application of ultrasounds to determine carrot juice properties. *Annals of Warsaw University of Life Sciences - SGGW - Agriculture (Agricultural and Forest Engineering)*, 70:143–147.

[Rathod, 2019] Rathod, V. T. (2019). A Review of Electric Impedance Matching Techniques for Piezoelectric Sensors, Actuators and Transducers. *Electronics*, 8(2):169.

[Ricci et  al., 2006] Ricci, S., Boni, E., Guidi, F., Morganti, T., and Tortoli, P. (2006). A programmable real-time system for development and test of new ultrasound investigation methods. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 53(10):1813–1819.

[Richard et  al., 2008] Richard, W. D., Zar, D. M., and Solek, R. (2008). A low-cost B-mode USB ultrasound probe. *Ultrasonic Imaging*, 30(1):21–28.

[Robin et  al., 2017] Robin, J., Arnal, B., Tanter, M., and Pernot, M. (2017). 3D Imaging with a Time Reversal Cavity: Towards Transcostal Focusing for Shock Wave Therapy. *IRBM*, 38(4):234–237.

[Rodrí guez-Olivares et  al., 2018] Rodríguez-Olivares, N., Cruz-Cruz, J., Gómez-Hernández, A., Hernández-Alvarado, R., Nava-Balanzar, L., Salgado-Jiménez, T., and Soto-Cajiga, J. (2018). Improvement of Ultrasonic Pulse Generator for Automatic Pipeline Inspection. *Sensors*, 18(9):2950.

[Roman, 2019] Roman, A. (2019). *Open-Source Test-Bench Design for Applications in Autonomous. Ultrasound Imaging.* PhD thesis, CASE WESTERN RESERVE UNIVERSITY.

[Roman et  al., 2018] Roman, A., Dehghanzadeh, P., Pashaei, V., Basak, A., Bhunia, S., and Mandal, S. (2018). An Open-Source Test-Bench for Autonomous Ultrasound Imaging. In *2018 IEEE 61st International Midwest Symposium on Circuits and Systems (MWSCAS)*, pages 524–527, Windsor, ON, Canada. IEEE.

[Romero-Laorden et  al., 2013] Romero-Laorden, D., Villazn-Terrazas, J., Martnez-Graullera, O., and Ibez, A. (2013). Strategies for Hardware Reduction on the Design of Portable Ultrasound Imaging Systems. In Gunarathne, G. P. P., editor, *Advancements and Breakthroughs in Ultrasound Imaging*. InTech.

[Rymarczyk et  al., 2019] Rymarczyk, T., Kozłowski, E., Kłosowski, G., and Niderla, K. (2019). Logistic Regression for Machine Learning in Process Tomography. *Sensors*, 19(15):3400. Number: 15 Publisher: Multidisciplinary Digital Publishing Institute.

[Saijo, ] Saijo, Y. Development of an ultra-portable echo device connected to USB port. - PubMed - NCBI. 10.1016/j.ultras.2003.11.009.

[Saiz-Vela et  al., 2020] Saiz-Vela, A., Fontova, P., Pallejá, T., Tresanchez, M., Garriga, J. A., and Roig, C. (2020). A low-cost development platform to design digital circuits on FPGAs using open-source software and hardware tools. In *2020 XIV Technologies Applied to Electronics Teaching Conference (TAEE)*, pages 1–8.

[Santagati et  al., 2020] Santagati, G. E., Dave, N., and Melodia, T. (2020). Design and Performance Evaluation of an Implantable Ultrasonic Networking Platform for the Internet of Medical Things. *IEEE/ACM Transactions on Networking*, 28(1):29–42.

[Sarvazyan et  al., 2009] Sarvazyan, A. P., Fillinger, L., and Gavrilov, L. R. (2009). A comparative study of systems used for dynamic focusing of ultrasound. *Acoustical Physics*, 55(4-5):630–637.

[Schneider et  al., 2010] Schneider, F. K., Agarwal, A., Yoo, Y. M., Fukuoka, T., and Kim, Y. (2010). A Fully Programmable Computing Architecture for Medical Ultrasound Machines. *IEEE Transactions on Information Technology in Biomedicine*, 14(2):538–540.

[Scholle and Sinapius, 2018] Scholle, P. and Sinapius, M. (2018). Pulse Ultrasonic Cure Monitoring of the Pultrusion Process. *Sensors*, 18(10):3332. Number: 10 Publisher: Multidisciplinary Digital Publishing Institute.

[Schueler et  al., 1984] Schueler, C. F., Lee, H., and Wade, G. (1984). Fundamentals of Digital Ultrasonic Processing. *IEEE Transactions on Sonics and Ultrasonics*, 31(4):195–217.

[Seo et  al., 2016] Seo, D., Neely, R. M., Shen, K., Singhal, U., Alon, E., Rabaey, J. M., Carmena, J. M., and Maharbiz, M. M. (2016). Wireless Recording in the Peripheral Nervous System with Ultrasonic Neural Dust. *Neuron*, 91(3):529–539. Publisher: Elsevier.

[Seo, 2018] Seo, J. (2018). *A non-invasive central arterial pressure waveform estimation system using ultrasonography for real-time monitoring*. Thesis, Massachusetts Institute of Technology.

[Shah et  al., 2019] Shah, D., Hung, E., Wolf, C., Bazanski, S., Gisselquist, D., and Milanovic, M. (2019). Yosys+nextpnr: An Open Source Framework from Verilog to Bitstream for Commercial FPGAs. In *2019 IEEE 27th Annual International Symposium on Field-Programmable Custom Computing Machines (FCCM)*, pages 1–4. ISSN: 2576-2613.

[Shahshahani et  al., 2018] Shahshahani, A., Laverdiere, C., Bhadra, S., Zilic, Z., Shahshahani, A., Laverdiere, C., Bhadra, S., and Zilic, Z. (2018). Ultrasound Sensors for Diaphragm Motion Tracking: An Application in Non-Invasive Respiratory Monitoring. *Sensors*, 18(8):2617.

[Sharma, 2015] Sharma, J. K. (2015). Development of a wide band front end echo sounder receiver circuit.

[Shomaji et  al., 2019] Shomaji, S., Dehghanzadeh, P., Roman, A., Forte, D., Bhunia, S., and Mandal, S. (2019). Early Detection of Cardiovascular Diseases Using Wearable Ultrasound Device. *IEEE Consumer Electronics Magazine*, 8(6):12–21.

[Shrisha et  al., 2018] Shrisha, M. R., Chakraborty, N., Mahapatra, D. R., and Sunkara, S. (2018). FPGA based Ultrasonic thickness measuring device. In *2018 International Conference on Advances in Computing, Communications and Informatics (ICACCI)*, pages 779–784. ISSN: null.

[Sikdar et  al., 2014] Sikdar, S., Rangwala, H., Eastlake, E. B., Hunt, I. A., Nelson, A. J., Devanathan, J., Shin, A., and Pancrazio, J. J. (2014). Novel Method for Predicting Dexterous Individual Finger Movements by Imaging Muscle Activity Using a Wearable Ultrasonic System. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 22(1):69–76.

[Smith et  al., 2015] Smith, K. J., Graham, D. J., and Neasham, J. A. (2015). Design and Optimization of a Voice Coil Motor With a Rotary Actuator for an Ultrasound Scanner. *IEEE Transactions on Industrial Electronics*, 62(11):7073–7078.

[Sobhani et  al., 2016] Sobhani, M. R., Ozum, H. E., Yaralioglu, G. G., Ergun, A. S., and Bozkurt, A. (2016). Portable low cost ultrasound imaging system. In *2016 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4.

[Sosnowska et  al., 2019] Sosnowska, A., Vuckovic, A., and Gollee, H. (2019). Training Towards Precise Control Over Muscle Activity with Real Time Biofeedback Based on Ultrasound Imaging. *World Congress on Medical Physics and Biomedical Engineering 2018*, pages 49–52.

[Soto-Cajiga et  al., 2012] Soto-Cajiga, J. A., Pedraza-Ortega, J. C., Rubio-Gonzalez, C., Bandala-Sanchez, M., and Romero-Troncoso, R. d. J. (2012). FPGA-based architecture for real-time data reduction of ultrasound signals. *Ultrasonics*, 52(2):230–237.

[Svilainis et  al., 2014] Svilainis, L., Dumbrava, V., Kitov, S., Aleksandrovas, A., Tervydis, P., and Liaukonis, D. (2014). Electronics for Ultrasonic Imaging System. *Elektronika ir Elektrotechnika*, 20:51–56.

[Tang and Clement, 2014] Tang, S. C. and Clement, G. (2014). A computerized tomography system for transcranial ultrasound imaging. *Proceedings of Meetings on Acoustics*, 22(1):020001.

[Taylor et  al., 2017] Taylor, Z. D., Jonveaux, L., and Caskey, C. T. (2017). Development of a Portable and Inexpensive Ultrasound Imaging Device for Use in the Developing World.

[Techavipoo et  al., 2012] Techavipoo, U., Keinprasit, R., Pinunsottikul, P., Jewajinda, Y., Punyasai, C., Thajchayapong, P., Siritan, T., and Worasawate, D. (2012). An ultrasound imaging system prototype for raw data acquisition. In *The 5th 2012 Biomedical Engineering International Conference*, pages 1–4.

[Tortoli et  al., 2009] Tortoli, P., Bassi, L., Boni, E., Dallai, A., Guidi, F., and Ricci, S. (2009). ULA-OP: an advanced open platform for ultrasound research. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 56(10):2207–2216.

[Triger et  al., 2008] Triger, S., Wallace, J., Wang, L., Cumming, D. R. S., Saillant, J.-F., Afroukh, F., and Cochran, S. (2008). A modular FPGA-based ultrasonic array system for applications including non-destructive testing.

[Vadalma, 2020] Vadalma, A. (2020). *Smartphone ultrasound imaging*. Master of Philosophy, Queensland University of Technology.

[van  der Meulen et  al., 2017] van der Meulen, P., Kruizinga, P., Bosch, J. G., and Leus, G. (2017). Spatial compression in ultrasound imaging. In *2017 51st Asilomar Conference on Signals, Systems, and Computers*, pages 1016–1020, Pacific Grove, CA, USA. IEEE.

[Vasudevan et  al., 2014] Vasudevan, V., Govindan, P., and Saniie, J. (2014). Programmable analog front-end system for ultrasonic SoC hardware. In *IEEE International Conference on Electro/Information Technology*, pages 356–361.

[Veenstra, ] Veenstra, V. Generating high frame rate MR images using surrogate signals | Robotics and Mechatronics.

[Vogt and Ermert, 2005] Vogt, M. and Ermert, H. (2005). Development and evaluation of a high-frequency ultrasound-based system for in vivo strain imaging of the skin. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 52(3):375–385.

[Wagner et  al., 2016] Wagner, D. R., Cain, D. L., and Clark, N. W. (2016). Validity and Reliability of A-Mode Ultrasound for Body Composition Assessment of NCAA Division I Athletes. *PLOS ONE*, 11(4):e0153146.

[Wahab et  al., 2016] Wahab, M. A. A., Sudirman, R., Omar, C., and Ariffin, I. (2016). Design of an A-mode ultrasound amplifier for bone porosity detection. In *2016 International Symposium on Electronics and Smart Devices (ISESD)*, pages 79–84.

[Wall, 2010] Wall, K. (2010). *A High-Speed Reconfigurable System for Ultrasound Research*. Thesis.

[Wang and Saniie, 2019] Wang, B. and Saniie, J. (2019). A High Performance Ultrasonic System for Flaw Detection. In *2019 IEEE International Ultrasonics Symposium (IUS)*, pages 840–843. ISSN: 1948-5727.

[Wang et  al., 2019a] Wang, R., Fang, Z., Gu, J., Guo, Y., Zhou, S., Wang, Y., Chang, C., and Yu, J. (2019a). High-resolution image reconstruction for portable ultrasound imaging devices. *EURASIP Journal on Advances in Signal Processing*, 2019(1):56.

[Wang et  al., 2019b] Wang, X., He, C., Xie, W., and Hu, H. (2019b). Preliminary Research on the Nonlinear Ultrasonic Detection of the Porosity of Porous Material Based on Dynamic Wavelet Fingerprint Technology. *Sensors*, 19(15):3328. Number: 15 Publisher: Multidisciplinary Digital Publishing Institute.

[Wang et  al., 2017] Wang, X., Seetohul, V., Chen, R., Zhang, Z., Qian, M., Shi, Z., Yang, G., Mu, P., Wang, C., Huang, Z., Zhou, Q., Zheng, H., Cochran, S., and Qiu, W. (2017). Development of a Mechanical Scanning Device With High-Frequency Ultrasound Transducer for Ultrasonic Capsule Endoscopy. *IEEE Transactions on Medical Imaging*, 36(9):1922–1929.

[Warner et  al., 2013] Warner, M., Ratcliffe, A., Nangoo, T., Morgan, J., Umpleby, A., Shah, N., Vinje, V., Štekl, I., Guasch, L., Win, C., Conroy, G., and Bertrand, A. (2013). Anisotropic 3D full-waveform inversion. *Geophysics*, 78(2).

[Wei et  al., 2020] Wei, C., Chen, H., and Chen, Y. (2020). Design of an automatic impedance matching circuit based on frequency tracking of ultrasonic transducer. In *2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC)*, pages 162–165.

[Wen et  al., 2019] Wen, L., Tan, C., Dong, F., and Zhao, S. (2019). Design of Ultrasonic Tomography System for Biomedical Imaging. In *2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pages 1–5.

[Weng et  al., 2015] Weng, C.-K., Chen, J.-W., and Huang, C.-C. (2015). A FPGA-based wearable ultrasound device for monitoring obstructive sleep apnea syndrome. pages 1–4. IEEE.

[WHO, 1985] WHO (1985). *Future Use of New Imaging Technologies in Developing Countries*. World Health Organisation.

[Winter et  al., 2019] Winter, L., Pellicer-Guridi, R., Broche, L., Winkler, S. A., Reimann, H. M., Han, H., Arndt, F., Hodge, R., Günyar, S., Moritz, M., Ettinger, K. M., de Fresnoye, O., Niendorf, T., and Benchoufi, M. (2019). Open Source Medical Devices for Innovation, Education and Global Health: Case Study of Open Source Magnetic Resonance Imaging. In Redlich, T., Moritz, M., and Wulfsberg, J. P., editors,  *Co-Creation: Reshaping Business and Society in the Era of Bottom-up Economics*, Management for Professionals, pages 147–163. Springer International Publishing, Cham.

[Worthing, 2016] Worthing, R. T. (2016). *Using ultrasound to measure arterial diameter for the development of a wearable blood pressure monitoring*. PhD thesis. 10.14288/1.0320796.

[Xiao et  al., 2013] Xiao, D., Shao, J., Ren, H., and Xu, C. (2013). Design of a high voltage pulse circuit for exciting ultrasonic transducers. In *2013 Far East Forum on Nondestructive Evaluation/Testing: New Technology and Application*, pages 224–230.

[Xu et  al., 2019] Xu, K., Kim, Y., Boctor, E. M., and Zhang, H. K. (2019). Enabling low-cost point-of-care ultrasound imaging system using single element transducer and delta configuration actuator. In *Medical Imaging 2019: Image-Guided Procedures, Robotic Interventions, and Modeling*, volume 10951, page 109510W. International Society for Optics and Photonics.

[Xu et  al., 2008] Xu, X., Sun, L., Cannata, J. M., Yen, J. T., and Shung, K. K. (2008). High-frequency Ultrasound Doppler System for Biomedical Applications with a 30 MHz Linear Array. *Ultrasound in medicine & biology*, 34(4):638–646.

[Xu et  al., 2010] Xu, X., Venkataraman, H., Oswal, S., Bartolome, E., and Vasanth, K. (2010). Challenges and considerations of analog front-ends design for portable ultrasound systems. In *2010 IEEE International Ultrasonics Symposium*, pages 310–313. ISSN: 1948-5719.

[Ylitalo and Ermert, 1994] Ylitalo, J. T. and Ermert, H. (1994). Ultrasound synthetic aperture imaging: monostatic approach. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 41(3):333–339.

[Yu et  al., 2020] Yu, H., Kim, J., Kim, H., Barange, N., Jiang, X., and So, F. (2020). Direct Acoustic Imaging Using a Piezoelectric Organic Light-Emitting Diode. *ACS Applied Materials & Interfaces*, 12(32):36409–36416.

[Yu, 2012] Yu, Z. (2012). *Low-power receive-electronics for a miniature 3D ultrasound probe.* [s.n.], S.l. OCLC: 840459881.

[Zeiss, 1962] Zeiss, C. (1962). Sonovisor 2. *Journal of Scientific Instruments*, 39(10):538–538.

[Zhang et  al., 2017] Zhang, D.-l., Yang, C., Jian, X.-h., Zhang, Q., and Cui, Y.-y. (2017). A multi-channel a-scan ultrasound system for real-time, non-invasive study of carotid artery compliance. In *2017 Symposium on Piezoelectricity, Acoustic Waves, and Device Applications (SPAWDA)*, pages 486–489. ISSN: null.

[Zhang et  al., 2016] Zhang, H. K., Cheng, A., Bottenus, N., Guo, X., Trahey, G. E., and Boctor, E. M. (2016). Synthetic tracked aperture ultrasound imaging: design, simulation, and experimental evaluation. *Journal of Medical Imaging*, 3(2):027001.

[Zhang et  al., 2018] Zhang, H. K., Kim, Y., Lin, M., Paredes, M., Kannan, K., Moghekar, A., Durr, N. J., and Boctor, E. M. (2018). Toward dynamic lumbar puncture guidance using needle-based single-element ultrasound imaging. *Journal of Medical Imaging*, 5(02):1.

[Zhang, 2012] Zhang, L. (2012). *FPGA embedded system for ultrasonic non-destructive testing*. Thesis, Brunel University London.

[Zhang et  al., 2019a] Zhang, Q., Song, J., Zhou, L., Peng, Y., Zhou, Q., Wang, S., Sun, X., Ding, M., and Yuchi, M. (2019a). A high throughout, extensible and flexible ultrasonic excitation and acquisition system for ultrasound imaging. In *Medical Imaging 2019: Ultrasonic Imaging and Tomography*, volume 10955, page 109550L. International Society for Optics and Photonics.

[Zhang et  al., 2019b] Zhang, W.-T., Lin, Y.-C., Chen, W.-H., Yang, C.-W., and Chiang, H.-H. K. (2019b). A Free-Hand System of the High-Frequency Single Element Ultrasound Transducer for Skin Imaging. In *Future Trends in Biomedical and Health Informatics and Cybersecurity in Medical Devices*, pages 91–99. Springer, Cham.

[Zhang, 2015] Zhang, X. (2015). *Design of a single element 3D ultrasound scanner*. Thesis, Massachusetts Institute of Technology.

[Zhang et  al., 2019c] Zhang, X., Fincke, J. R., Wynn, C. M., Johnson, M. R., Haupt, R. W., and Anthony, B. W. (2019c). Full noncontact laser ultrasound: first human data. *Light: Science & Applications*, 8(1):119.

[Zimmermann, 2018a] Zimmermann, H. (2018a). High Frequency 1-Ch System.

[Zimmermann, 2018b] Zimmermann, H. (2018b). Miniaturized Multi-Channel System.

[Zimmermann, 2019] Zimmermann, H. (2019). Highly Miniaturized 8-Ch System.

1. Lead of the un0rick.cc project [↑](#footnote-ref-2)