Waaca

A scale project

The gospel of wheat and stone

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Introduction

This project was the first real venture into making a working electrical product for our four man team. We had accumulated some theoretical knowledge about the subject and the circuits needed for the project during the course lectures, so this was our opportunity to put that knowhow to the test and make an actual working product. None of us had any significant previous experience in designing and building circuits, so this was a first for all of us. We didn't really distribute the workload (except during the virtual instrumentation design phase) because we wanted everyone to be a part of everything we did regarding the physical product, so everyone was involved in every part of the process.

In this project, our task was to create our own "bathroom scale" using load sensors from a stripped-down normal off-the-shelf consumer scale. The idea was to make a scale that would be sufficiently accurate for measuring human body weight, so the optimal measuring range would be about 0-100 kg with the accuracy being around ±0.1 kg, if possible.

The scale's skeleton only had the strain gauges in it. All the other electronics had been taken out, and we had to fashion the necessary hardware to get the information from the sensors to a computer screen. In practice, this meant that we needed to amplify the voltage that came out of the sensors and send it into a PC via an A/D converter and make the results readable. We needed the scale body with the strain gauges, two amplifiers, a breadboard, gain resistors for the amplifiers, capacitors for the low-pass filter, a data acquisition device / A/D-converter and a ton of wires to connect it all.

We didn't set a strict schedule for ourselves, because the backbone of the amplifier system was built during doing the labs for the course. By the beginning of the time dedicated for building the project, we already had quite a clear idea of what we were going to build in order to have decent results. Most of the time we dedicated to the project was used to take test measurements, and looking for ways to get consistent results.

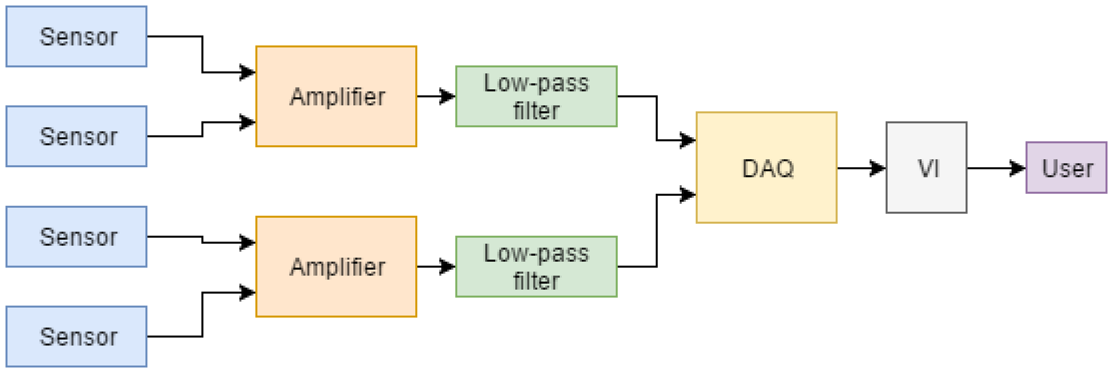

Figure 1. Basic block diagram of the hardware.

Technical specifications

Wheatstone bridge

As a base component for the project we received a scale “skeleton” with a glass plate onto which the measured load is applied and four pressure sensors, one in each corner of the plate (figure 2). Each of the sensors consists of two resistors, connected in series, that respond to the force applied on the plate: the first one grows in resistance as the pressure increases, while the other one decreases.

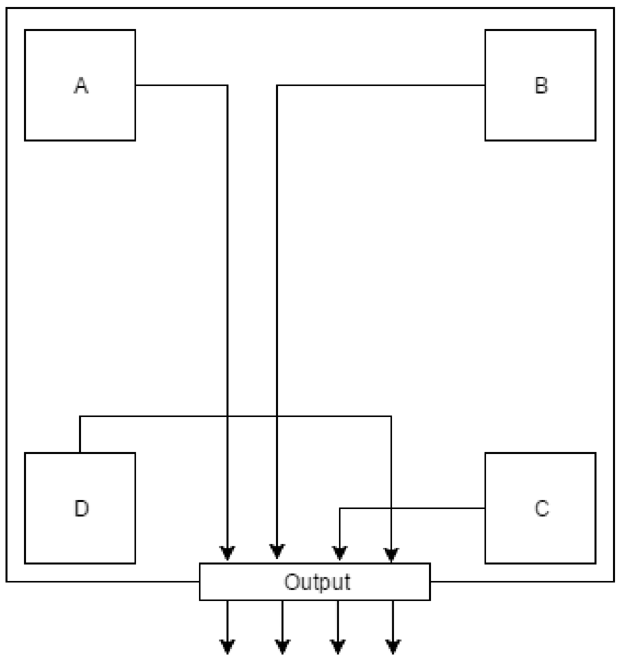

Figure 2. Locations of the sensors

Each resistor pair acts as a voltage divider, that outputs a certain fraction of the input voltage that is applied to the circuit. As the load on the scale changes, each individual corner outputs either a growing or decreasing fraction of the input voltage, depending on which of the two resistors is wired to the positive voltage terminal and which one is connected to the ground.

By connecting two corners of the scale to a simple circuit called a Wheatstone bridge (figure 3), we were able to measure the voltage differential between the two corners with a DMM. This voltage differential would, after amplification and A/D conversion, produce a somewhat accurate indication of the amount of mass applied on the scale.

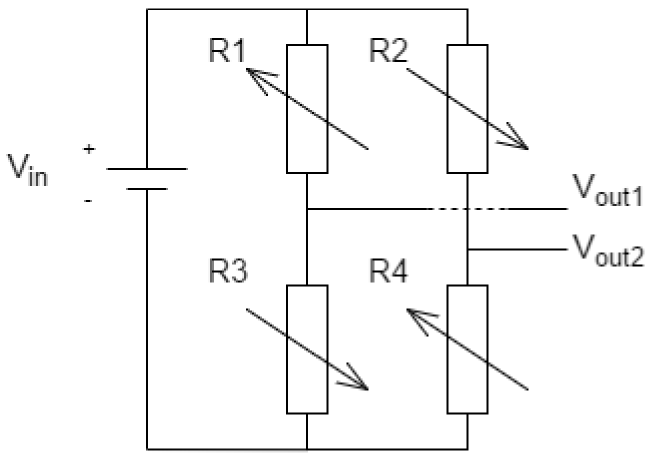

Figure 3. Principle of Wheatstone bridge

After some initial testing, the measured differential between corners A & C, when resting with no weight on the scale, settled around -1 mV, which was a slight disappointment to us, as in the ideal scenario we would have had a slightly positive voltage going to our amplifier input at all times. Without applying a correction, this would have caused the voltage to be amplified in the “wrong direction” and our circuit would have produced large negative voltages.

Luckily, this problem was easily avoided by applying a so called reference voltage of 2.5V to one of the amplifier pins. This simply means that the reference voltage is added by the op-amp to the output signal after amplification. This way, the amplified voltage will remain positive even when no weight is applied. Without the correction, the output of the empty scale would have been somewhere around -300 to -400 mV. Ideally, we would have chosen a smaller reference voltage, preferably something around 1V, as it would have eaten up a smaller proportion of our effective measuring range and still been sufficient for correcting the error. However, we had to settle for the only option available in the DAQ interface.

After hooking up our single Wheatstone bridge setup utilizing only two of the scale corners to our VI software, we noticed that the signal captured by our DAQ device was quite erratic and even after evening out some of the peaks by taking a running average of the sampled values, the measurement error, when converted to kilograms, was unacceptable. The error was approximately +10 kg or -10 kg depending on which corner pair was used.

Because of this, we decided - against our original plan - to construct another identical Wheatstone bridge for the other corner pair and to connect the outputs of both amplifier circuits to different input ports in the DAQ, thus utilizing all four corners of the scale. By taking an average of these two input signals, we were able to improve the accuracy of the scale remarkably.

Purpose of signal amplification

Amplifying the input signal for our scale application is crucial for producing readable results. Without an amp circuit, the changes in voltage when load is applied would be very small: only in the scale of millivolts. Especially with smaller weights this would be far less than our equipment could reliably detect. Also, the actual signal would be practically impossible to distinguish from the noise.

Choosing the gain factor

Considering that our effective voltage range for measurements was supposed to be 2.5V - 5V, we needed to calculate the gain factor for our op-amp so that the maximum weight load allowed by our design would map to a voltage not higher than 5V (as we used a 5V power supply, the signal would of course clip at that point).

Through some empirical testing, we found out that with a gain of 400 we could achieve results ranging from approximately 2.3V at 0 kg to 4.3V at 100 kg. The minimum and maximum values varied a bit between the two amp circuits.

This satisfied our requirements so we ended up choosing our gain resistors by using the following formula from the INA122 documentation:

$G = 5 + 200\ k\Omega / R_G$
from where we solved for R_G:
$R_G = 200\ k\Omega / G - 5$

When we insert our values to the equation we get:

$R_G = 200\ k\Omega / 400 - 5 = 0.5063\ k\Omega$

As we didn't find resistors that correspond exactly to our calculated value, we ended up using the following:

Corner AC: 0,4984 kΩ
Corner BD: 0,4981 kΩ

When inserted to the formula above, these resistors give us the following exact gain factors:

$G_{AC} = 5 + 200\ k\Omega / 0{,}4984\ k\Omega = 406{,}28$
$G_{BD} = 5 + 200\ k\Omega / 0{,}4981\ k\Omega = 406{,}53$

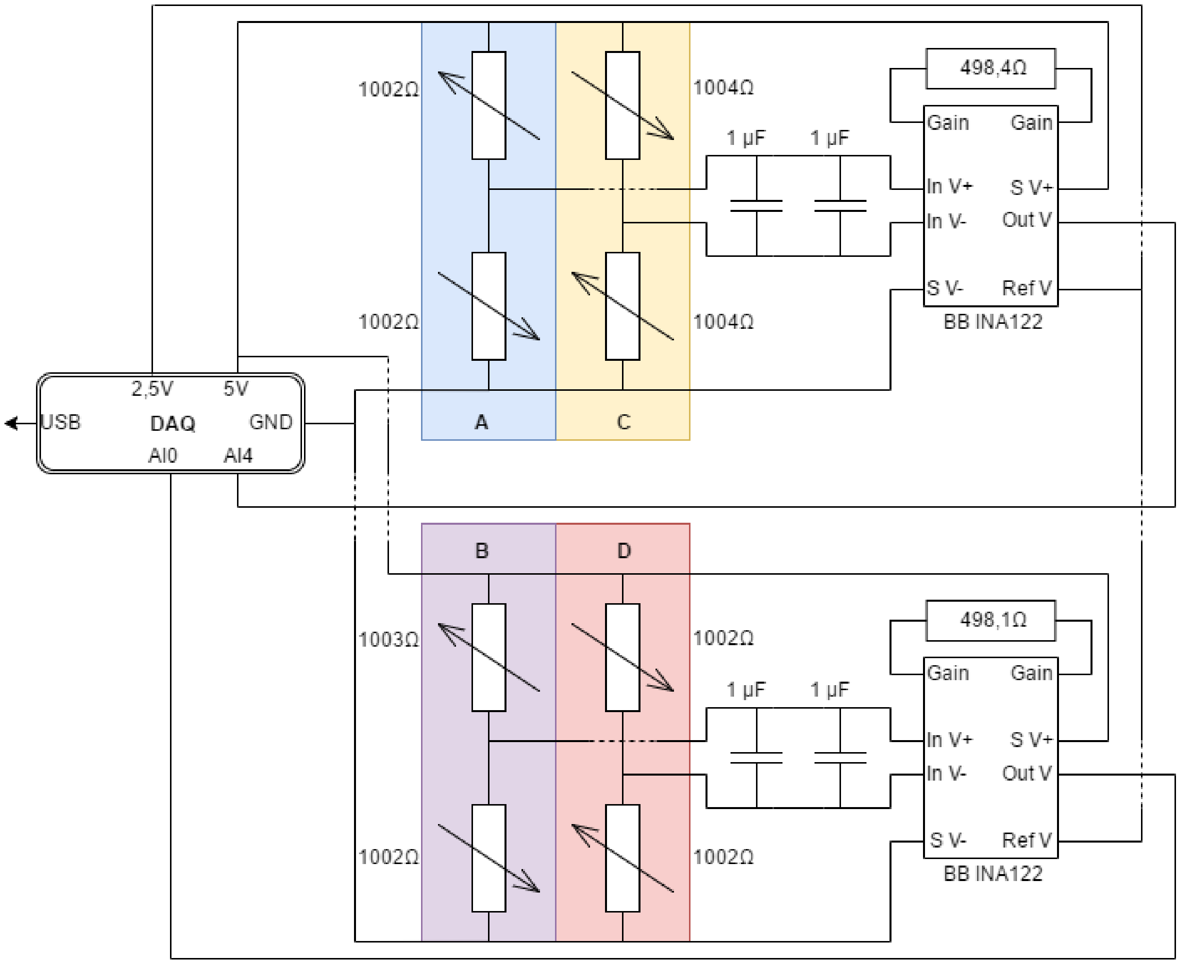

Figure 4. Circuit diagram of the final assembly

VI

To make the measurements readable, virtual instrumentation was needed. We designed a relatively simple VI that was capable of showing the user the measured weight and a graph of the recent measurement history as well as saving snapshots of the results to a file and taring the scale.

As the two voltage readings come in to the VI from the USB-6009, 1000 samples are taken every second, and of those 1000 samples a mean value is taken (separately for both amplifiers). The voltage mean values are then converted to kilograms using a multiplier, calculated by comparing the measured voltages and the respective test weights they were measured with. Some tweaking is also done to correct for the slightly non-linear voltage curve. This means that a constant value, which is determined by a manually calculated correction value at different intervals in the 0-100kg range, is subtracted to make the result a bit more accurate at different levels.

Of the two weight readings, an average is taken. Also, if the user has chosen to tare the scale, this is where the correction is applied. The result that is shown to the user is a running average of the last three readings, or in other words, the average of the measurements from the last three seconds. This value is shown as a numeric indicator, a waveform graph and speedometer-style gauge. It can also be stored into a file along with the date and time using the snapshot function.

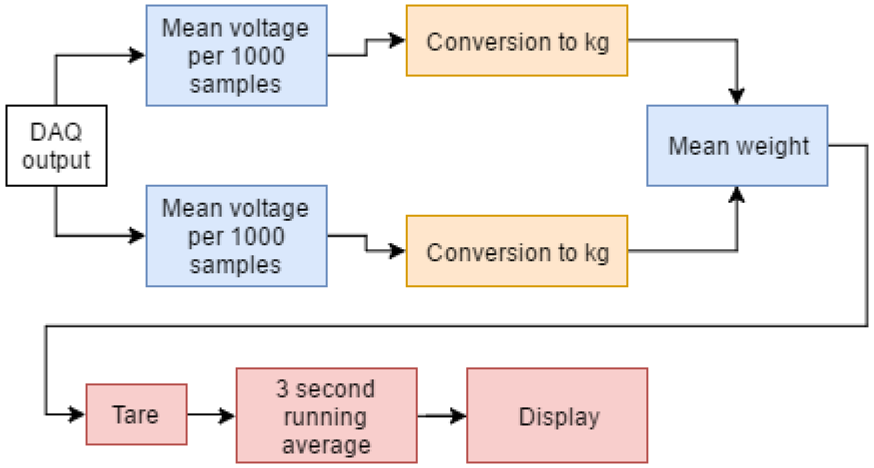

Figure 5. Logical map of the VI

Testing

The project required extensive amounts of testing to get accurate results. First we tried using only one Wheatstone bridge thus only making use of 2 corners of the scale, but we soon noticed that the results were not reliable enough. Making use of two Wheatstone bridges gave us much more linear results, easing the later phases of the project.

We tested different gain resistors to try to maximize the voltage range for our scale. We ended up using a 498,4 Ω resistor for the AC bridge and a 498,1 Ω resistor for the BD bridge. We selected resistors that were as close to each other in resistance as possible to get the same amplification for both bridges. With these gain resistors the voltage range was around 2,3 V- 4,3 V Two capacitors were also to be used as a low-pass filter, but the change in results was minimal.

We used the weights from the school gym as our reference weights, but there were some big disparities between the weights. This made the measuring part a bit difficult since we didn't know if a 20 kg weight was exactly 20 kg or not. The scale was calibrated using these weights from 0 to 100 kg and we documented the results in an excel file attached below.

Results

The final results of our project are in line of our initial predictions and the goals we set out to accomplish. The two most important aspects of a scale, accuracy and reliability, work almost better than expected with a target range of 100 kilograms. The measurements were fairly linear within our target range with slight variations especially in the low end of the range (approximately from 0 kg to 15 kg).

Our results are rounded to the closest 100 grams, since it is an appropriate accuracy for a bathroom scale. Our measured results reflect the weight of our calibration weights very accurately, any errors being in the range of ±0.1 kg after applying our correction formula within the VI. The varying errors are the result of 5 separate averaged segments in the range from 0 kg to 100 kg, which were extrapolated by calculating the difference between the supposed weight and measured weight.

The reliability of the scale is imperative, since a non-reliable system would display varying results with each consecutive measurement, rendering it effectively useless. Our scale on the other hand performs excellently in this aspect. Repeated measurements with identical weight loads systematically display identical results, which is a requirement for a trustworthy scale.

The addition of the second pair of corners increased the accuracy of the system dramatically. Not only did it provide us with better measurement accuracies, but the 4-corner setup decreased the measurement variance with an uncentered or changing weight distribution. The better measurement results were especially clear in the event of measuring the weight of an actual person, as it is really hard to stand perfectly still and centered on a scale. It could also be considered unreasonable, considering the intended use of the project. The change in the displayed weight with a swaying subject was roughly in the range of ±5 kg.

The scale has two active code ranges, one for each corner pair (AC and DB). Of the total code range (2^13 = 8192), AC ranges from 3488 to 6968, while BD ranges from 3257 to 7084. The total ranges are 3480 (AC) and 3827 (BD) respectively.

The theoretical resolution of the AC corner pair is 0,00002124 Volts per gram, or 21.24 μV/g, while the resolution of BD is 0,00002336 Volts per gram, or 23,36 μV/g. The number of bits per 100 grams is 3.48, rounded down to 3 bits/gram.

End thoughts

In the end we managed to get the scale working well enough to meet the requirements we set for it. We were happy with the results we got by using all four corners of the scale.

Figuring out the theory behind the amplifier was difficult but also a valuable learning experience for all of us. The most time consuming part was measuring different weights and checking whether or not they are linear enough.

To calibrate the scale more effectively, better weights would be required as the ones used in this project varied too much in weight and we could never know their exact weight. Alternatively another scale would be required to measure them.