Development of a Portable and Inexpensive Ultrasound Imaging Device for Use in the Developing World

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BRIEF. A portable and inexpensive ultrasound device that could be used in the developing world was developed and tested.

ABSTRACT. People in developing countries have limited access to life-saving diagnostic equipment. Because medical imaging devices are stationary and costly, there exists a need for imaging technology that is not only accurate and portable, but also inexpensive. To address this issue, we developed and tested an inexpensive portable ultrasound device. Three microprocessing boards compose the device: a SeeedStudio BeagleBone Green, an Arduino Uno, and a Murgen board. The BeagleBone powers and controls the Murgen board. The Murgen board pulses a 5MHz single-element transducer, rotated by the Arduino, and receives the echoes. We programmed acquisition and image reconstruction procedures for the device and assessed the signal-to-noise ratio (SNR) in images of high-contrast graphite laboratory phantoms as well as standard clinical phantoms manufactured by Computerized Imaging Reference Systems, Inc. (CIRS). Reconstructed images of laboratory phantoms yielded an SNR of 9.3 dB, which was acceptable for imaging high-contrast targets. Some targets in the CIRS phantom were visible, but the SNR remained below an acceptable threshold, revealing the need for additional signal processing and noise reduction. All in all, we have demonstrated the feasibility of, identified further improvement for, and laid the foundation for an inexpensive portable ultra-sound device.

INTRODUCTION.

Accurate medical imaging is necessary for proper diagnoses as patients often do not show outward symptoms until it is too late for treatment. However, people in developing countries have limited access to life-saving diagnostic methods, often having to travel long distances to larger, more affluent cities for medical care [1]. A mobile and low-cost imaging option has the potential to benefit patients in remote areas who have limited access to such devices. Because ultrasound does not require large scanners like magnetic resonance imaging (MRI) or computerized tomography (CT), it is the ideal modality for a portable imaging device. In this project, an ultrasound device that is inexpensive, portable, and accurate has been developed and tested.

Ultrasound devices transmit and receive sound waves via a transducer. The time difference between wave transmission and reception can be mapped to a one-dimensional image. This type of imaging is called one-dimensional (A-mode) imaging. Though A-mode imaging is inexpensive to implement because it uses only one transducer, it has limited use for medical diagnostics. Two-dimensional (B-mode) images are more widely used in medical ultrasound applications, such as prenatal, trauma, and cancer imaging [2]. However, B-mode devices usually consist of multiple transducers, each with its own receive circuit, and thus are prohibitively expensive. In order to achieve two-dimensional imaging while maintaining a low cost, in our device the transducer is rotated, and one-dimensional images are taken in rapid succession as the transducer sweeps through a 60-degree angle. This is called sector scanning.

Sector scanning can be used to generate B-mode images while helping keep the device low-cost. Furthermore, integrated circuits exist for all necessary components of an ultrasound scanner, including transmit-receive switches, noise amplifiers, and ADC converters. These can be combined with minimal computing power, with the potential to cost less than $300. In this study, a single-element ultrasound device was developed and tested in order to assess the feasibility of generating accurate ultrasound images for a low cost.

Portable ultrasound has been the focus of various recent research studies [1], one of which was tested in a Level-I trauma hospital in Detroit, Michigan. Kirkpatrick *et al.* developed and tested the effectiveness of a portable ultrasound device (HHFAST) to perform Focused Assessment with Sonography for Trauma (FAST) ultrasound exams [3]. The HHFAST Sonosite 180, a 2.4kg portable ultrasound scanner, was implemented in a hospital triage setting with a 97% accuracy in predicting the clinical outcome. Kirkpatrick *et al.* shows that a small and portable ultrasound device would be feasible for getting clinically useful and valuable data that could be used for diagnosis. While the Sonosite imaging device provides an accurate and portable option, it costs up to $25,000 [4]. The next step towards ubiquitous medical imaging technology is the development of inexpensive diagnostic devices.

MATERIALS AND METHODS.

Board Descriptions.

The device consisted of a 5MHz single-element transducer and three open-source microprocessing boards each with a different task to perform: a SeeedStudio BeagleBone Green, a Murgen board, and an Arduino Uno. The BeagleBone is a low-cost development platform that runs Debian Linux [5]. It is powered and controlled the timing of the Murgen board, developed by Luc Jonveaux *et al.* as a novel platform for a low-cost ultrasound machine [6] that functions as transmit-receive switch and high voltage pulser. The Murgen board also contains circuitry for envelope detection and analog-to-digital conversion, but testing these components was beyond the scope of this project. The Murgen board and BeagleBone have high sampling rates and fast image processing. The Arduino is an open-source microprocessing board. As its limited clock speed of 16MHz [7] is less than the 25MHz sampling rate needed for ultrasound, it was only used to rotate the Servo motor.

Table 1. Costs and functions of device components.

Component	Cost	Function
SeeedStudio BeagleBone Green	$40	Control Murgen Board
Murgen Board	$500	Time pulses; process echoes
Arduino Uno	$25	Rotate transducer
Transducer	$200	Send pulses; receive echoes
Total	$765	Collect signal for image reconstruction

Data Acquisition.

The three microprocessing boards are connected to make the whole device (Fig. 1). The BeagleBone initialized two consecutive pulse width modulation (PWM) waves that were then sent to trigger the Murgen board at an interval of 250 microseconds. Upon receiving these trigger waves, the Murgen board pulsed the transducer, and it then received the resulting pulse-echoes back from the transducer.

To generate two-dimensional images, the Arduino rotates the transducer via a Servo motor (Batan model S1213). At each angle in a sweep of 60 degrees, MATLAB gathers 20 datasets from the Murgen board using GageScope and averages the datasets to reduce noise.

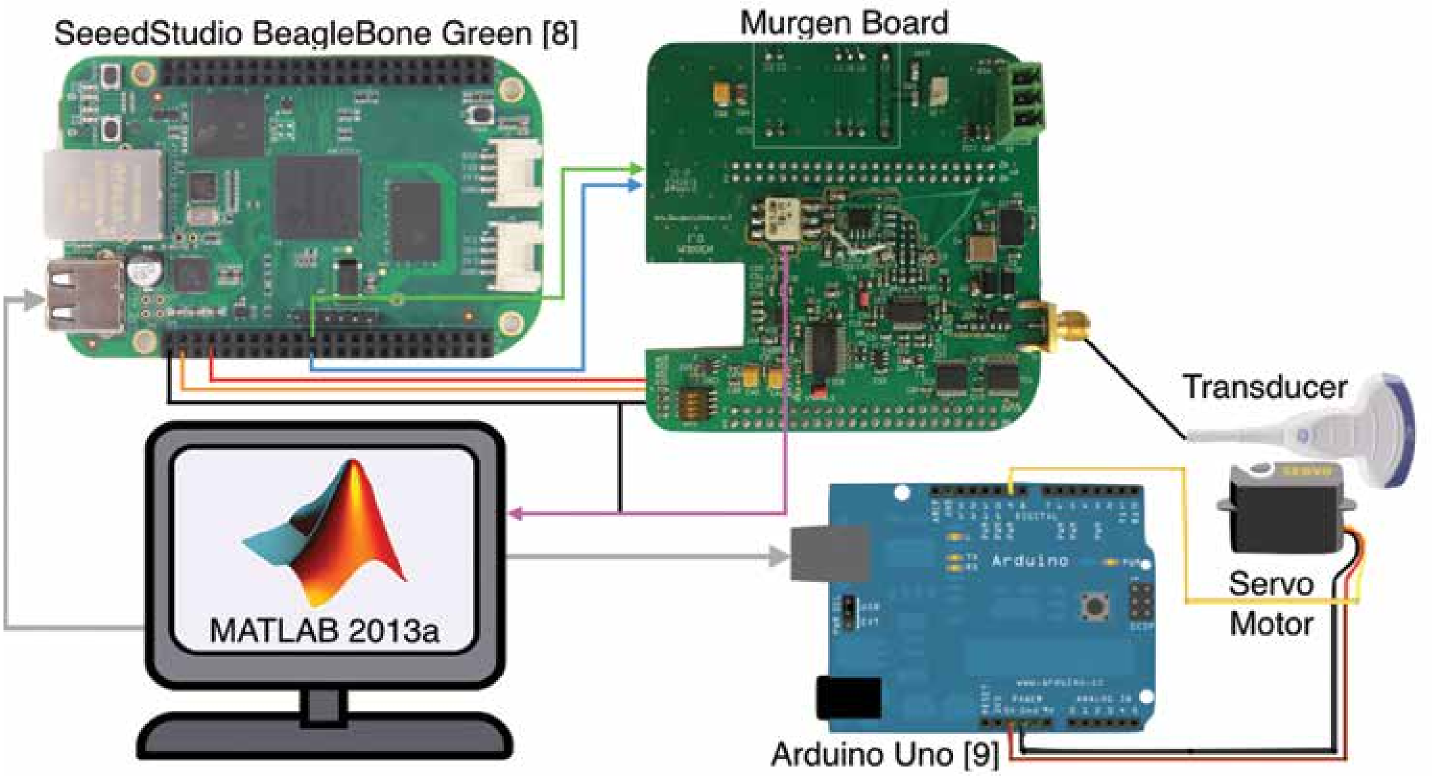

Figure 1. Device schematic. The BeagleBone triggers the Murgen board at a set interval. The Murgen board pulses and receives echoes from the transducer. The Arduino controls the rotation of the transducer. MATLAB 2013a is used to gather data and control the Arduino.

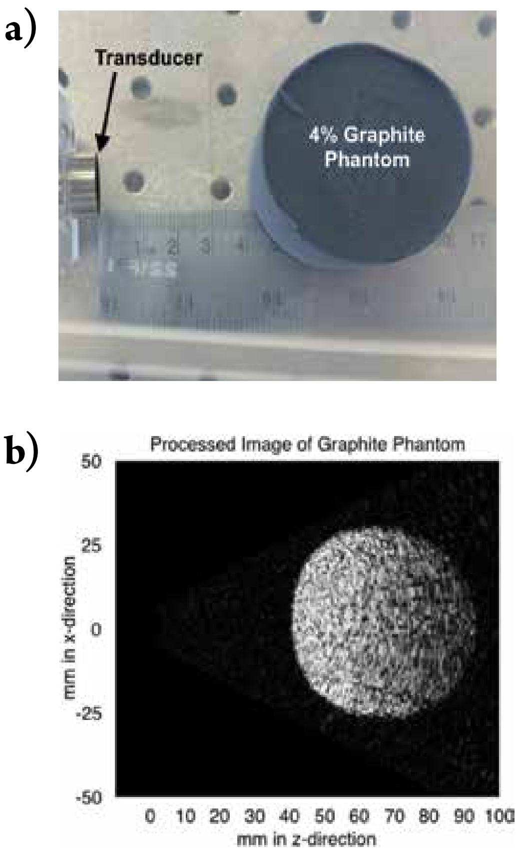

Figure 2. The ultrasound image of a graphite phantom. The front edge of the phantom is 40mm away from the transducer. Fig. 2a is the setup of a submerged phantom and 2b is the reconstructed image.

Image Processing.

Datasets were gathered and averaged twenty times in MATLAB using GageScope with CompuScope, and then the average dataset for each angle underwent further signal processing and image reconstruction in Python 3.5. The signal at each angle underwent noise reduction via a Butterworth bandpass filter and envelope detection via a Hilbert transformation. Since the transducer sends 5MHz pulses, any received signal that is not between 4.5MHz and 5.5MHz is considered noise and reduced by the Butterworth filter. Envelope detection ensures that the final image accounts for the entire body of a solid object (rather than just its edges) and results in an overall smoother image. Envelope detection also removes the carrier frequency from the signal in order to emphasize the locations of the echoes in the final image. Next, because the data was collected by rotating a Servo motor, it is converted from polar coordinates to Cartesian coordinates. This was accomplished by mapping a grid of squares each with a side length of 0.25mm. For each of these square sections in rectangular coordinates, the corresponding polar coordinates were calculated. The square section was then assigned the value of the dataset at the calculated polar coordinates. Finally, the signal is log-compressed so as to further differentiate the envelopes from background noise and therefore boost the image contrast.

Phantom Imaging and Image Analysis.

Two phantoms were imaged in this study by submerging the transducer in water. A high-contrast graphite phantom made in-house by a graduate student and a standard medical phantom manufactured by Computerized Imaging Reference Systems, Inc (CIRS). The in-house phantom was made by adding 4g graphite and 3g agar to 8mL n-propanol and 92mL water and heating the solution. The resulting substance is then set in a cylindrical mold and allowed to set in a refrigerator. This phantom was placed 40mm away from the submerged transducer face in the tank (Fig. 2a). Similarly, the CIRS phantom was placed 15mm away from the transducer face. To quantify the results, the processed image was analyzed for SNR in ImageJ between the phantom and the surrounding water by dividing the mean intensity of the signal by the mean intensity of the background noise. SNR is then converted to an intensity value in decibels (Equation 1).

$$\text{Intensity(dB)} = 10 * \log_{10}(\text{SNR}) \qquad (1)$$

RESULTS.

Image Reconstruction.

2D images were successfully acquired by reconstructing echoes received from the Murgen board. In the reconstructed image of the graphite phantom (Fig. 2b), the front edge of the phantom is at 40mm. As expected, the signal intensity from the phantom fades with increasing distance from the transducer. There is an SNR of 5.42, with a signal intensity of 7.34 dB. Moreover, it meets Rose's criterion, which states that for an image to have 100% clarity, its SNR must be greater than 5 [10].

Comparing to a Clinical Standard.

The CIRS ultrasound phantom (Fig. 3a) is used as a standard to compare ultrasound image quality [11]. The Murgen device (Fig. 3b) was compared to the Verasonics commercial-grade ultrasound machine (Fig. 3c). Both devices imaged the CIRS phantom, and corresponding targets are circled in red. The Murgen device yielded an SNR of 2.36, with an intensity of 3.73 dB. Verasonics had an SNR of 6.29, with an intensity of 7.99 dB. The Murgen device did not meet Rose's criterion when imaging the CIRS phantom, though the Verasonics did. The Murgen device had visible point scattering (Fig. 3b). Moreover, echoes off the front edge of the CIRS phantom reflected, resulting in periodic, diminishing white bands to appear in the image where no object existed (Fig. 3b).

DISCUSSION.

Imaging the Graphite Laboratory Phantom.

In imaging the graphite phantom, the front face of the phantom was placed 40mm away from the transducer (Fig. 2a). In the re-constructed image (Fig. 2b), the front of the phantom also appears at 40mm, so the distance scale is accurate. The phantom also appears slightly elongated in the x-direction because the sweep of the Servo motor was not quite parallel. The phantom also appears to get darker with distance from the transducer. This phenomenon called attenuation is common in ultrasound imaging and is corrected for by incorporating time-gain compensation in the image processing. Time-gain compensation artificially boosts the signal strength with respect to distance from the transducer [2].

The image of the graphite phantom had a SNR of 5.42, which meets Rose's criterion. Therefore, our device can image graphite phantoms with 100% clarity. Further testing will need to be done to determine its feasibility in imaging tissue.

Imaging the CIRS Phantom.

The Murgen device successfully imaged a commercially standard phantom (Fig. 3a-c). There is visible point scattering in the Murgen device. Incorporating deconvolution in the image processing will correct for this fuzziness. Deconvolution is used to decrease the fuzziness of the image. The retreating white bands in the Murgen's image of the CIRS phantom (Fig. 3b) are reflections of the echo off the phantom's front edge, a result of the particular arrangement of the transducer and phantom. Furthermore, there was an SNR of 2.36, not meeting Rose's criterion. Therefore, our device does not image commercial phantoms with 100% clarity. Targets in the CIRS phantom were expected to be more difficult to image than the submerged graphite phantoms because it is used for quality testing.

Device Optimization.

By implementing front-end signal processing on the Murgen board, the necessary computing power of the device reconstructing the images would be reduced. In the future, data could be gathered directly onto the BeagleBone using an ADC connection between it and the Murgen. This would eliminate the necessity of MATLAB/GageScope, which are currently used for data acquisition; using the onboard ADC would thus make the device more portable. The BeagleBone would still control the Servo via a serial connection with the Arduino, which has already been accomplished. Furthermore, the need for a computer could potentially be eliminated by attaching a screen to the BeagleBone to show the reconstructed image. The resulting design is common among portable ultrasound devices, such as the GE VScan [4].

The device currently executes a full sweep and reconstructs an image in about two minutes. The majority of this time is due to heavy averaging implemented at each angle during data collection. The incorporation of signal processing on the front end (i.e., by the Murgen board) would reduce the need for averaging and thus increase the frame rate. The ultimate goal would be to reduce signal processing for each angle to less than 10ms, as this is the fastest rate that the Servo motor can rotate to each angle. The scan conversion is the most time-consuming function of the image reconstruction program. However, since the scan conversion could run in parallel with image acquisition, it will not affect the acquisition time at each angle.

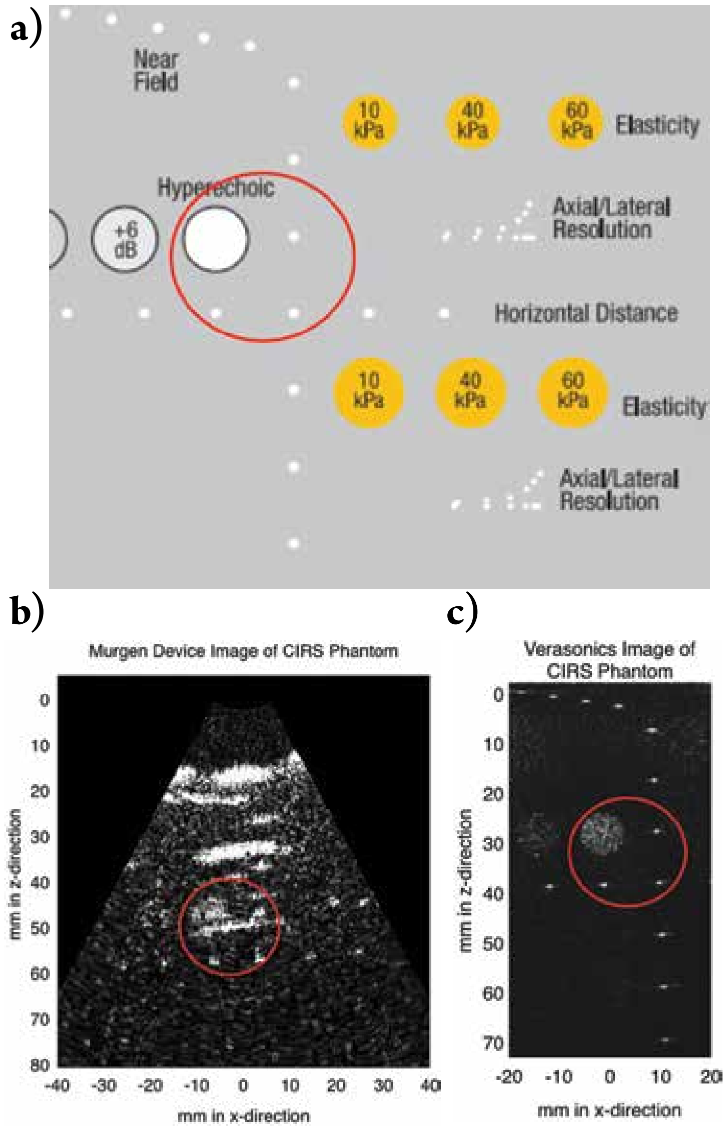

Figure 3. Comparing images of the CIRS phantom taken by the Murgen and Verasonics. Fig 3a. is a diagram of the targets in the CIRS Model 040GSE Multi-Purpose, Multi-Tissue Ultrasound Phantom is a standardization tool for ultrasound imaging devices. Corresponding targets are circled in red. (Fig. 3a source: [11]). 3b and 3c show the reconstructed image from the Murgen and Verasonics imaging devices, respectively. Corresponding targets are circled in red.

In this project, a portable and inexpensive ultrasound device was developed. The device takes accurate images of laboratory phantoms, but needs further improvement before it could be commercially implemented. The device costs 97% less than commercial scanners (Table 1), which can cost up to $25,000 [4]. To further drive down cost, a transducer built in-lab could be implemented. This would drive down the cost of the device even further. This project lays the groundwork for a portable ultrasound device of comparable quality to commercial grade scanners and at a substantially lower price.

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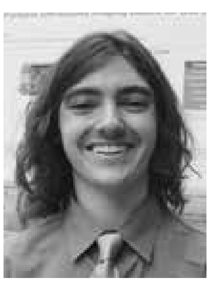

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