

# A low-cost, arduino-like dev-kit for single-element ultrasound imaging\*

Luc Jonveaux<sup>1</sup>

**Abstract**—Ultrasound imaging is developing an open-source ecosystem especially for software frameworks. Little exists on the open-hardware side. Hence a focus was put on producing easy-to-use technological (hardware and software) kit to allow anyone - scientists, academics, hackers, makers to have a experimental setup for ultrasound imaging at a low cost, at home, with no specific equipment required.

To this end, open source, arduino-like modules have been developed to build a simple, but complete, single channel analog front-end system, where all intermediary signals are readily accessible by the user. A single-channel architecture allows to avoid the beam-forming head, though it limits the quality of the image obtained, and brings robustness to the system. Moreover, complex RF processing, being shifted to the analog side, limits the quality of the final image.

There were tested with re-purposed ultrasound mechanical scanner heads, as well as re-purposed medical imaging transducers, and provided interesting images. Moreover, such modules could also be used in RF projects, non-destructive projects, low-cost medical imaging projects.

## I. INTRODUCTION

Ultrasound imaging has evolved since the first ultrasound machine appeared. The first machines were using single-transducers techniques, coupled to mechanical scanning. This technology was then replaced by more resource-consuming transducer-array-based probes with the exception of endo probes, where the physical size of the probe is a limiting factor.

Mechanical scanning has its limitation, but also its strengths: the single element means that corresponding analog electronics are simplified, and the cost reduced. Moreover, with progress made in different technical fields, mechanical probes are seen on the market again. Search found little to no documentation of previous research to rebuild these mechanical ultrasound imaging machine functions.

To the best of the authors knowledge, there are no open-source hardware design nor electronics accessible online, even if there are several open-source software initiatives (like PLUS) or focus-ultrasound control systems (like Vanderbilt's Open-Source Small-Animal MR-Guided Focused Ultrasound System), or articles suggesting electronics architecture for ultrasound systems. In 2009, Tortoli et al [21] created a 64-channel open platform, with a relatively complex architecture. So far, state of the art systems cannot be built with abundant modular and easily assembled components. A simpler 4-channel acquisition setup was built with an annular array, but no automated movement A more recent approach combines relatively a 4-channel[22], similar to our design,

coupled to a Raspberry Pi. Other DIY approaches include signal generators [23].

To bridge this gap, this work provides pieces of kit to allow anyone to understand and recreate the inside of an ultrasound machine. Each electronic module takes the place of a function in the signal processing chain, or allows tapping into the different signals circulating between the blocks. We have chosen to use a module approach to make sure that each key component inside ultrasound image processing can easily be replaced and compared with another module.

A focus has been put on documentation and corresponding infrastructure. The project's documentation is backed by a script, extracting relevant information from the work logs in the repository, allowing a continuous update of information.

## II. OVERALL IMPLEMENTATION AND DESIGN

### A. Simpler and smaller ultrasound devices

Several publication point at the integration of such hardware in the scan head itself, and describe prototypes of single element transducers [4], [5], [9] or piezo arrays [1], [3], [7], in integrated, hand-held devices.

### B. Using echoes for imaging

Ultrasounds, high frequency sound waves, are used in medical application for both diagnosis and treatment of patients. Their frequencies can vary from 2 to approximately 15 MHz for regular imaging, sometimes higher frequencies are used for a finer surface imaging.

The ultrasound waves comes from the mechanical oscillations of a crystal in a transducer, excited by electrical pulses (which is called the piezoelectric effect). These pulses of sound are sent by the transducer, propagate through the different media being imaged, and then come back to the transducer as "reflected echoes" when they meet an interface. These reflected echoes are converted back into an electrical signal by the transducer and are further processed so to form the final image.

In general, these sound waves, as classical waves, are reflected at the interfaces between the tissues of different acoustic impedance (linked to the density of the medium), the strength of the echo being proportional to the difference in impedance. On the other hand, echoes are not produced if there is no acoustic difference, hence no impedance interface, between media. Homogeneous fluids are on the other hand seen as echo-free structures.

### C. A modularized approach

The aim of the kit being to allow one to explore the mechanisms of ultrasound processing, and to replace elements of

\*This work was not supported by any organization

<sup>1</sup>Luc is just a independant maker, reachable at [kelu124@gmail.com](mailto:kelu124@gmail.com)

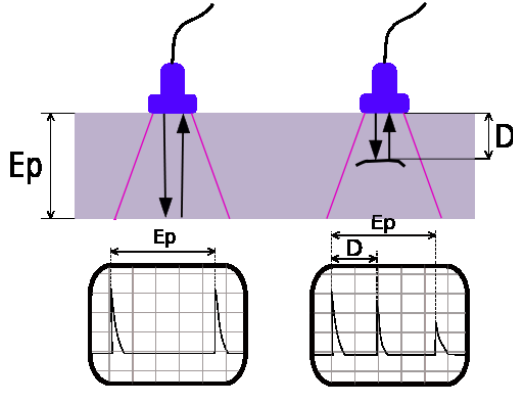


Fig. 1. Principles of ultrasound.

the processing chain as desired, a modular approach was considered. Each module can be considered as a breakout board of the most central elements, intended for easy experimentation with usual equipment, such as breadboards and standard power supplies.

#### D. Requirements

State-of-the-art publication show a common structure for the different ultrasound systems [3]. One can note that recent developments, and research, show the feasibility to produce compact ultrasound imaging devices, which can interface with a smartphone [8], wirelessly or through USB [20].

A central element in the kit is the sensor, the ultrasound transducer. As we chose a single-channel processing unit, the transducer is a mono-element piezoelectric. This element has a fixed focal depth. For the sake of simplicity, a frequency on the lower range of ultrasound imaging was chosen. Larger characteristic period enable simpler, slower controls and ADCs. A frequency of 3.5MHz was chosen, with a focal distance of 70mm, which is commonly used for obstetric and gynecological imaging. As a consequence, we chose a repetition period chosen was 300us. This corresponds to an imaging depth of 230mm, more that was is required to image between 20 and 150 mm. This project focused also on single element transducers to avoid developing a more complex beam-former component. The drawback is slow scanning, mechanical fragility, and insensitivity [12]. To increased the framerate, several transducers and corresponding connections can be integrating in a sweeping or rotating scan head [13], as it was done on previous mechanical probes.

The kit requires a pulser component: to have the transducer emit a signal, a high voltage pulse, precisely controlled in amplitude and in time, needs to reach the transducer. We chose off-the-shelf components after bibliography and research. Existing ICs exist, such as the MAX14808 [8], but are relatively complex, as they are octal or quad chain components.

The kit then requires an "analog processing" component. After the acoustic wave leaves the transducer, echoes appear due to the acoustic impedance ruptures taking place in the

medium being imaged. These echoes are captured by the transducer, and transformed back into a weak electrical signal, which needs to be processed. Classical processing includes filtering the signal around the central frequency of the transducer, then apply a low-noise amplification, then correcting the time-based attenuation. The image being the envelope of this last signal, one also needs to extract the envelope of this signal and pass this image to a digital converter. As filtering and band pass consume most of the processing power (up to 80% of processing power)[11], the module allows signal envelope detection with a ADL5511 IC. This also enables a first compression of the data to be transmitted to the user.

On the digitization side, an echo being typically a couple of periods long, the envelope of the signal, hence the ultrasound image, would have a 1 MHz frequency, which would required specific ADCs. Open hardware boards have onboard ADCs, but very few have ADCs above the Msp range, This implies that an analog envelope detection takes place on the board. However, we have used an existing open-source 40Mps DAQ on one of the modules, and have as well tried a 6Mps arduino IDE-compatible micro-controller to acquire the signal and stream it over wifi.

The design in modules, along with selected easily-accessed signal interfaces, provides access to the different intermediary signals.

#### E. A embedded-linux first iteration

A first iteration of the hardware was embodied in a beaglebone-black extension (cape), where the cape 10 Mps ADC would be tapping into the two PRUs to acquire the signal. A special attention was given to simplify power supply, limiting the inputs to 5V and 3.3V, the most common levels.

#### F. Designs of modules

This first iteration permitted tests, and validated parts of the design. Despite its test points, this board did not provide all the insights that can be extracted from the hardware, so a redesign was considered, to expose all key inputs and outputs of the signal processing. While existing compact elements exists, such as the AFE5808 (which which include low noise amplifiers (LNA) and analog-to-digital converters - ADCs ) [8], we preferred using separate ICs, so that the user can measure exactly the target signal.

For the sake of simplicity, a design of two separated modules emerged.

- One is the pulser module, where the high voltage and connection to the transducer lies.
- The other is the analog processing modules. A dual input for the clipped raw signal from the transducer was integrated, as well as different jumpers and pots, to control the VGA gain, as well as the ADC reference voltage. The high-speed ADC was removed, and replaced with a on-board serial 2Mps ADC.

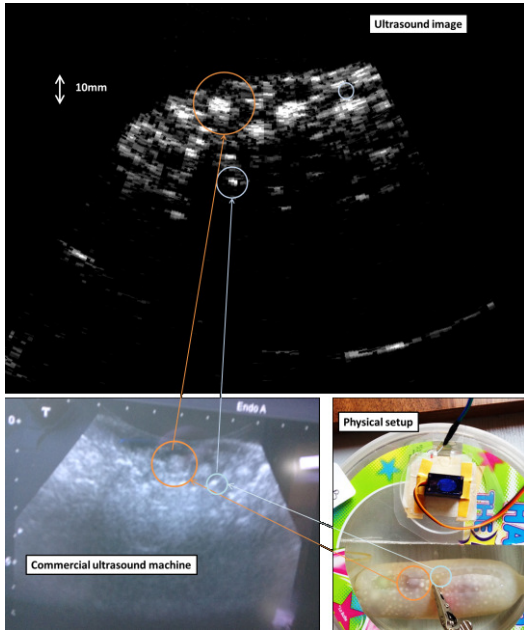


Fig. 2. Image obtained with the first iteration, on a beaglebone cape design, data being captured with a Bitscope Micro at 5 Msps

The remaining modules are micro-controllers, processing units, or power supplies that can be easily obtained and easily modified and programmed.

The latest set of modules is based on a wireless-enabled, arduino-compatible STM32, which has a 6 Msps on-board ADC, strictly compatible with the analog processing module for the envelope detection.

#### G. A selection of integrated ICs

To save on costs and complexity, and to ensure the robustness of the designs, the two modules being designed leverage existing ICs:

- The pulser module requires both a high-voltage source, and a pulser control. These functions used the R05-100B to generate a stable high-voltage, which level is determined by a potentiometer, and a HV7360 to precisely control the pulse level and duration.
- The analog processing uses a single channel ultrasound Time gain compensation IC, the AD8331, which gain can be controlled by an external 0 to 1V track. The amplified signal is fed into a RF envelope detector, the ADL5511. The envelope is the debiased with a AD8691 amplifier and optimized for the last item, the 12-bit, 3 Msps ADC AD7274.

### III. QUALITY CONTROL

#### A. Safety

Most of the modules are found on usual open-source hardware procurement websites. However, the two modules specifically developed for this project fail to enter this category.

One of the modules uses a DC-booster, which can raise the voltage it delivers above 100V. However, design has limited

high-voltage to specific points within the module, and to the SMA connector going to the transducer. The other pins of the module have inputs/outputs that range in the  $[-5V ; 5V]$  bracket. During the tests that took place, the full setup, without the motor, did not use more than 170 mA at 9V. The ATL3 probe, alimeted at 3.3V, brought the total power envelope to 330mA at 9V. The difference of stimulating the transducer caused a 5 mA at 9V difference.

### IV. CALIBRATION

#### A. Emulating the signal

In order to obtain repeatable signals, the DAC of a arduino-compatible board was used and integrated on a separate module. This module is capable to simulate a 2MHz signal, using an arbitrary signal profile. This signal can be used to characterize the analog processing module, as well as the DAQ modules.

#### B. Calibrating the signal

Calibration of ultrasound electrical signal processing requires a standard signal, which is difficult to provide if using a classical transducer. Moreover, due to the variety of transducers, it would be extremely difficult to obtain a standard setup and signal. A calibration tool has been built (the DAC module), based on a STM32F205 DAC. This permitted to record the calibration signal, and to simulate the behavior of the pulser module.

Qualification and calibration of the high-voltage level on the pulser module is done using an oscilloscope.

Finally, the gain level of the analog processing module is in the tests described below adjusted once and for all at the beginning of the experiment, to use the full range of output signal and obtain the best image possible. The level of gain can be selected, either from one input signal, coming from an external DAC for example, or with a potentiometer, the choice between the two being made possible by a jumper.

#### C. Developing a home-made reference material

A home-made phantom was used to test the first iteration of the board. It was made of a gelatin phantom, with tapioca inclusions of two types (2mm and 8mm), the medium being contained in a condom (as in the picture above). This type of phantom does not conserve well, and was not reused for the second iteration.

#### D. General testing

General testing has been done, especially for the two modules:

- For the pulser, the criteria of the tests were the duration of the pulse, which should match the input signals, as well as the voltage of the pulse, being set by a potentiometer. Tests were done using an oscilloscope.
- For the analog processing unit, the DAC module allowed a standard input to be processed, and the result of the processing analyzed.

General conditions of the tests were that of a 150ns, 70V-pulse for the pulser unit, with a repetition every 300us.

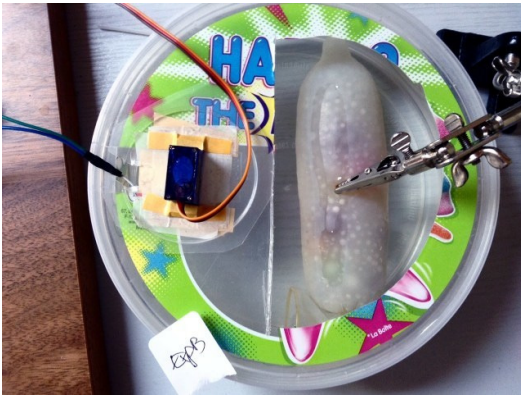


Fig. 3. The home-made phantom

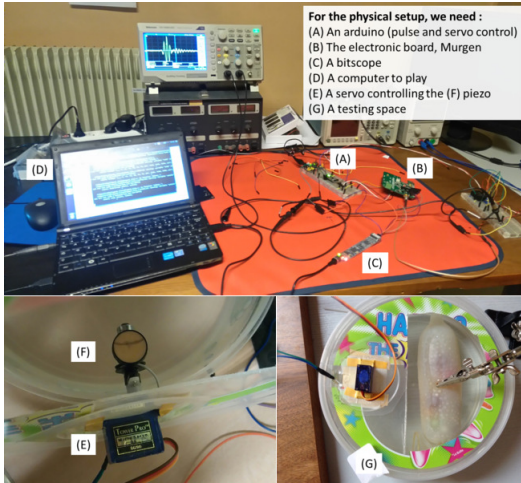


Fig. 4. The work space, with the first iteration, a salvaged piezoelement, and a servo motor imaging a home-made phantom

The gain setting on the analog processing board was set to maximize the range of the signal and match it to the DAQ unit.

## V. APPLICATION

### A. Use case(s)

#### B. General use case

The modules can be assembled in a minimum set using power-supply, pulser control, pulser module, and data acquisition.

The Beaglebone cape setup is relatively simple. The pulser control was realized using a Trinket Pro (point A), controlling the board (B). The data was acquired with a Bitscope.

Setup with the second iteration, the modules were used with a vintage probe found on ebay and the Beaglebone PRUDAQ cape, replacing the bitscope.

With the wireless setting, the setup simplifies, and only need to be powered with a USB cable.

1) *Testing a single element transducer:* A first test was done using a single-element transducer, salvaged from a used endovaginal S-VRW77AK ultrasound probe. The transducer was moved by a basic servomotor controlled by a Trinket

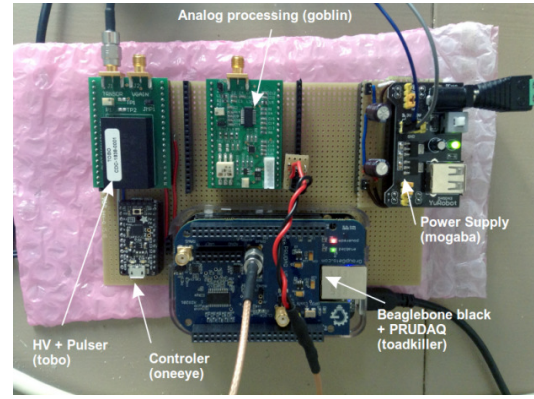


Fig. 5. The setup with a ATL probe, along with a PRUDAQ cape and the two home made modules

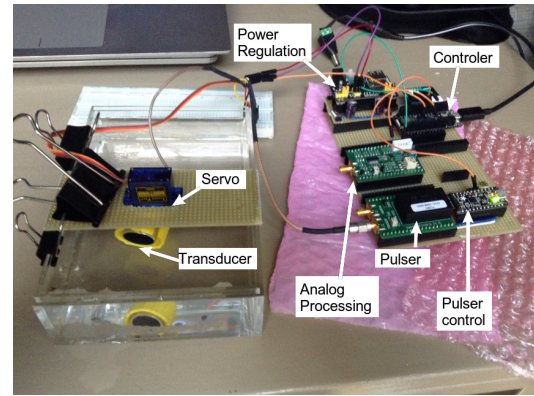


Fig. 6. The setup with a single element piezoelement, the two home-made modules, and an arduino-IDE-compatible micro-controller, streaming data over wifi

Pro 5V, which doubled as the controller sending the pulse commands. Data was acquired on the first iteration at 5Mps with a bitscope unit (BS10). Noise kept the SNR low, but nonetheless provided a source of data, and permitted to assess the performances of the different blocks.

2) *Testing different a commercial transducer:* The dev-kit has been tested with a ATL-3 probe found on ebay. This mechanical probe has 3 rotating transducers, a characteristic of this series of ATL probes. The ATL Access 3 probe connector to the transducers is extremely simple, and consists in a BNC cable. The other connectors pins may correspond to the control of the probe motor. The probe's motor was connected to a 3.3V, allowing the transducers to rotate freely in the body of the probe.

A first acquisition try took place using a bitscope micro (BS10), similarly to the previous application. However, the interval between two captures did not lead to satisfactory acquisitions. A second try was done using the PRUDAQ, a faster, real-time acquisition unit, designed as an extension of the beaglebone. The PRUDAQ was connected to the amplified envelope signal of the analog processing module, clipped at 1.4V to protect the DAQ input. 32MB were acquired,

With 32MB containing two signals encoded over 16 bits

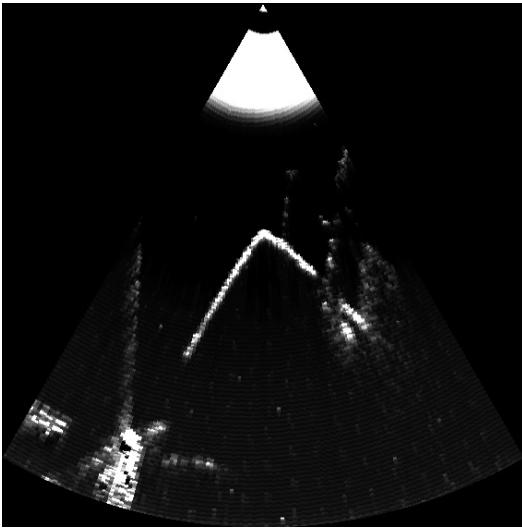


Fig. 7. Example of image acquired with the PRUDAQ and a ATL 3 probe

each, there is 8388608 points of data, or approximately 839ms. With a pulser set at 300us intervals, we should see around 2796 lines of data, which was the case. Rebuilding the image, we could see close to 12 full images, for a framerate of 14 fps, meaning that the motor was at approximately 290rpm.

The setup was used on a ultrasound phantom, as well as on a small dice (10mm side), as seen on the image above.

Further testing was done with a ATL 10PV,

3) *Datasets*: A small library of images obtained on home-made phantoms with the first iteration is available at <https://github.com/kelul24/murgen-dev-kit/tree/master/software/examples>.

Full data from the regular phantom imaging can be found on <https://github.com/kelul24/echomods/blob/master/include/20160822/2016-08-22-Fantom.md>.

The data corresponding to the image of the dice can be found at <https://github.com/kelul24/echomods/blob/master/include/20160814/2016-08-14-HackingUltrasoundProbe.md>.

## VI. REUSE POTENTIAL AND ADAPTABILITY

### A. Reuse potential

1) *Application for non-destructive testing (NDT)*: The technology developed here does not differ from the technology used in NDT. Therefore, the whole set of modules can be used as-is in NDT, or its design can be adapted to NDT requirements.

2) *Application for transducer professionals*: Often, ultrasound equipment repair professionals need to check each element in probe-arrays, and thus only need a single channel equipment. This kit would possibly be useful in this purpose.

3) *High speed DAC*: Having worked with the DAC module enables one to be able to work on the acquisition system, based on a known-signal input. This enables repeatability of the input, contrarily to images that are usually capture using a probe on a ultrasound phantom. This DAC can go up to

2MHz, on a limited voltage range, and could be used in testing analog signals processing

4) *Pulser*: It is suggested that the pulser can be used in medical ultrasound image devices, or for test applications. Its up to 35 MHz operating frequency and 2 ns matched delay times allow higher frequencies uses, such as superficial imaging or doppler analyses [1].

5) *Analog processing*: The analogue processing module was tested for signals from 2MHz to 10MHz, with some distortion happening on the higher end of the bracket. However, it can be noted that, with the possibility to measure and control the inputs and outputs of between each processing unit, this module could possibly be used for signal demodulation.

6) *High-speed, wireless DAQ*: The wireless DAQ module we built can go up to 6 Msps, with a 10-bit resolution, on a [0;3.3V] input range, and can work on a battery, as there is a battery management system already built-in. This module could therefore be used in systems where rapid acquisition and wireless streaming need to be used. For example, for Software Defined Radio (SDR), this module can be used after the demodulation step.

### B. Adaptability of the home-made modules

1) *Other uses*: The modules source code has been released, it is relatively easy for electronic engineers to reuse this code.

Apart from the well-know obstetrics and gynecology uses, ultrasound devices have been developed for several uses, which the current hardware could support, such as: doppler ultrasonography, contrast ultrasonography, molecular ultrasonography, elastography, non destructing testing, bladder measurement, ... . An interesting one, suggested by Richard et al [3], would be to provide visual biofeedback to stroke victims relearning to control muscles. The same board could be reused for work on sonar-like systems [14].

2) *A low-cost option*: Apart from the wireless-enable micro-controller at 35\$, the two custom modules components cost 60 and 85 euros respectively. This low-cost lifts the barrier of high-cost equipment purchase, and hence facilitates the reuse of these designs.

### C. Support

This project benefits from an infrastructure that is completely open: github for the storage of files, and a gitbook to synthesize the complete documentation. A mailing-list gathers the community of different contributors, friends, .. which enables a community-based support.

## VII. BUILD DETAILS

### A. Availability of materials and methods

Most of the modules can be sourced from usual, well known open-hardware online suppliers. Moreover, the two specific modules can either be produced with a proper surface mount equipment, or the manufacturing files sent to a fab. The HV7360 becoming obsolete, a new version of the board has been published.

## B. Ease of build

When the first iteration had 4 layers, the two newly made modules are 2-layer designs, for the sake of simplicity.

The design also relies on off-the-shelf ICs to limit the number of its components. A trade-off had to be found when some ICs were BGA ICs.

The non-custom modules can be found commercially, or built.

Most of systems are FPGA (or DSP) based, especially for higher imaging frequencies [4], [5], as well as using multiple-element transducers [7] -while maintaining costs and power consumption low. We considered that programming FPGA (even DSPs) was a steep requirement for non-specialists, hence we focused on alternatives. However, it can be noted that a FPGA module could be developed to interface with existing modules.

## C. Operating software and peripherals

The hardware has modules that require software to operate. These modules rely on the arduino IDE, and their code was compiled using Arduino IDE 1.6.9. For the wireless module, the WICED BSP version used was 0.5.5.

To collect the data, the beaglebone module simply uses the beaglebone black with its PRUDAQ cape installed, where the data being acquired is available on a device (/dev/beaglelogic). With the wireless module, any wifi-enabled device can acquire the UDP stream.

## D. Dependencies

- Most of the processing code is using Python 2.7, which is GPL-compatible.
- The Beaglebone module is using a BeagleBone Black, which is under a Creative Commons Attribution-Share Alike 3.0 license.
- The Feather WICED module is, Open Hardware and Open Source for its software.
- The code for the arduino-compatible modules is developed under Arduino IDE.
- The two boards developed under this project are following the Open Hardware TAPR license.
- The source documents for these two boards was originally developed using Altium (proprietary), but the source has been ported to KiCad, which is under a GNU General Public License(GPL) version 3.

## E. Hardware documentation and files location

The module approach that has been followed enables the posting of all code, source files, images, and general documentation in a single github repository.

For each module, a Readme file presents the module, provides clear images of the module, the inputs and output of each module, and describes what is required to build and run the experimental setup.

- Name: Github repository for the ultrasound arduino-like modules
- Persistent identifier: <https://github.com/kelu124/echomods/>

- Release: <https://github.com/kelu124/echomods/releases/tag/v1.0>
- Filetypes: both boards are available in Altium and in Kicad format
- Licence: TAPR Open hardware license under which the documentation and files are licensed
- Publisher: Luc JONVEAUX
- Date published: 31/10/16

The full documentation, available as a gitbook, provides more details on the rationale of the designs, as well as more general comments on the setup and the author's work-log. It can be found at: <http://kelu124.github.io/echomods/>

# VIII. DISCUSSION

## A. Conclusions

As a first try to hardware by the author, this work has been an endlessly source of learning.

We finally obtained a cheap (400\$) set of modules for ultrasound imaging, leveraging on existing open-source hardware and integrated circuits. Power consumption fitting within a USB power envelope, it can easily be powered by off-the-shelf 5V power banks, as well as a small design (A5 format) and light weight, allow for the easy of manipulation.

The modules allow for surprisingly good images at this level of complexity. The module design, as building blocks, will allow users to use the existing sets of modules, then tailor each different module, if necessary, to their own requirements.

## B. Future Work

This set of modules shows that ultrasound imaging can profit from a usable dev-kit. Several points in this work however have to be reviewed, if not improved. Indeed:

- In general, the design of the boards can be greatly improved. For example, having only two layers on the current design may be a source of noise. Moreover, applying a RF net to the board or using a RF shield for the sensitive parts may be an idea.
- The pulser-module design uses only two inputs, and one high voltage source. However, the chip enables more complex uses as a pulser, which can be further explored.
- The PRUDAQ has a real-time access to the digital information, as well as a linux userspace. Further programming would enable the beaglebone platform to be a real server and controller of the setup.
- The modules are slightly too wide for a breadboard: an effort could be done to make the pins available on a standard breadboard.
- A whole field left unexplored so far is that of the transducer. As the key sensor in the kit, it would be interesting to explore relevant technologies to develop a low-cost, good-enough transducer.
- The transducer at the moment lies in water. For ease of work, scan head will have to be developed. A difficulty will be to determine the acoustic window material and

its thickness. Several works already give pointers in that sense [1].

- An additional module would be a wire phantom, use to qualify the images obtain with such a system. Wire phantoms are commonly used [9], where 20 micrometer wire would be used.
- A multiplexer module can be used, to interface this single channel kit with an array probe. Doing this would permit to do synthetic aperture imaging, and to characterize as well each element in the array.
- From a software point of view, the modules could be wirelessly controlled, leveraging the existing wireless communication channel, so that researchers can use a single unit for a laboratory, controlled from personal computers.
- For these high frequencies, a robust scan head can be used to obtain 130 fps, with light-weight transducer, and magnetic drive mechanism [2]. A bimorph actuator would be sufficient to drive the imaging transducer [4], [5] immersed in the probe. The advantage of such a scanning device would be to precisely know the position of the line being imaged, while being cheaper, and more robust as there are no mechanical parts. An other alternative would be a ultrasound motor [6].
- An additional module could link the ADC with a USB interface, providing as well the power for the other modules. We have shown that our modules can be run with a power bank, and previous work show is it possible to stay within the USB power envelope [3].

Having a set of unexpensive arduino-like modules will support the development of ultrasound imaging research, and provide the keys to the researchers, makers and curious-minded persons to explore this field.

## OTHERS

### *Acknowledgements*

A huge thanks to the friends in the community for their sharing their ideas and giving their support. Thanks as well to Prof Charles and Zach to have given a try at testing the first iteration, Sofian for his help on the hardware, the Hackaday community for giving me the chance to go to the 2016 finals, Nicolas for his interest, the echOpen community (Benoit, Farad, Vincent, Jerome, Virginie, Emilie and the others) who have all kept me motivated!

### *Funding statement*

This project has been funded by personal funds, and supported by two prizes from the hackaday 2016 contest.

### *Competing interests*

The author declare that he has no competing interests. Though LJ is a founder of the echOpen's project, this work has been pursued individually, the echOpen association having no involvement with this work.

### *Upcoming publication*

This document is pre-print version of a publication submitted for the Journal of Open Hardware (JOH).

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