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Using low cost single-board microcontrollers to record underwater acoustical data

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ABSTRACT

Over recent years there has been a rapid increase in the availability of single-board microcontrollers. In this paper we review three such microcontrollers; the Arduino Mega2560, the Raspberry Pi and the Beaglebone Black. We show how these devices can be used to produce low cost, low power, deployable, configurable at-sea measurement systems. We also highlight the advantages and disadvantages of each type of single-board microcontroller. We show how these devices can be configured to acquire either digital or analog data from a variety of sensors, as well as process, store and transmit the results. We present some results of high sample rate analog recordings which have been obtained at a fraction of the cost of the more common commercial alternatives. We also highlight some of the pitfalls associated with using these leading-edge devices. Keywords: Data acquisition systems, Calibration, Automated Data Processing I-INCE Classification of Subjects Number(s): 71.8,71.9,74.4
(See `http://www.inceusa.org/links/Subj%20Class%20-%20Formatted.pdf`.)

1. INTRODUCTION

In this paper we look at some alternatives for low cost, deployable, configurable microcontrollers which allow for the measurement, processing, storage and transmission of a number of at-sea parameters. We are mainly concerned with measuring underwater sound, but there are a number of other parameters we would like to measure including temperature, acceleration, depth and salinity.

We have investigated three different microcontrollers. We begin in Section 2 by discussing the key requirements of a microcontroller for use in an at-sea deployable system. In Section 3 we highlight the characteristics of each of the microcontrollers investigated, assessing how each microcontroller fulfils the requirements of the previous section, highlighting both the strengths and limitations of each device. Section 4 gives some examples of the types of tasks that a microcontroller can perform, including comparing their analog acquisition capabilities to a Brüel and Kjær Type 3050-B-060. We show that the Beaglebone Black can perform as a 12-bit 100 kSPS ADC, whilst simultaneously carrying out signal processing. The Beaglebone Black has great potential as a stand-alone measurement device however we also show that there are considerable advantages to using a combination of the available microcontrollers. Section 5 highlights some of the pitfalls associated with using such leading-edge technology. Finally, we draw some conclusions and point to some further research regarding microcontrollers in at-sea deployable systems.

2. DEPLOYABLE MICROCONTROLLER REQUIREMENTS

There are a wide variety of commercial devices available for taking underwater measurements, however these devices are generally costly and have been geared towards a specific task. There is a demand for more compact, low cost, light weight alternatives(1). In this paper we look at using microcontrollers to acquire, store and analyse underwater measurements. Below we list our various requirements for a microcontroller to be used in an at-sea measurement system.

2.1 Low cost

Of primary concern is the cost of the over-all measurement system. Being able to create a low cost system, as compared to a more expensive commercial system has a number of advantages. Firstly, in the current tightly constrained economic climate, it means that more projects utilising such devices are likely to get approved. Secondly, each device is effectively expendable. Thirdly, it becomes viable to create a number of such systems.

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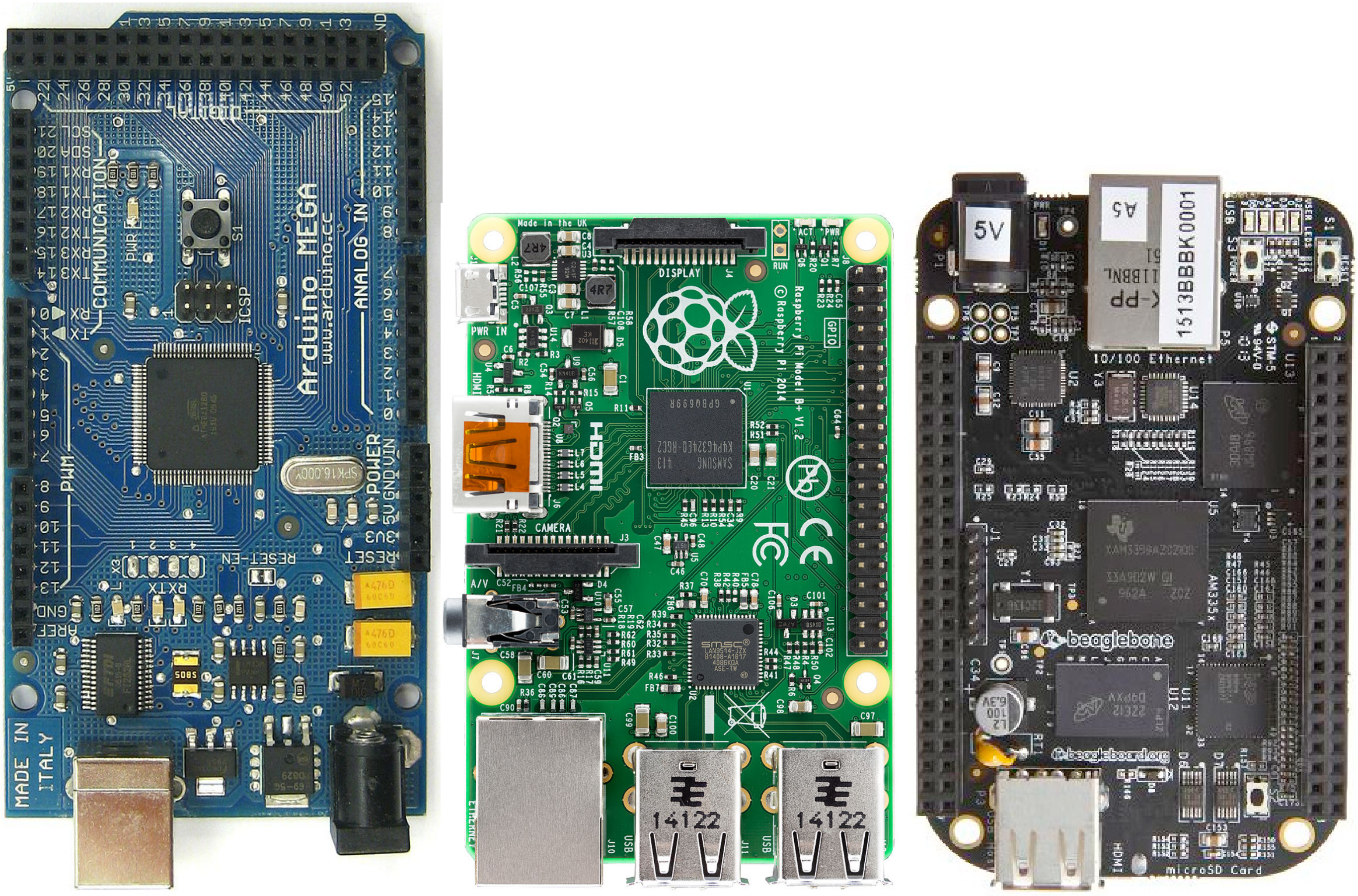
2.2 Portability

The current crop of microcontrollers investigated in the paper have a very compact profile. They are generally not much larger than a credit card (see Figure 1 for an idea of the size of the microcontrollers), and have a thickness of less than 20 mm. This small footprint has the key advantage that a deployable system will only need a correspondingly small mass added to the system to achieve neutral or negative buoyancy. The microcontrollers are also very energy efficient, enabling them to be powered by a relatively small battery, further reducing the size and mass of the deployable system.



(a) (b) (c)

Figure 1 – (a) The Arduino Mega2560. Photo courtesy of David Mellis(2), (b) The Raspberry Pi. Photo courtesy of Lucasbosch(3), (c) The Beaglebone Black. Image taken the Beaglebone Black website(4). These microcontrollers are shown actual-size when document is printed at A4 size.

2.3 Configurability

One of the key advantages of these microcontrollers are that they are highly configurable. They are highly configurable in the sense that they can generally utilise a number of different operating systems and they can be easily programmed in your choice of programming language. They are also configurable in the range of sensors that they can control. As well as analog measurements, they can control any device which uses communication protocols such as UART, SPI or I^2C. Finally, the amount and type of signal processing done on the microcontroller can also be varied.

2.4 Usability

As we pointed out, one of the key benefits of these microcontrollers is the extent to which they can be configured. Unfortunately this configurability often comes with an associated cost to usability - the more options there are for configuring a device, generally the harder the device will be to use. Another problem with usability is often the lack of documentation associated with these microcontrollers. They are created using the latest available components, and this can mean that rigorous testing has not been carried out. A good example of this is the programmable real-time units (PRUs) on the Beaglebone Black which are discussed in Section 3.3. These are a very powerful addition to the microcontroller, but little effort has been made by the manufacturer to make these components user-friendly. Indeed, apart from some very recent third-party libraries (e.g. (9)), the only way to use the PRUs is to program them directly in the ARM assembly language. Ideally, all components of a microcontroller would be easily controllable using common operating systems and programming languages.

One final characteristic which makes a microcontroller more usable is an active online community, which provides a good support network for trouble shooting the problems which can occur in developing novel applications using the devices.

3. CHOOSING A MICROCONTROLLER

There are a variety of single-board microcontrollers currently available on the market. We chose to investigate the Arduino Mega2560, the Raspberry Pi and the Beaglebone Black. In this section we highlight the characteristics of each of these microcontrollers and determine how well they fulfil the requirements outlined in the previous section. Table 1 provides a summary of some of the key characteristics of each microcontroller. A more detailed explanation of each microcontroller is provided in the subsequent subsections.

Table 1 – Comparison of microcontroller characteristics

	Arduino Mega2560	Raspberry Pi	Beaglebone Black
Current retail price	AU$ 45	AU$ 38	AU$ 64
CPU speed	16 MHz	700 MHz	1 GHz
Analog inputs	16	0	8
GPIO Pins	54	17	92
Maximum analog sample rate	55 kSPS	NA	100 kSPS
USB	1 B	4 A, 1 micro-B	1 A, 1 mini-B
UART	4	1	4
SPI	1	2	2
I^2C	1	2	2
Ethernet	0	1	1
Wifi dongle	No	Yes	Yes[1]
Real-time processing	Yes	No	Yes[2]
Onboard memory	256 kB	0[3]	4 GB
Onboard RAM	12 kB	512 MB	512 MB

1 - Although possible, we found wifi on the Beaglebone Black to be unreliable.

2 - Using the programmable real-time units - see Section 3.3.

3 - The Raspberry Pi uses an SD card for booting and persistent memory.

3.1 Arduino

Developed in Italy, the Arduino is a single-board open-source microcontroller, first introduced in 2005. It has proven to be popular in the electronic hobbyist market, as it provides an easy and inexpensive platform to interact with a variety of sensors and actuators(5).

The Arduino that we chose to evaluate is the Arduino Mega2560 (6), a photo of the board is shown in Figure 1 (a). The Arduino Mega2560 currently retails for AU$ 45, so it certainly fulfills the low cost requirement. Its processor is the least powerful of the microprocessors that we evaluated. The microprocessor at the heart of the Arduino Mega2560 is the ATmega2560. This is an 8-bit processor, which runs at 16 MHz. The Mega has 256 kB of Flash memory, which is used to store the current program, however this memory can not be rewritten while the Arduino Mega2560 is running. It has only 8 kB of SRAM (where the programs variables are stored) and 4 kB of EEPROM. However, the strong suite of the Arduino Mega2560 is the number of input and output pins available. The Arduino Mega2560 has 54 Digital input/output pins, 15 of which can provide Pulse Wave Modulation (PWM) output, which can be used to simulate analog output. It also has 16 analog input pins, which are fed into a single 10-bit analog-to-digital converter (ADC). The board is power by a DC voltage anywhere in the range of 6 to 20 volts - an input range of 7 to 12 volts is recommended for optimal operation. The device provides four hardware UARTs for serial communication as well pins for SPI and I^2C communication.

The Arduino Mega2560 comes with its own open-source integrated development environment (IDE). The environment is written in Java and uses its own open source programming language, based upon the *Processing* programming language. The configuration and testing process involves writing a program using the Arduino Mega2560's IDE and then using the IDE to transfer the compiled binary to the device via USB.

Additional memory storage can be attached to the Arduino Mega2560 via its SPI communication pins, however the reading and writing of the attached memory will consume CPU operations, thereby limiting the concurrent signal processing and data acquisition.

By default the ADC on the Arduino Mega2560 samples at a relatively low rate of 9600 Hz, however the pre-scale factor on the clock used by the ADC can be increased, which enables the ADC to sample at a rate of approximately 55 kHz. This sample rate is only achieved under the proviso that the Arduino is doing nothing else whilst it is acquiring the analog data.

The limit of 8 kB of SRAM severely restricts the amount of signal processing that the Arduino Mega2560 can accomplish, whilst the single 16 MHz processor restricts the speed at which the ADC can collect data.

Thus, while the Arduino Mega2560 is low cost, portable, reliable, and rather user-friendly its lack of processing power and memory makes it not as versatile as the Beaglebone Black.

It is ideally suited as an interface linking together many sensors, under the proviso that they do not require high sample rates.

3.2 Raspberry Pi

The Raspberry Pi (7) is a much more recent edition to the single board microcontroller market. Available since 2012, it has proved to be remarkably popular (over 2.5 million boards had been sold as of February 2014). As with the Arduino, the Raspberry Pi definitely fulfils the criterion of portability, at approximately the size of a credit card (See Figure 1 (b)). It also runs on very little power - approximately 3 Watts. The Pi more than adequately fulfils the low cost criterion, being the cheapest of the three microcontrollers investigated, it currently retails for AU$ 38. The Pi also scores high on reliability and usability. There are a variety of flavours of Linux readily available for the Pi, as well as a RISC operating system.

The processor on the Raspberry Pi is an ARM processor which has been configured to run at 700 MHz (it can be over-clocked to run at 1 GHz however this is not within the manufacturers original specifications and we did not test the device at this speed). The model we tested had 512 MB of RAM. There is no onboard persistent memory - booting and persistent memory is provided by an attached SD card.

However the main weak point of the Raspberry Pi for our purposes is the low number of input and output pins. It has no onboard ADC, which means that if it is to be used to collect analog data, it needs to be used in conjunction with another microcontroller, or it needs to be attached to a dedicated ADC chip, such as the ADS1271(8)[1].

Whilst lacking an ADC, the Raspberry Pi is more stable when using peripheral communication devices than the Beaglebone Black. For example, the wifi on the Beaglebone Black is notoriously unstable, whilst the Raspberry Pi has much greater stability. This means that the Raspberry Pi is useful as an intermediate device, attaching directly to another microcontroller, it allows stable wifi communication. This is useful, because a plastic cased underwater measurement device can be brought to the surface, and have data extracted, and even be re-programmed without needing to open the casing or attach any devices, reducing the requirement for under water connectors.

3.3 Beaglebone Black

The Beaglebone Black (BBB) is a single board microcontroller produced by Texas Instruments(4). Like the Raspberry Pi, the BBB has undergone a number of changes since its initial release in 2013. The BBB combines many of the advantages of the Raspberry Pi with those of an Arduino microcontroller. The BBB is capable of running a Linux distribution, like the Raspberry Pi and like the Arduino it has an onboard ADC. However, the Beaglebone Black's ADC is 12-bit rather than 10-bit and is capable of running at over 100 kSPS. Like the other microcontrollers, the Beaglebone Black is certainly portable, running at around 3 Watts, and very similar in size to the Raspberry Pi (See Figure 1 (c)), it is slightly more expensive at AU$ 64, however definitely still considered low cost. The processor on the Beaglebone Black is an ARM Sitara, running at 1 GHz.

The key advantage of the BBB over both the other microcontrollers is the presence of two programmable real-time units (PRUs). Each of these 32-bit processors run independently of the main processor, yet they are able to exchange information with the main processor through the use of shared RAM and a number of interrupts. The PRUs run at a clock speed of 200 MHz, significantly faster than the 16 MHz of the Arduino Mega2560. Unfortunately the PRUs are not supported by the manufacturer, which means that it is very difficult to obtain reliable information as to how to program them. The PRUs can get direct access to external

[1]Although we had access to an ADS1271, we were unfortunately unable to successfully connect the chip to either the Raspberry Pi or the Beaglebone Black before the submission date of this paper.

sensors through the GPIO pins on the Beaglebone Black, however configuring these pins is rather complicated. The PRUs need to be programmed in assembly language, which makes application development very time-consuming. Fortunately there has very recently been some open source third-party libraries written(9), which allow the PRUs to do analog data acquisition at over 100 kSPS.

4. USING A MICROCONTROLLER

Having outlined the requirements for a microcontroller to be used in an at-sea measurement system and described the key characteristics of the three microcontrollers that we have investigated, in this section we give some brief examples of how the microcontrollers might be used in order to make a low cost, portable and configurable measurement system.

4.1 Digital peripheral sensors

Perhaps the easiest peripheral sensors to connect to a microcontroller are ones that have already digitised their input. These devices then need only transfer their measurements to a microcontroller for processing or storage. As shown in Table 1, all three microcontrollers are able to connect to devices using a variety of protocols including universal asynchronous receive/transmission (UART), serial peripheral interface (SPI) and inter-integrated circuit (I^2C) protocols.

During our testing we were able to successfully connect a number of digital sensors to all three types of microcontroller including a TMP006 infra-red thermopile sensor(10), a MAX31855 thermocouple(11) and an MMA7361L accelerometer(12). Each of these sensors require a relatively low frequency transfer rate, however we did have problems when connecting an ADS1271, which requires a much higher transfer rate.

4.2 Analog peripheral sensors

One of the key aims of our investigation of the various microcontrollers was to find a low cost alternative to commercially available analog-to-digital converters for use in the at-sea environment. As was pointed out in Section 3.2, the Raspberry Pi has no onboard ADC, so in this section we test the performance of the Arduino Mega2560 and the Beaglebone Black. To assess the ADC performance we compared the results with measurements obtained using a Brüel and Kjær Type 3050-B-060 6-ch Input Module LAN-XI 51.2 kHz(13). The Brüel and Kjær Type 3050-B-060 records data at 24-bit precision at sample rates up to 131 072 samples per second. Using the libpruio library(9), we were able to get the Beaglebone Black to record data at 12-bit precision at a sample rate of 100 000 samples per second. The Beaglebone Black requires analog input signals to be within the range 0 V to 1.8 V. By changing the pre-scale factor on the ADC clock, we were able to record data on the Arduino Mega2560 at a precision of 10-bit and a sample rate of 55 556 samples per second. The Arduino Mega2560 can split its 10-bit precision over any voltage range from 0 V up to 5 V. We chose to set the voltage reference at 1.8 V to allow a direct comparison with the Beaglebone Black. As stated in Section 3.1, the Arduino Mega2560 has very limited memory, allowing the collection of only 3600 samples of continuous data.

Figure 2 depicts the noise floor of the two microcontrollers and the Brüel and Kjær Type 3050-B-060. The Arduino and the Beaglebone Black show reasonably comparable results, although the Arduino is not able to measure up to the same frequency as the Beaglebone Black, and it also does not have the same frequency resolution, due to the limited number of samples. Both microcontrollers have a noise floor which is approximately 40 – 50 dB above the noise floor of the Brüel and Kjær. Most of this difference will be due to the much higher resolution of the Brüel and Kjær.

We also tested the ADC devices with a variety of different input signals. The results of a white noise measurement are depicted in Figure 3, whilst Figure 4 depicts the result of a sinusoidal signal at a frequency of 5 kHz.

These signals were generated using an Agilent 33220A(14) signal generator. The white noise in Figure 3 was generated by the Agilent with a peak-to-peak voltage of 1.6 V and a DC offset of 0.9 V so that the signal would be within the input range required by the Beaglebone Black and the Arduino. As expected, the frequency spectrum produced by both microcontrollers is relatively flat. Figure 4 depicts the results of measuring a 5 kHz sine wave with a peak-to-peak voltage of 1.6V and a DC offset of 0.9 V. This graph shows that the Arduino Mega2560 can adequately detect the frequency, however its performance is markedly below that of the Beaglebone Black. As expected, the Brüel and Kjær performs much better than either microcontroller.

4.3 Onboard Signal Processing

In the previous two sections we have discussed the ability of the microcontrollers to acquire data from digital and analog sensors, however there is another significant advantage of using these single-board microcontrollers, and that is their ability to do onboard signal processing. The 8-bit processor on the Arduino Mega2560

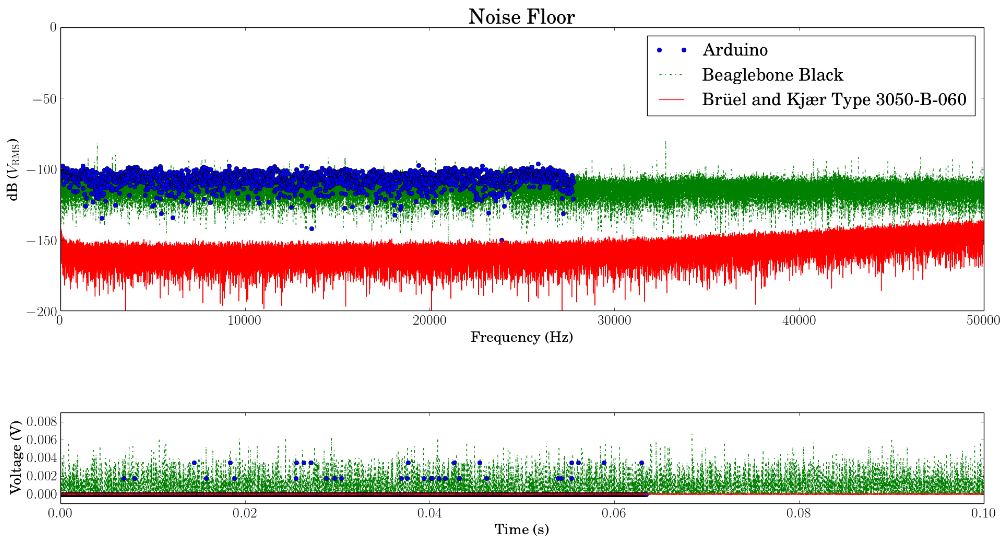


Figure 2 – The noise floor of the the Arduino Mega2560 (Blue), the Beaglebone Black (Green) and the Brüel and Kjær Type 3050-B-060 (Red).

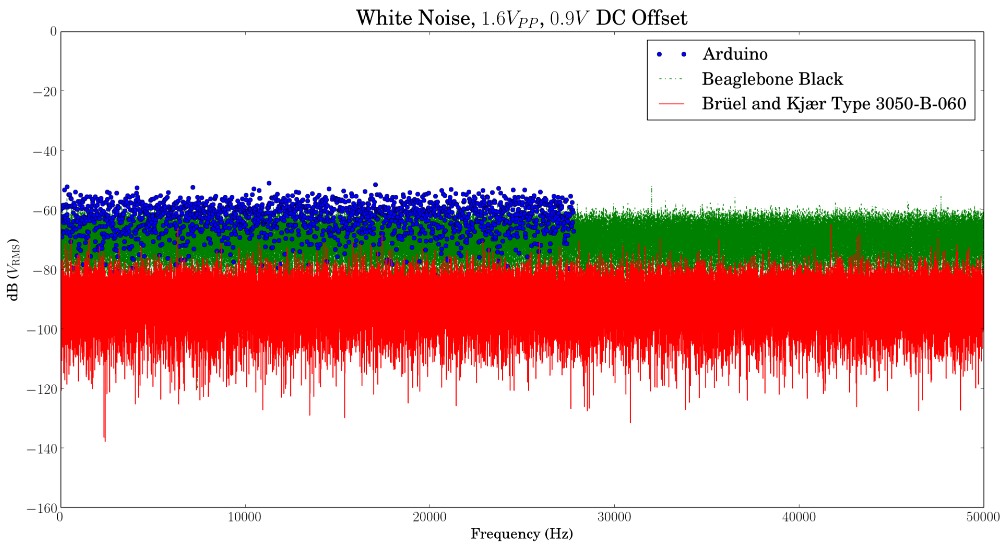


Figure 3 – White noise signal, as recorded by the Arduino Mega2560 (Blue), the Beaglebone Black (Green) and the Brüel and Kjær Type 3050-B-060 (Red).

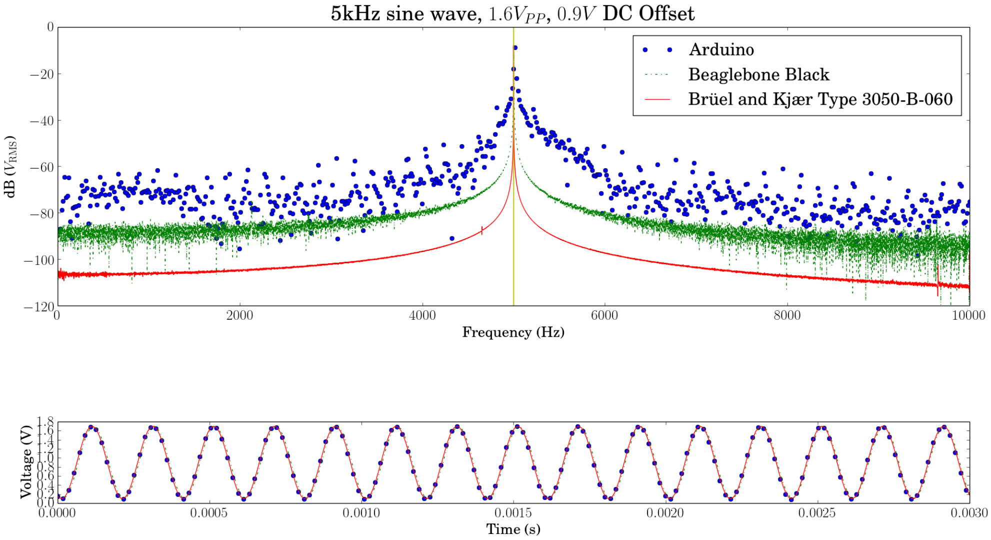


Figure 4 – Sinusoidal signal at a frequency of 5 kHz as recorded by the Arduino Mega2560 (Blue), the Beaglebone Black (Green) and the Brüel and Kjær Type 3050-B-060 (Red).

effectively rules it out as a useful signal processor, however the Beaglebone Black and the Raspberry Pi have more than adequate processing power to do many signal processing tasks. The fact that these devices run a full Linux distribution means that there is easy access to programming languages such as python. Python has a number of free and open-source packages such as numpy and scipy which include many signal processing algorithms, FFTs and a wide variety of filtering and spectral analysis algorithms. Thus the Beaglebone Black can do simultaneous signal processing on the data which are being acquired using the PRUs, or it can alternatively pass the data over to a Raspberry Pi for signal processing, using an Ethernet connection as described in the next section.

4.4 Communications

We have already discussed in Section 3 how these microcontrollers can communicate to various peripheral devices using protocols like UART, SPI and I^2C. However the Beaglebone Black and the Raspberry Pi also have Ethernet and Ethernet-over-USB which means that they can easily communicate with and control other Ethernet-enabled devices. These Ethernet-enabled devices might be other microcontrollers, or they could be other types of data acquisition modules. For example, the Brüel and Kjær Type 3050-B-060 which gathered the data depicted in Figures 2-4 was completely controlled by a Beaglebone Black. Being able to link microcontrollers together can allow for the distribution of the acquisition or processing tasks, but it can also be used to circumvent some of the weaknesses of particular microcontrollers. For example, by linking a Beaglebone Black with a Raspberry Pi a device is created which is capable of rapid analog data acquisition and the ability to transfer the results of the signal processing over a stable wifi connection. The wifi connection can prove very useful because it provides the opportunity to interrogate and re-configure plastic cased deployable system without having to open any water-proof casings.

5. PITFALLS

As has already been mentioned in the previous sections, there are certainly some problems associated with working with these low cost devices. Many of the features in these microcontrollers are not well supported by the manufacturers. The Beaglebone Black being a prime example - the PRUs which make the device so powerful and useful are not supported at all by the manufacturer. The ADC which has the capability of sampling at 200 kSPS is throttled back to a measly 8 kSPS by the manufacturer. Reliability can certainly be another problem. Even after extensive testing, we were unable to get reliably wifi on the Beaglebone Black. To a certain extent, these devices are put on the market, and the development and testing is carried out by the users. This means that it is necessary to almost constantly monitor the online community support network for advances and contributions from the diverse online user-base.

One final issue is the fast rate at which these microcontroller devices are being developed. It is very likely that by the time a device is ready for deployment in an at-sea measurement system it will have been superseded.

6. CONCLUSIONS AND FURTHER RESEARCH

In this paper we have shown that the current crop of single-board microcontrollers are potentially suitable for use in a variety of data acquisition and signal processing tasks. Their small footprint and low power consumption can aid in the production of portable and light weight at-sea measurement systems. Their low cost is a distinct advantage compared to the main commercial alternatives. Each of the microcontrollers that we reviewed have their strengths and their weaknesses. The ease with which the microcontrollers can be linked together allows for even greater configurability in the measurement system. The Arduino is possibly out-dated but can still be useful for controlling a number of low sample rate sensors. The Beaglebone Black can acquire analog data at a very respectable rate of 100 kSPS, however utilising the ADC at this speed is currently not straight forward. The Raspberry Pi is useful for providing stable communication, whilst both the BBB and the Pi can perform useful signal processing. These devices have proved useful, but are certainly not replacements for high precision data acquisition modules such as the Brüel and Kjær Type 3050-B-060.

This has been a preliminary investigation of single-board microcontrollers as data acquisition, processing and storage devices for use in deployable at-sea measurement systems, and there is much more that we would like to pursue. Some natural progressions would be to trial these units with a variety of hydrophones, before testing their duration/reliability etcetera in some at-sea trials. It would also be interesting to use the PRUs on the Beaglebone Black to communicate with some low cost, high precision ADC chips.

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