HIGH RESOLUTION UNDERSEA ACOUSTIC DATA ACQUISITION USING SINGLE-BOARD MICROCONTROLLERS

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Abstract

There are a number of situations in the undersea environment in which it would be useful to have a low-cost, low-power, deployable, high resolution acoustic data acquisition system. Thanks to the rapid technological advances within the mobile computing industry, there are now a number of small, low-cost, single-board microcontrollers available that lend themselves to the tasks of data acquisition and processing. In this paper, we show how a single-board microcontroller, along with a 24-bit analogue-to-digital converter chip, and some amplification and filtering circuitry can be combined with a PVDF hydrophone to record and analyse high resolution acoustic data. We compare the performance of this low-cost acoustic data acquisition system with a commercial alternative.

1. Introduction

Over recent years there has been a flourishing of low-cost, configurable single-board microcontrollers. In a previous work[1] we compared the performance of a number of these devices with regard to undersea acoustic data acquisition. The highest precision that we investigated was 12 bits, and this was recording only a single channel. In this work we couple a Beaglebone Black to an ADS1271 to obtain two channel recordings at 24 bit precision and 130208 samples per second.

In Section 2 we describe the Beaglebone Black in some detail, concentrating on the programmable real-time units (PRUs) in Section 2.1. Then, in Section 3, we introduce the ADS1271 which is a delta-sigma, 24-bit analog-to-digital converter. We discuss how the PRUs can be used to allow the Beaglebone Black to control the ADS1271 chips, and also highlight the need for over-voltage protection circuits. Having explained how a Beaglebone Black and an ADS1271 can be coupled to produce a low-cost, configurable, high-speed, high-precision, real-time data acquisition system, in Section 4 we compare this system's performance to a commercial alternative. In Section 5 we briefly show how this data acquisition system can be combined with some PVDF hydrophones and some charge amplification circuitry to produce a complete undersea acoustic data acquisition system. We discuss the on-board signal processing capabilities of the Beaglebone Black in Section 6. Finally, we draw some conclusions and point to some further research regarding microcontrollers in at-sea deployable systems.

2. Beaglebone Black

The Beaglebone Black (BBB) is a single-board microcontroller/computer produced by Texas Instruments[2, 3]. It currently retails at around AU\$ 70. The Beaglebone Black is open-source hardware, designed to run open-source software. With a physical footprint not much larger than a credit card, and drawing less than 2 Watts, it has 512 Mb of RAM, 4 Gb of onboard memory (which can be expanded by using the attached microSD slot), and a plethora of interface options including USB, Ethernet, HDMI, SPI, I^2C, UART and a large number of GPIO pins. There are a range of choices for the open-source operating system on the Beaglebone Black. For this paper, we used the currently recommended choice of Linux Debian[4]. Most of the features of the Beaglebone Black are contained within a single chip: the AM335x Sitara [5]. The main processor on the AM335x Sitara runs at 1 GHz. The small size, low cost and configurable nature of the Beaglebone Black mean that the device is well suited as the basis for the creation of smart acquisition systems[6, 7]. However, the component which sets the Beaglebone Black apart from other single-board microcontrollers currently on the market is a subsystem of the AM335x Sitara known as the programmable real-time units (PRUs).

2.1 Programmable real-time units

The PRUs are two independent processors contained within the AM335x Sitara chip on the Beaglebone Black [8, 9]. Each of these processors are 32-bit, running at 200 MHz and are independent of the main processor. They each have 8 KB of programmable memory and direct access to general inputs and outputs. These processors are able to exchange information with the main processor and each other through the use of shared RAM and a number of interrupts.

The PRUs allow for the development of applications on the Beaglebone Black which require real-time processing. Unfortunately the manufacturer does not provide direct support for developers wishing to utilise the PRUs in the development of applications requiring real-time processing. Instead, the manufacturer has provided an open-source package of code called the AM335x PRU Package[10], and a online community support website[11]. Programs for the PRUs need to be written in assembly language. As well as some documentation, the PRU package contains an assembler program, which translates the assembly language program into binary code which is executable on the PRUs and it also contains a Linux driver which allows the main processor to control the PRUs.

The PRUs can get direct access to external sensors through the GPIO pins on the Beaglebone Black, however configuring these pins is rather complicated, and not all pins are accessible to the PRUs in all configurations. For example, both the 4 Gb storage and the HDMI port on the Beaglebone Black use GPIO pins which are shared with the PRUs, meaning that these devices need to be disabled in order to access all the GPIOs of the PRUs.

3. ADS1271

The AM335x Sitara chip on the Beaglebone Black includes an analog-to-digital converter (ADC) however this internal ADC has only 12 bits of precision, and even though it is possible to convert from eight different channels, this is done sequentially, limiting the device to effectively one 12-bit channel if you wish to run at the maximum sample rate. Often, 12 bits of precision will be insufficient for undersea acoustic recordings. We therefore turn to an external ADC for greater precision. We chose to use the ADS1271, which is a 24-bit, delta-sigma ADC[12, 13]. It has been designed for data rates up to 105kSPS (although in our testing we managed to successfully record at a rate of 130kSPS). This device has a number of features which make it attractive for use in an undersea acoustic acquisition system including low drift and low in-band noise. For easy of utilisation, it is possible to acquire two of these chips on a evaluation board (ADS1271 Evaluation Module [14]), which assists greatly in interfacing with the Beaglebone Black.

The ADS1271 chips are able to communicate with external microcontrollers using either an SPI or a frame-sync serial interface. Given the 200 MHz clock speed limitation of the PRUs, we found it easier

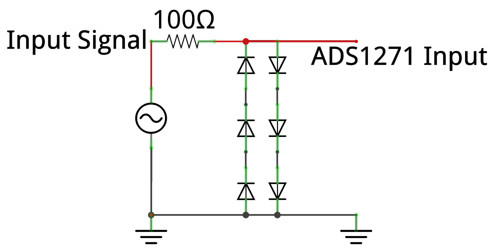

Figure 1: Simple circuit to protect the ADS1271 chips from damage due to excessive input voltage.

to link the ADS1271 and the Beaglebone Black using the frame-sync interface as discussed in Section 3.2. The ADS1271 has three different operating modes, in turn optimising for speed, resolution or power. For our requirements, we ran the chips in the mode which allows for the greatest sample rate.

3.1 Over-voltage protection

The ADS1271 requires an external reference voltage. For the recordings contained in this paper we used the 2.5 V reference voltage provided by the ADS1271 Evaluation Module. Thus, according to the data-sheet for the ADS1271 [13], the input signals must be kept between -2.8 V and 2.8 V. We used the simple diode protection circuit depicted in Figure 1 to keep the input voltages well within these limits.

3.2 Connecting the Beaglebone Black and the ADS1271

In this section we give a brief overview of the technique we used to interface the ADS1271 to the Beaglebone Black using the PRUs in order to create a low-cost, configurable, high-speed, high-precision, real-time data acquisition system.

We utilised both PRUs in the process of interfacing with the two ADS1271 chips contained on the ADS1271 Evaluation Module. One of the PRUs is used to produce two synchronised clocks, which are both fed into the two ADS1271 chips; one clock acts as the master clock for the ADC and another, slower clock is used in the frame-sync serial communications protocol. The second PRU also receives the two clocks from the first PRU and additionally it receives the digital output from the two ADS1271 chips.

The sample rate of the system is determined by the clock rate of the PRUs. As previously mentioned, the PRUs run at 200 MHz. This means that each clock cycle takes 5 ns. It takes six PRU clock cycles to complete one ADC clock cycle. This is because, for each clock cycle, we need to set the FSYNC output pin, the ADC clock output pin and the serial clock output pin, taking three cycles. We need the down-cycle to be equal to the up-cycle for the ADC clock, so we need a further three cycles for clearing the various pins. When the ADS1271 is running in fast frame-sync mode, there needs to be 4 ADC cycles for every serial clock cycle, and 64 serial clock cycles between each new ADC output. This means that the total time to acquire a sample from each ADS1271 ADC is $5 \times 6 \times 4 \times 64 = 7680$ nanoseconds, which gives a sample rate of approximately 130208 samples per second.

The second PRU is able to store the 24-bit samples from the two ADCs in a buffer, which by default is only 256 Kb, but is reconfigurable to a maximum size of 8 Mb. The second PRU actually uses two buffers; when one buffer fills, it begins using the second buffer, whilst also signalling the Beaglebone Black primary processor to copy the full buffer across to file storage. This memory copy is infrequent enough that under normal load conditions the primary processor is able to consistently complete the task without any dropped packets.

4. Data acquisition system performance

We tested the BBB/ADS1271 system with a variety of different input signals, and compared the output to the output recorded on a Brüel and Kjær Type 3050-B-060 [15]. The frequency response for two sinusoidal inputs are depicted in Figure 2 and Figure 3. These show the responses of both the BBB/ADS1271 and

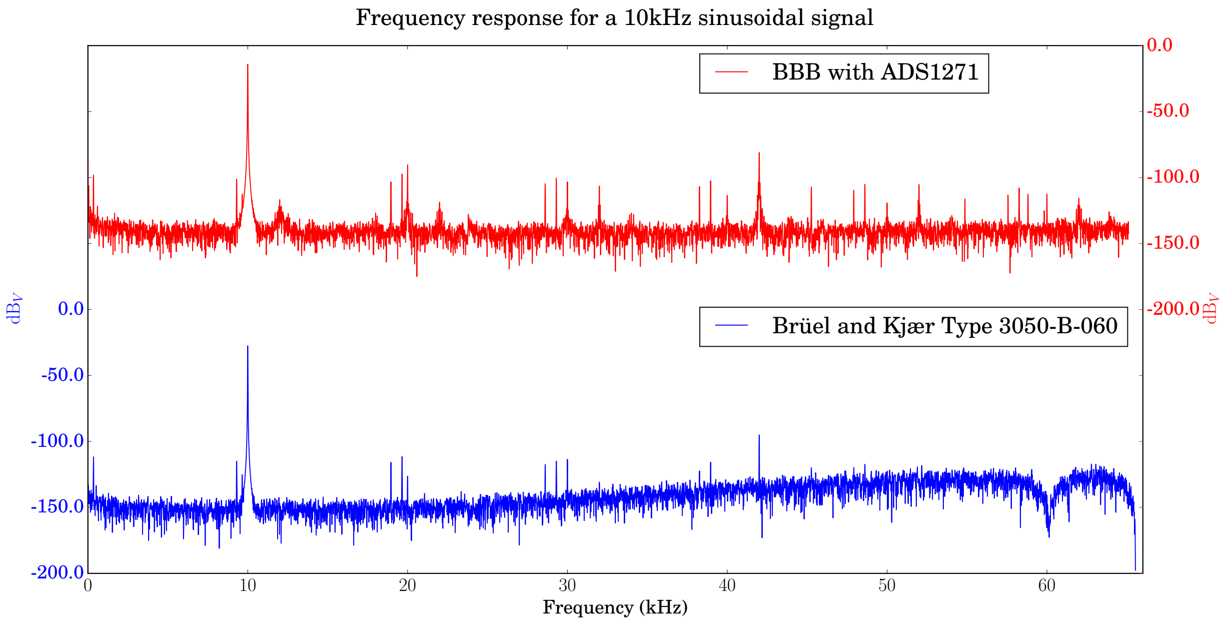

Figure 2: Frequency response to a 10kHz sinusoidal signal of the BBB/ADS1271 (Red) and the Brüel and Kjær Type 3050-B-060 (Blue).

the Brüel and Kjær Type 3050-B-060 to sinusoidal signals at 10 kHz and 42 kHz respectively. These signals were generated using an Agilent 33220A[16] signal generator.

It is evident from Figure 2 and Figure 3 that the noise-floor and signal level of the BBB/ADS1271 acquisition system is comparable to that of the Brüel and Kjær Type 3050-B-060. Both devices also have a comparable maximum sample rate.

5. Underwater acoustic data acquisition

In linking a Beaglebone Black to an ADS1271 Evaluation Module as described in Section 3.2 we now have a two-channel, low-cost, configurable, deployable, high-speed, high-precision data acquisition system. In this section we describe how we utilised this acquisition system to compare the performance of a PVDF hydrophone with a HTI-96-MIN hydrophone[17]. For details of using PVDF film as a hydrophone see [18], [19] and references therein.

The HTI hydrophone comes with an internal pre-amplifier, so it is able to be directly connected to the analog input of the ADS1271 (utilising the over-voltage protection circuit described in Section 3.1). The PVDF hydrophones that we were testing required some amplification and filtering before connecting to the ADS1271. We used a Reson CCA1000 Conditioning Charge Amplifier[20] as the amplifier, and a simple passive RC band-pass filter, depicted in Figure 4.

The charge amplifier runs on 12V DC at approximately 50 mA, which is about a third of the power needed to run the Beaglebone Black. The amplifier is only required when the unit is recording, and so it makes sense to use the Beaglebone Black to power up the amplifier only when required. Unfortunately the charge amplifier uses a ground which is common with the negative of the input and output signal. This means that a single transistor can not be used as a low-side switch, instead we use one of the GPIO pins on the Beaglebone Black, and a simple high-side switching circuit depicted in Figure 5.

5.1 Measurements in a tank

Our first series of tests were conducted in a cylindrical freshwater tank (the tank has a depth of 1.0 metres and a diameter of 1.8 metres). Given the relatively small size of the tank, it was necessary to conduct the tests at high frequencies to minimize the effects of reverberation. Figure 6 shows an example of the results

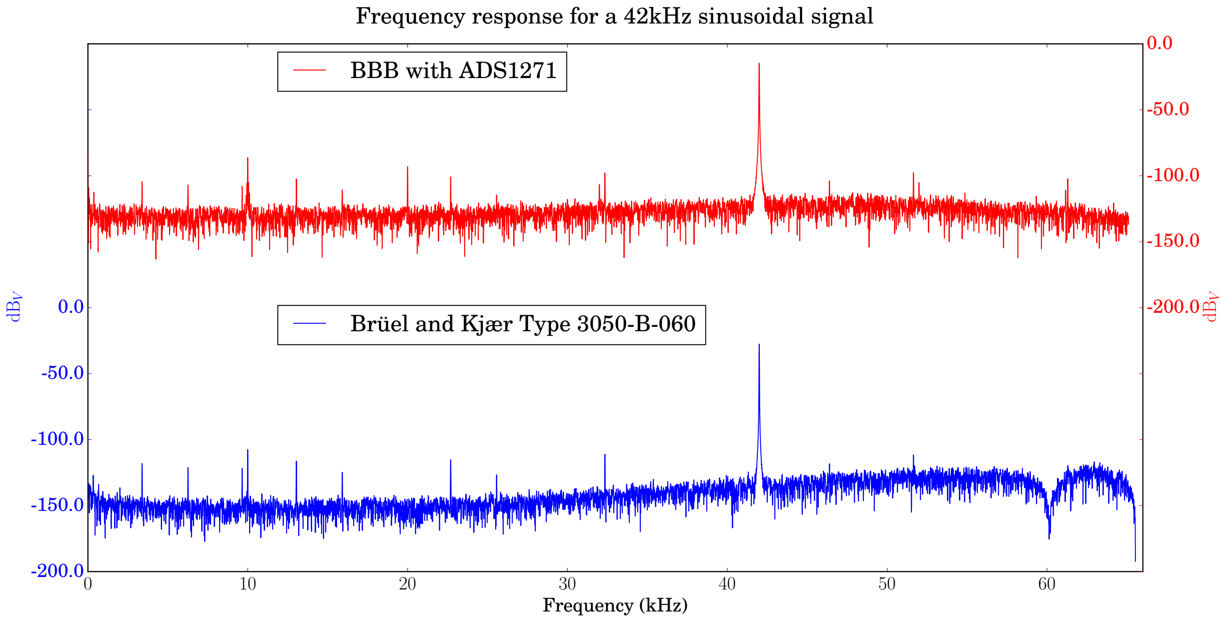

Figure 3: Frequency response to a 42kHz sinusoidal signal of the BBB/ADS1271 (Red) and the Brüel and Kjær Type 3050-B-060 (Blue).

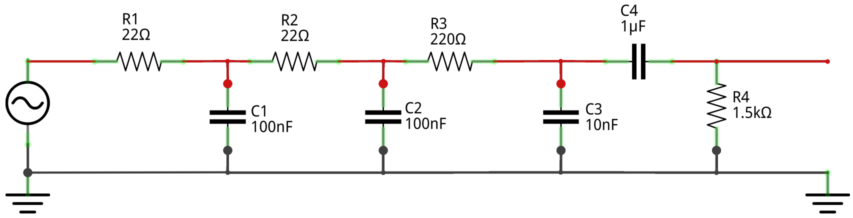

Figure 4: Simple circuit to provide some analog filtering.

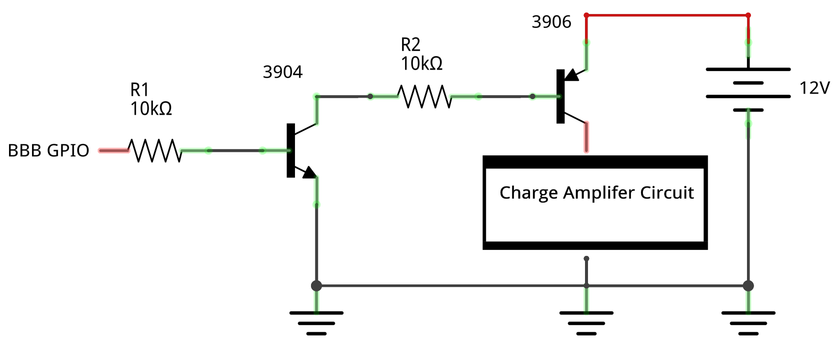

Figure 5: Simple circuit to provide a high side switch for the charge amplifier.

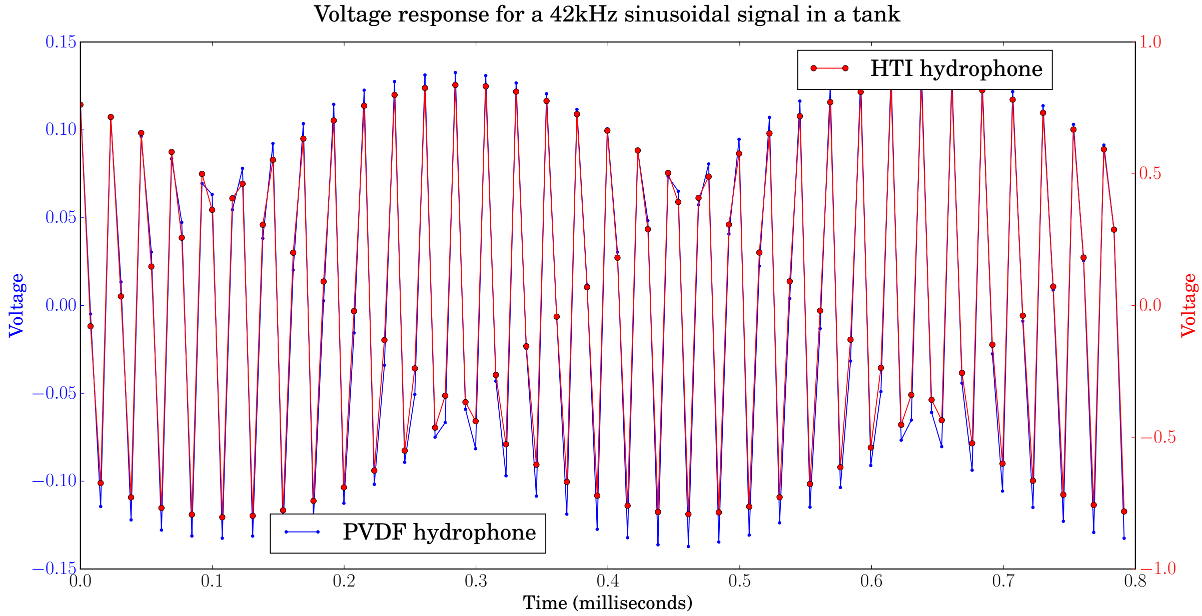

Figure 6: Voltage response from an HTI hydrophone (Red) and a PVDF hydrophone (Blue). These voltages were recorded using the BBB/ADS1271 acquisition system. The sinusoidal signal in the tank was generated by an ITC 1042.

obtained by simultaneously recording both a PVDF hydrophone and a HTI hydrophone. The sinusoidal source signal was generated by an ITC 1042[21] fed with an input signal of 42 kHz at 4 V_{RMS}. The charge amplifier attached to the PVDF hydrophone had input capacitance and input resistance set at 47 pF and 330 kΩ respectively, and a gain of 32 dB was also used. This still created voltage levels significantly below that of the HTI hydrophone, but the 24-bit precision on the ADC meant that a meaningful comparison could still be conducted. It is clear from Figure 6 that the performance of the PVDF hydrophone and the HTI hydrophone is comparable at this particular frequency. It should be noted that 42 kHz is outside the design frequency of the HTI hydrophone that we used, however, as stated the small size of the tank required a high frequency.

5.2 Measurements at sea

Having tested the BBB/ADS1271 acquisition system in a laboratory environment, we then inserted the system into a small self-contained deployable module to ensure that the system was able to perform in an at-sea environment. The deployed module consisted of a cylindrical nylon capsule, with an outer diameter of 16 cm and a height of 40 cm. Along with the BBB/ADS1271 system, the capsule contained a 12 volt lead-acid battery, providing 7 Amp-hours of power. It also contained the amplifier and filtering circuitry and an additional microcontroller to facilitate communication when surfaced. The module was deployed approximately 2 metres below the surface in a near-shore ocean environment with a water depth of approximately 5 metres. Once again the charge amplifier was set at a capacitance of 47 pF, a resistance of 330 kΩ and a gain of 32 dB. The Beaglebone Black was set to record for an extended period of time. The device was then brought to the surface so that the data could be extracted and analysed. Figure 7 shows an example of an impulsive signal recorded on both hydrophones. Unlike the tests conducted in the tank (Figure 6), the amplitudes of the two signals are approximately the same.

6. On-board signal processing

Given that the Beaglebone Black is running a Debian Linux distribution, it is possible for the BBB/ADS1271 device to act as more than simply a data acquisition system: there is also the possibility of doing on-board

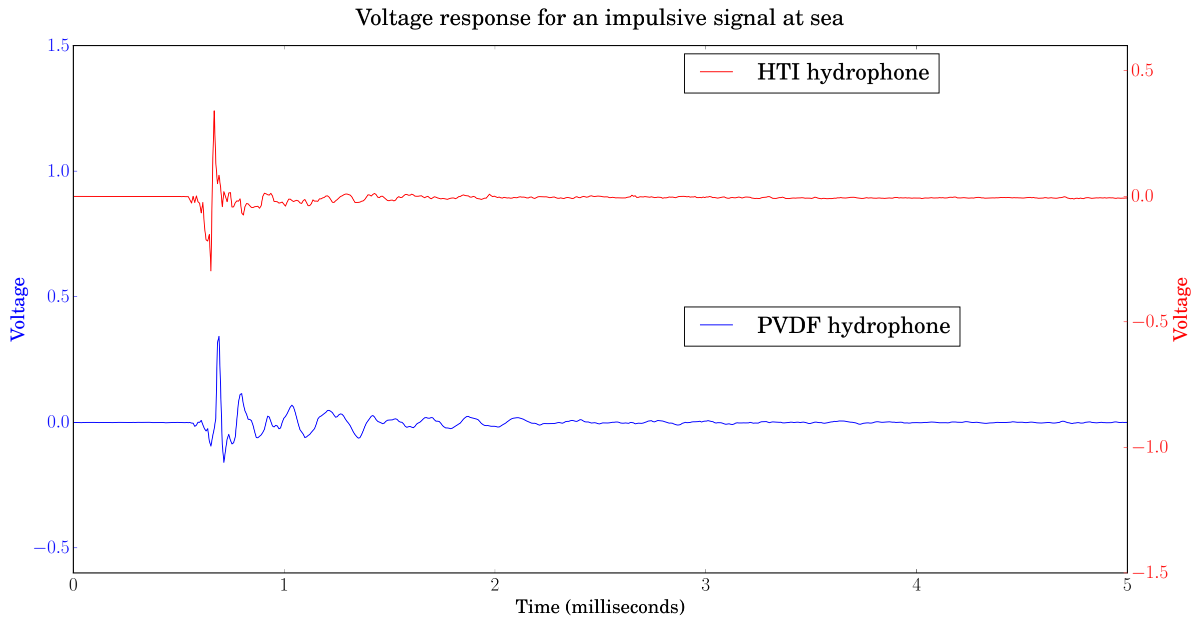

Figure 7: Voltage response from an HTI hydrophone (Red) and a PVDF hydrophone (Blue) recorded using the BBB/ADS1271 acquisition contained in a small deployable self-contained module.

processing. Development of on-board processing becomes relatively straight forward with the use of SciPy[22]. SciPy is a Python-based ecosystem of open-source software for mathematics, science, and engineering. The packages bundled in SciPy include many signal processing algorithms, FFTs and a wide variety of filtering and spectral analysis algorithms. Python also comes with a variety of useful test and evaluation modules for testing the performance of your code and the microcontroller itself. In many instances, the Beaglebone Black can simultaneously do signal processing on the data which are being acquired using the PRUs, however, if the processing load is too high for a single Beaglebone Black it can pass the data over to an auxiliary microcontroller for signal processing, using an Ethernet connection.

7. Conclusions and further research

In this paper we have shown that by utilising the programmable real-time units on a Beaglebone Black it is possible to use an ADC chip to produce a low-cost, configurable, high-speed, high-precision, real-time data acquisition system. Using a single Beaglebone Black and a ADS1271 Evaluation Module we were able to reliably record two channels of 24-bit data at a rate of 130208 samples per second. We showed that the recording speed, precision and noise-floor of this acquisition system is comparable to a more expensive commercial alternative. As an example of the uses of this acquisition system, we compared the output of two different types of hydrophone. We also highlighted the on-board signal processing potential of the Beaglebone Black, which is made readily available through the use of open-source scientific computing tools such as SciPy.

Future avenues of research that we intend to pursue include testing the capacity of the Beaglebone Black to do concurrent signal processing while gathering data and expanding the number of input channels. We also intend to conduct more at-sea trials to test the durability and reliability of the system.

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