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Breaking Down Development Cost Barriers for Geothermal Reservoir Monitoring Systems 'Anyone' Can Program

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ABSTRACT

The paragraphs should not have line breaks between them – the Normal style This paper examines the use of Arduino systems for developing geothermal well monitoring systems and logging tools. The Arduino is a low cost, public domain micro processing system commonly used for teaching machine programming at the high school level. These systems enjoy open domain support and many levels of self-help books. The Arduino enjoys worldwide acceptance for teaching high school students how to build and program robotic machines. The Arduino system is so popular, Ebay lists 2,244 "Arduino Kits" with kits for robotics, 3D printers, sensors and other. This paper examines using the Arduino system for scientific measurement purposes. Three application examples are given: 275C well monitoring tool interface, a simple, very low cost temperature probe and an orientation tool. This paper highlights two new Arduino Shield for scientific measurements: a 22Bit ADC and a 12Bit DAC low noise programmable power supply for powering sensors.

1. INTRODUCTION

The author has been working in geothermal for approximately 25 years as an electric hardware engineer designing logging and drilling tools. The geothermal market is very small. The most popular logging tool is the well production logger (Pres, Temp and Spinner). The market for the production logger is estimated 20 at tools a year worldwide by the author. In the world of electronics, a build of 20 is equal to 0. In fact, the oil industry with builds something in the order of 200 and this is also consider near 0 by the electronics industry. As such, even the much larger oil industry is an electronic niche industry. The best means for reducing costs within a niche market is to adapt technology from much larger markets. Geothermal needs to look beyond the oil industry for cost saving technology.

Now that the obvious is cleared away, time to talk about well monitoring. The Perma Works geothermal well monitoring tool is based around the same electronics being developed for commercial aircraft engines. These electronics have a 5 year, 225°C operating specification. The future aircraft engine market is approximately 500,000 per year[1]. However, to support the downhole tool, custom designed surface electronics are developed to provide tool power, tool communication, data storage and downloading a laptop PC.

The cost of the surface electronics and developing software is significant. I estimate the software development for the surface electronics was well over $100K. Given the small market and the cost of maintaining software companies can charge $20K just for surface hardware and software.

As an engineer hardware designer, I got tired of having to go to the programmers to make changes in the surface software to run a new test or new tool upgrade. So, I designed a simply manual interface with push buttons, LED for feedback and a voltage meter for manual reading of tool data. This works in the lab.

Enter the Arduino system. The Arduino system is based on 8bit microcontrollers from Microchip Technology, costing around $2 each. The Arduino people created a simple programming environment and provide a blog for user to share their work. They also released the Arduino board design as public domain. To learn more go to: https://www.arduino.cc/

The Arduino enjoys worldwide acceptance for teaching high school students how to build and program robotic machines. At the time of this writing, the Arduino system is so popular, Ebay lists 2,244 "Arduino Kits" for robotics, 3D printers, sensors, etc. Amazon.com lists more than 20 help books on working with the Arduino system. Many books are targeting high school age students while other are more technical.

Playing with the Arduino Uno (basic system), I realized programming a real world interface is simple. For example, reading one of the 6 analog-to-digital converters (these are 10bit, 0 to 5V) required only one programming statement.

```
int data1 = analogRead(0);
```

Here data1 is a 16 bit integer inside the program: 'int data1'. The program sets the variable of data1 equal to the 10bit binary reading from the Arduino analog input 0: 'data1 = analogRead(0)'. The ';' simply ends the statement. The Arduino Uno has 6 analog inputs 0-5.

To use a digital output as a switch to control some function is also easy. To turn on a digital pin to 'high' (~5V) and 'low' (~0V) with a delay of 20mS is illustrated below.

```
  pinMode(2, OUTPUT);

 …

  digitalWrite(2,HIGH);

  delay(20);

 digitalWrite(2,LOW);
```

Here the pinMode statement is used in a part of the Arduino program which is run only once during the microcontrollers bootup. This tells the microcontroller that pin 2 is an output pin otherwise most pins are disabled at bootup. We could have also defined this pin as an input pin.

After boot, the processor starts running the program. Within the running program to set pin 2 to high requires the 'digitalWrite(2,HIGH)' statement. The same statement is used to set pin 2 to a low value. The 'delay(20)' statement tells the microcontroller to wait 20mS. We could ask it to wait 200mS or 20000mS, if desired.

This created a simple idea, why not use the Arduino to control the manual surface electronics used to run the downhole geothermal well monitoring tool? So, the photo shows such a system working with a high temperature geothermal well monitoring tool.

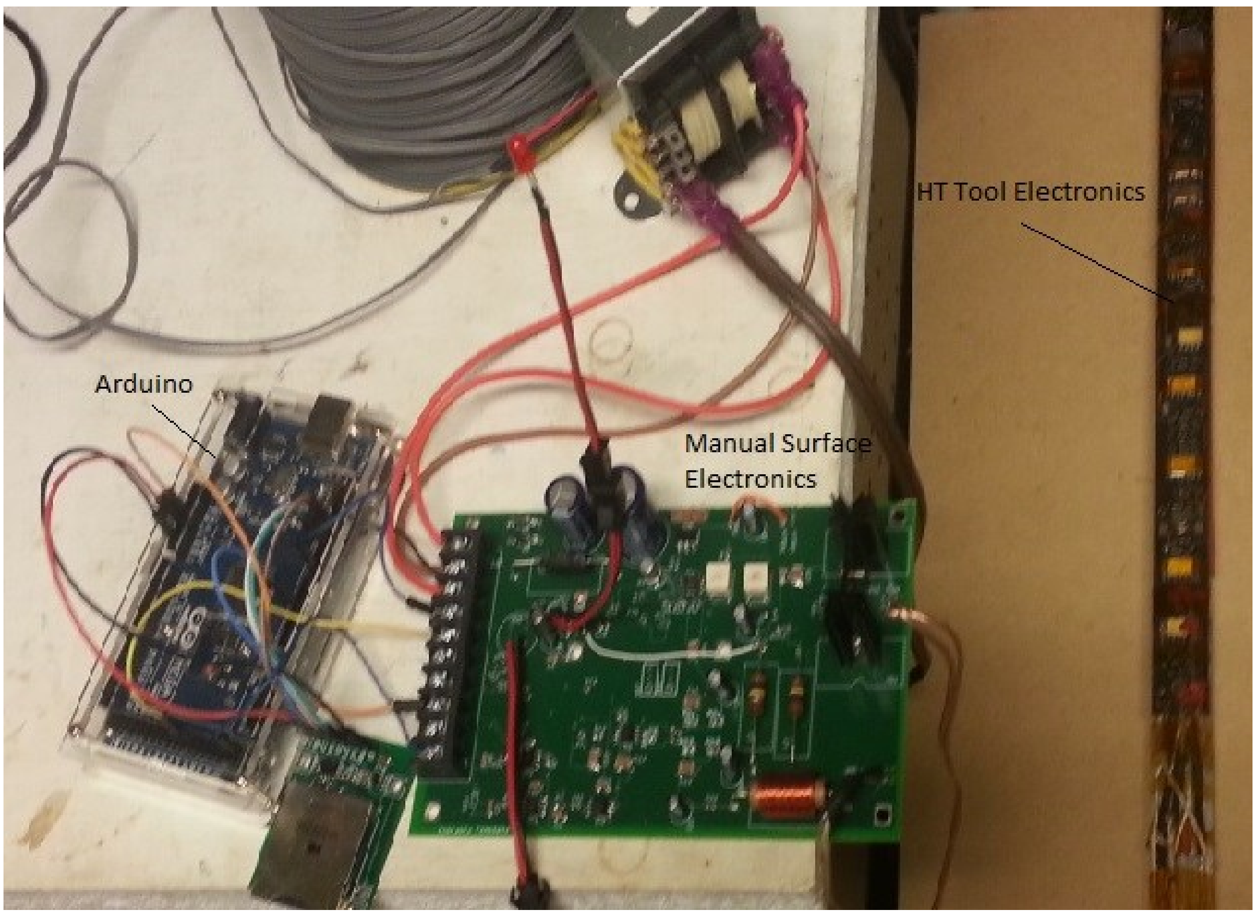


Figure 1. First use of an Arduino system to operate the surface electronics for monitoring a geothermal well monitoring tool.

2. USING THE ARDUINO FOR SCIENTIFIC MEASUREMENTS

The Arduino is a microcontroller and not a microprocessor which makes it great for interfacing to the real world. However, it's not the best choice for making scientific measurements. For controlling a robot or 3D printer, a 10bit Analog-to-Digital converter (ADC) is more than good enough but falls short for most scientific applications.

In the Arduino world people build 'shields' to add functions to the Arduino. A shield is simply a small circuit designed to work with the Arduino. The author has created two new shields to enable the Arduino system to make scientific measurements needed by the surface electronics used to monitor and record geothermal well data. These shields are a 22Bit ADC and a 12Bit DAC (Digital-to-Analog Converter). [*Note: perhaps 99% of Arduino shields are simply very low cost electronic toys – cheep 2 layer circuit boards and low cost passive components as 1-5% resistors with 100-200ppm/C drift. The two new shields demonstrated in this report are actually built on 4 layer circuit board with complete uninterrupted ground planes and use high quality 0.1% resistors with 25ppm/C drift rates as needed for solid performance*.]

The 12Bit DAC is used to create a low noise, programmable power supply. It can supply the well monitoring tool power down a cable. It can also be used to power surface well head sensors as temperature, pressure, flow or seismic. This is a very versatile shield for many scientific projects. The new ADC at 22Bits greatly increases the resolution of the Arduino for making very sensitive measurements. The ADC also has a built in filter to reduce local 60Hz or 50Hz noise.

Both of these new shields come with example programs for use with the Arduino system. Using one of these example programs, the DAC is used to create small changes in voltage which is then measured by the 22Bit DAC shield and compared to the internal 10Bit ADC of the Arduino. The results of such a test are shown below.

In the above data plot, there are three sets of reading from a precision lab voltage meter, the 22Bit ADC shield and the 10Bit internal Arduino ADC. The DAC is used to create the test voltage has a 0 to 10V output with 12bits of resolution. For this set of measurements, the DAC output was divide in half as the ADC converters are only 0 to 5V inputs. The Arduino was programmed to increase the 12Bit DAC to change the output voltage in 1 bit increments or approximately 1.2207mV per DAC step value.

The internal 10Bit ADC only has ¼ the resolution of the 12Bit DAC. So the 10Bit ADC is only changing values every four increments

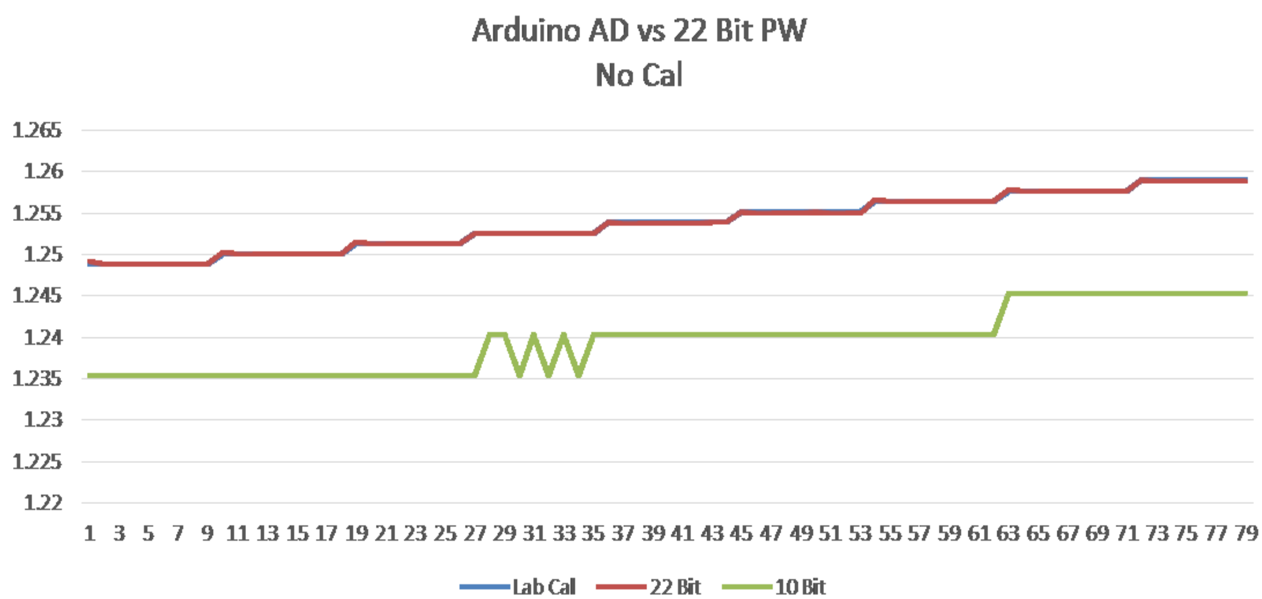


Figure 2 Actual voltage measurements taken both by the Arduino internal ADC, the external 22Bit shield and a 5.5digit calibrated voltage meter. The supplied test voltage is from the 12Bit DAC shield.

of the 12Bit DAC. The lab cal and 22Bit shield readings are too close to see a difference at this plotted resolution.

In short, the internal 10Bit ADC of the Arduino requires calibration but I don't chatter in bits which is great. The system noise floor is below the 10Bit or 4.88mV resolution. This may not be good enough resolution for most scientific applications however for measurement of room temperature or system operating voltages which can have secondary effects on primary scientific measurements, this resolution is quite reasonable and low noise.

The 22Bit ADC shield was also run without any calibration factors. Its performance here was approximately +/-20uV off the laboratory measured values or about 0.0016% error. Not only is the Perma Work shield using a 22Bit ADC, it's also using a higher precision voltage reference than the Arduino microcontroller. As already mentioned, the microcontroller used in the Arduino cost about $2 each which is a great deal for all of what it can do with processing power and 6 built in 10Bit ADC and a voltage reference. The Perma Works shield voltage reference has only one function, provide a precision voltage to the 22Bit ADC to compare against the unknown incoming voltage to be measured. The Perma Works shield voltage reference costs ~$4 each by itself. When it comes to making electronic scientific measurements, it's always worth investing in precision.

Now that we have two Arduino Shields designed for making scientific measurements, let's look at some examples. First is the 275°C geothermal well monitoring tool.

3. HIGH TEMPERATURE GEOTHERMAL WELL MONITORING TOOL

Below is a lab calibration test looking at the noise floor of the geothermal well monitoring tool operating at 250°C and fixed input pressure sensor reading of 1635 psi.

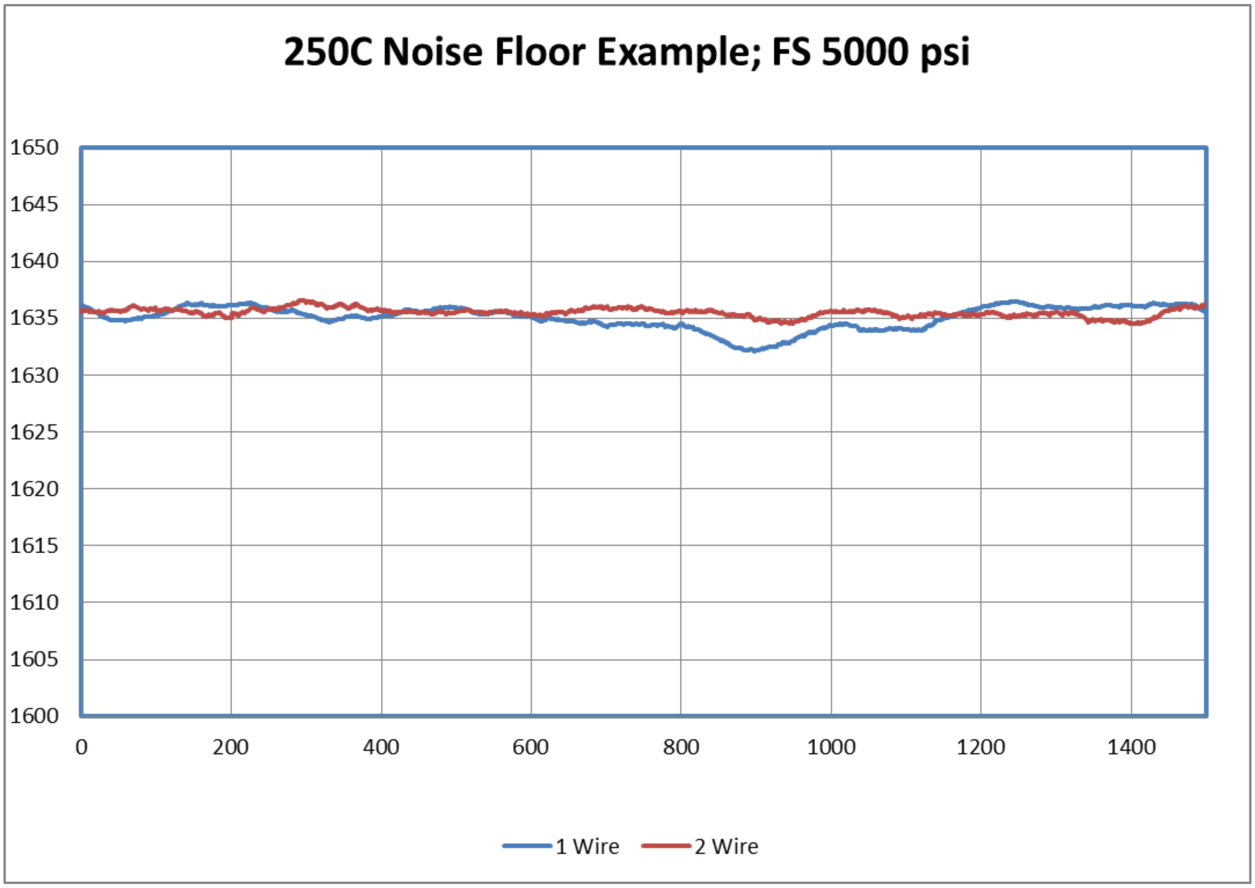


Figure 3 The electronic noise floor of a constant pressure transducers output at 1635 psi while the tool electronics are held at 250°C. The 1 wire trace places the pressure sensor output in to the tools supply current while the 2 wire allows the pressure sensor the advantage of a long signal wire.

Here we are looking at the surface readout of an analog signal tied to well pressure. The well pressure measurement was used because the pressure transducers has a very small signal. The high temperature transducer here has only 4uV/psi output. The tool amplifies the signal 200X using high temperature Perma Works amplifier circuits. There is a lot of opportunity for noise in the system. In the above plot, the blue trace (1 wire) is pressure measured as a function of tool current. This allow the tool to operate using standard logging cable found on 90% of all logging trucks. As the tool's power and tool pressure signal are on the same wire, there is an increase in the noise level as seen by our 22Bit ADC. If a second wire is available for the pressure signal only, the noise floor is reduced. This is because the 22Bit ADC has a high input impedance allowing the tool to drive very long logging cable.

4. VERY LOW COST TEMPERATURE PROBE

The AD590 is a very small, one wire electronic temperature sensor. The temperature reading is 1uA/K with a range of -55C to 150°C and operating voltage between 4V and 30V. This is an excellent low cost choice for building a simple temperature logging probe for low temperature geothermal wells. However, the 1uA/K is very sensitive to small leakage currents caused by poor cable head connections between the tool and logging cable while in conductive geothermal fluids.

A solution is to use the 12Bit DAC to power the cable at the surface and use the 22Bit ADC to measure the supply current. Armed with these two functions, the Arduino can detect error and in some cases correct the temperature measurement.

Simply provide 10V to the sensor from the surface while logging. The sensors temperature reading is 1uA/K (for example 25°C = 298K or as sensor current 298uA, for the max temperature of 150°C the current is 420uA). So, let's say we have a leakage current at the cable head of 10uA or as 10V/1MOhm = 10uA. This would be a +10°C error in our measurement which is unacceptable.

Using the programmable 12Bit DAC power supply, this error can be detected. The cable head leakage current is directly proportional to the sensor voltage while the sensor voltage is not effected, (in truth there is some small error, << 1C).

To detect an unwanted leakage current, simply hold the temperature probe at a static location in the well and change the cable voltage by some programmed DV as from 10V to 9V or DV = -1V. If no change in the temperature reading is detected, the tool and cable head are working well. If a change in current (DI) is detected, the error can be reduced knowing the DV, DI and the logging cables resistance. To estimate the value of the error supply current, we calculate the resistance of the short, Rleak.

Rleak = (DV - Rcable*DI)/DI; DV=change in Voltage; DI=change in current; Rcable=cable resistance

A lab test using an AD590 tool was conducted with the following results. The ambient AD590 measured temp of 30.348°C when a 1M Ohm resistor simulating a leakage current at the cable head was added. This shifted the reading to 41.057°C. However, the user would not know that error existed unless the Arduino was programmed to provide a DV. So, the surface voltage to the cable was changed from 10V to 9V and the temperature reading dropped to 39.953°C. That's about a +1°C difference, which is too much. Using programmed DV and measured DI and the known cable resistance of 1Kohm the Arduino calculated a new well temperature of 30.345°C. That's really good.

Also tried 100K ohm for 10 times the leakage current of the 1M ohm value. The ambient is now reading 30.649°C as the shop is heating in the summer sun. The 100K ohm leakage path increase the well temperature reading to 126.398°C. Dropping the voltage 1 volt reduced the temperature to 116.459°C, approximately a 10°C change. Correcting for the change in temperature with dropping voltage, the new well temperature is 30.928°C. That's good but we should consider removing the tool from the well and fixing the cable head.

5. ORIENTATION TOOL

There is a need to know the orientation of rock removed while core drilling a reservoir formation. For example, the reservoir engineer would like to directionally orientate fractures captured in the core as to inclination and azimuth.

Within 1 day and using two Arduino shields, one for inclination and the other an electronic compass, the system below was built using a non-magnetic aluminum rod and green electrical tape.

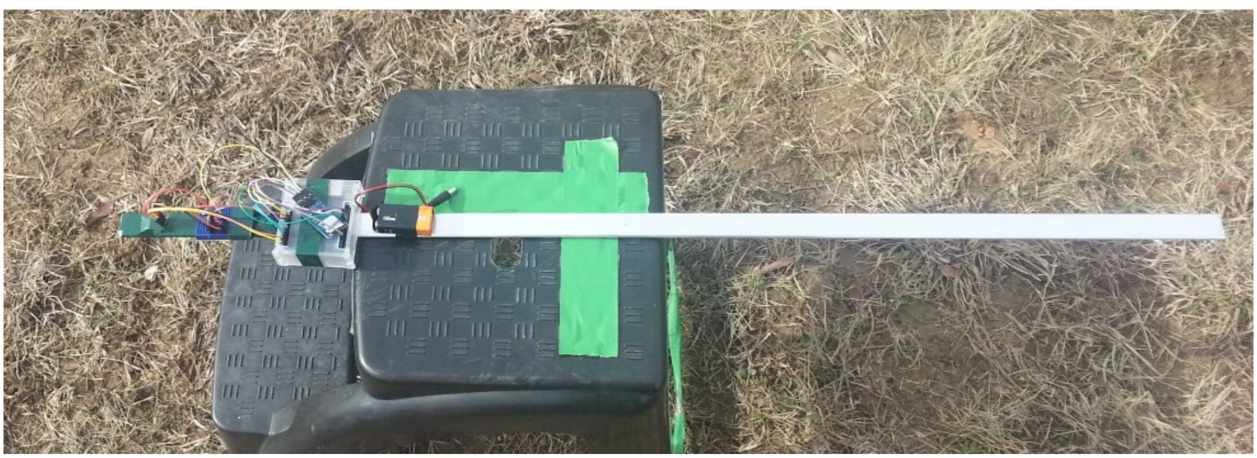
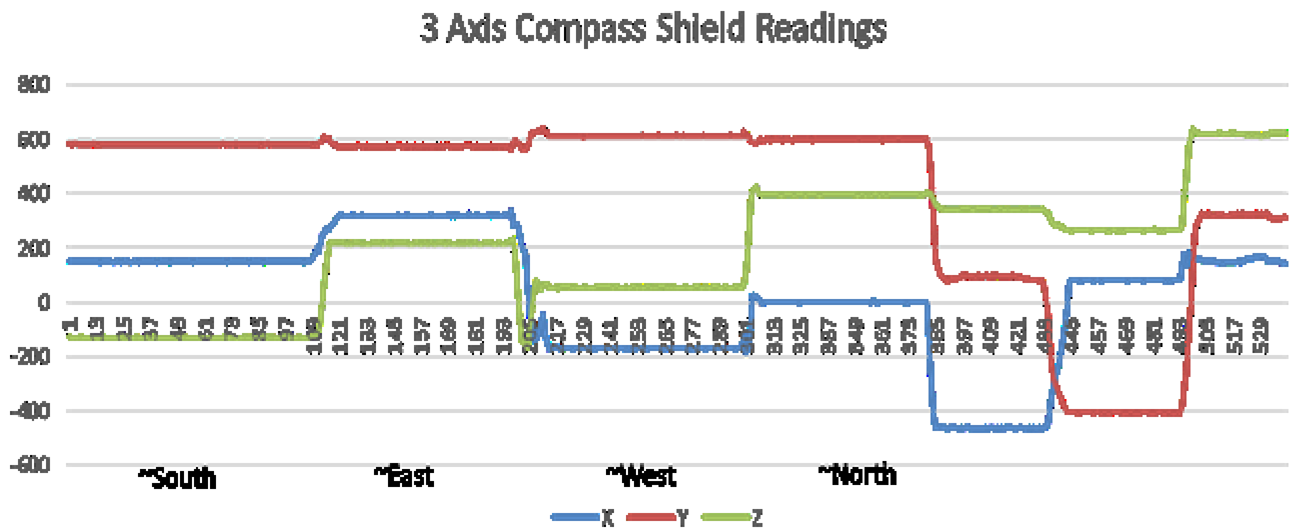


Figure 4 A simple exercise in programming an Arduino to measure orientation using three shields and a 9V battery.

The Arduino based orientation system (see figure 4) was placed in an open field away from magnetic metal structures. The system was powered by a 9V battery and the following measurements (figure 5) were made by manually moving the aluminum rod as described.



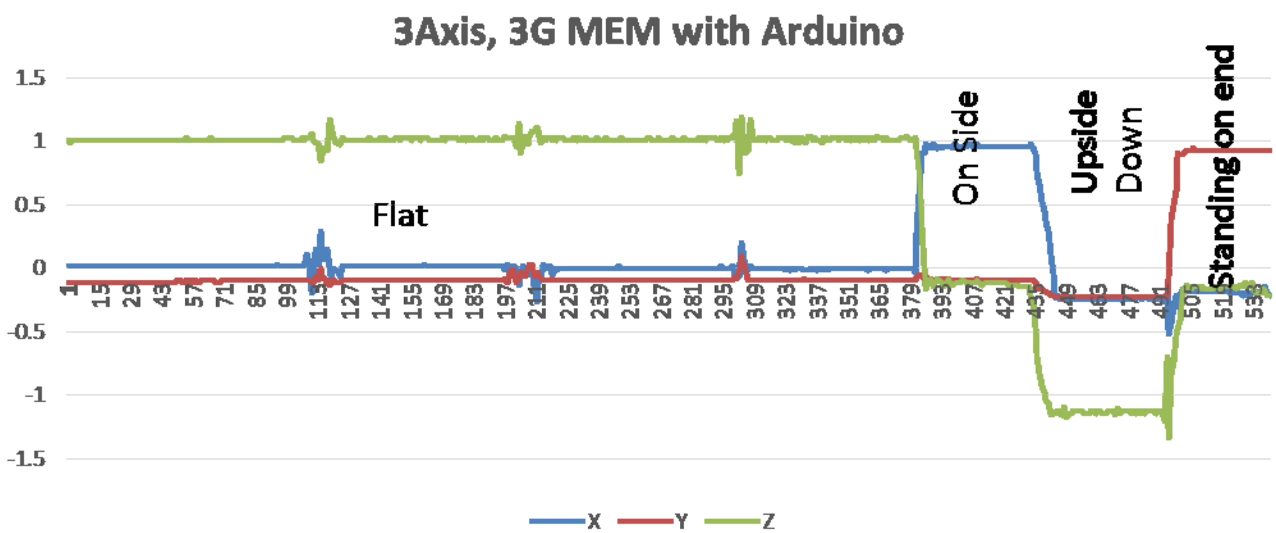


Figure 5 Orientation Arduino measurement system shown in figure 4 was manually moved in order to functionally test the system. The upper plot are the measurements from the 3 axis electronic compass. The lower plot are the measurements from the 3 axis, 3G inclination sensor. The system appears to be working.

The internal 10Bit ADC channels were used to make these measurements. Given the relative accuracy of such measurements downhole, this seems reasonable. The internal ADC is much faster than the higher resolution 22Bit ADC for capturing dynamic signals as inclination.

How, having functional tested this system, calibration could be performed. Once the designer is happy with the results, it's simply a matter of taking the public domain Arduino circuits and producing a set of tool electronics to fit within the pressure housing of a logging tool.

6. Future Scientific Shields

The 12Bit DAC and 22Bit ADC shields have been built and tested. These are key components for making scientific measurements using the Arduino system. However, other shield are being considered as:

1. Natural Gamma Counter
2. Large Solid-Sate Memory (to replace SD cards)

3. Logging Tool Communication both Surface and Inside the Tool
4. Spinner Counter for Flow Measurement

All Perma Works shields will be 1inch wide or less for going inside a 1.25inch pressure housing. This will allow not just surface electronic development but also future downhole tools.

CONCLUSION

The Arduino system is very low cost, open to public domain and is extremely popular being used to teach high school students basic machine programming as in robotics. This system is easy to program and is well supported with books written for beginners and advanced programmers. The author has developed two key circuits to make the Arduino system useful for scientific measurements providing examples of well monitoring and well logging tools.

The two circuits developed are a 22Bit Analog-to-Digital Converter (ADC) shield and a low noise, 12Bit programmable power supply shield for powering sensors. Together, these two circuits are controlled by the Arduino microcontroller to create a basic scientific measurement system. These two shields demonstrated very low noise margins in bench testing. The 22Bit ADC was comparable to an expensive lab grade voltage meter. By working with a public domain system as Arduino, the development costs and time to construct well monitoring systems or future logging tools can be reduced. Also, the future availability of new programmers needed to support the geothermal industry might be attending robotic classes in to today’s high schools.

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