College of Science and Engineering
Department of Electrical and Computer Engineering

EE 3951W Final Report

14-bit ADC for PIC24

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Introduction/Background

The current Analog to Digital converter that is built in the PIC24 has at most a 10-bit accuracy. As technologies advance, applications that utilize an ADC often desire improved accuracy when it comes to converting analog signals (eg. voltage) to a digital form so it can be read and processed by a microcontroller. This means the improved ADCs need better quantization levels and resolution. More quantization levels result in a more accurate representation of the original analog signal. For example, representing a signal with 14 bits instead of 10 bits would give us a more accurate representation of the analog signal, resulting in an improved ADC accuracy. This is the exact purpose of this project; this project aims to improve the current 10-bit ADC built in the PIC24 to a 14-bit ADC.

To increase the ADC to 14-bit accuracy, there needs to be roughly 3 mV of noise. Given the full-scale range of most ADCs, the corresponding noise level is around 3 mV. This noise level is necessary to ensure that the signal is accurately captured without being overwhelmed by noise while providing the highest gain possible. For this design, 2 LM741 op amps are used to produce the noise. By sampling at a higher rate than necessary, or oversampling, we can improve the accuracy of measurements in the presence of noise. By taking more samples of the signal over a given time period, the accuracy of the measurement is improved. Before the signal is read by the ADC, it will run through a low pass filter that will remove the unwanted noise outside of the frequency range.

Oversampling and averaging can improve SNR (signal-to-noise ratio) and the effective resolution of a converted signal. The basic idea is to sample the analog signal at a frequency higher than the Nyquist frequency, which is defined as half the sampling rate required to capture all the information in the signal. Sampling at higher frequencies enables ADC to capture more information about the input signal, which leads to a higher effective number of bits (ENOB) of the measured data, which increases SNR and produces a lower noise floor in the signal band. In addition, Oversampling and averaging can also be useful in reducing the impact of noise on the ADC's output. When a signal is oversampled and averaged, any noise in the signal is spread out over a larger number of samples. This reduces the impact of noise on the final digital output, resulting in a more accurate representation of the original analog signal. Oversampling can also allow for more effective use of a low-pass filter to remove unwanted noise outside the frequency range of interest.

Once the ADC code was implemented for the PIC24 and the printed circuit board (PCB) final layout created on Altium Designer, the designed circuit board was packaged in a Bud 750-1015 enclosure, which is a black plastic box. It has a switch, a LCD display, and four inputs: 5V, -5V, Vtest, and GND. The PIC24 was first programmed with the ADC code in the software MPLAB® X IDE, after which all the inputs and the oscilloscope will be connected and the LCD display will show the 14 bits ADC output. The error value was calculated by selecting at least five random voltages within 0V to 1V, comparing the accuracy of when the switch is on (with noise) or off (without noise). The error value should not be greater than 100 microvolts.

Group/Individual Contribution

Group	Yuan	Anh	Nashat	Nick
Debug circuit	Provided circuit materials and covered all extra materials budget. Assisted design and circuit setup for testing. Helped with soldering components on PCB. Debugging PCB circuit by Oscilloscope.	Assisted circuit setup for testing and taking measurements on the oscilloscope. Worked on schematic design on Altium. Debug and solder components on PCB.	Helped with designing the circuit on LTspice and simulating it to generate the required amount of noise. Assembled the pic24 circuit and set up the ADC code for it. Worked on PCB design on Altium. Debug and solder PCB. Implemented the code necessary for the pcb to run as needed.	Simulation and design of the noise amplifying circuit, and the coupling circuit. Helped with the logic of the ADC operation, and The 10 bit to 14 bit logic. Worked on PCB design on Altium. Soldering the PCB. Design and construction of the enclosure. Troubleshooting the PCB.

Table 1: Group/Individual Contributions

Product Design Specification:

Objective:

We are required to design a 14-bit high resolution and quantization analog to digital converter (ADC) on the Microchip PIC24FJ64GA002 by 256x oversampling and averaging. To achieve this, using two op-amps (LM741) to provide a noise source by amplifying resistor thermal noise, which is oversampled into the ADC for the calculation to obtain a more accurate input analog signal value. To achieve these specifications, we selected appropriate resistors and conducted circuit connection and simulation on LTspice. Based on our LTspice simulations, we implemented the circuit design onto Altium. The circuit board was enclosed in a Bud 750-1015 enclosure, featuring one switch, an LCD display, and four inputs: 5V, -5V, Vtest, and GND. The 14-bit voltage is displayed on the LCD, and to ensure accuracy, error values will be calculated by comparing at least five random voltages within 1V with the switch on or off. The maximum allowable error value is 100 microvolts.

Design Specifications:

Sampling rate:	256x	
Resolution:	14 bit	Ensure high accuracy of measurement.
Voltage Source	-5V/5V	V_+ and V_- for LM741.
Input voltage range:	0V-1V	Required to measure a randomly selected DC

		voltage between 0 and 1 volts.
PIC 24 operating voltage	3.3V	Given by using a voltage divider.
ADC reference voltage:	1V	It should be maximum of input voltage and given by potentiometers using voltage divider.
Noise	~3mV_{rms}	For greatest amount of gain and avoiding small bandwidth to destroy the noise.
Size and weight:	The project is to be packaged in a Bud 750-1015 enclosure with 4 input signals. The whole thing should be reasonably sized (6" on a side or less).	
Inputs of Bud 750-1015	5V, -5V, V_{test} , GND	
Peripherals	Switch and LCD display	

Table 2: List of Design Specifications

Design/Solution

The design consists of a hardware and software portion. The hardware portion uses the Johnson noise of a resistor coupled to a voltage that the ADC should measure. The software portion of this design is responsible for taking in the input samples, fills it in a circular buffer, and then computes its mean over the number of bits desired. The output of this operation should result in an increased accuracy in the current 10-bit ADC in the PIC24 with 4 extra bits of precision.

The Johnson/Thermal noise of a resistor can be described by the square root of spectral density equation $V(noise) = \sqrt{4kTR\Delta f}$. The equation clearly shows that the noise changes to the root power of temperature in Kelvin, resistance in ohms, bandwidth in Hz, and the Boltzmann constant is 1.38*10^-23 J/K. The RMS voltage value of noise can be converted from $\frac{V}{\sqrt{Hz}}$ in frequency domain to V_{rms} by $\sqrt{\int_{f1}^{f2} v^2(f)df}$. The noise attached to the voltage we want to measure must be about 3mV_{rms}., which is much larger than thermal noise by resistors. In order to reach that goal an amplifier circuit must be used, which results in output noise including both thermal noise from resistors and op-amps noise.

The circuit design on LTspice is rather simple with two LM741 op-amps; it consists of a two stage inverting amplifier which amplifies the thermal noise generated by a resistor. The first stage has a gain of 25 and the second stage has a gain of 100. These gains were chosen to give the greatest amount of gain while avoiding destroying the signal by having too small of a bandwidth. To couple the noise to the signal that the ADC should read from, a coupling capacitor was connected from the amplifier output to the ADC pin, and a resistor connected the voltage we wanted to read to the ADC pin.

The PIC 24 requires a 3.3V input to function and 1V reference for the ADC. To achieve this while using only a 5V input and minimizing costs, two voltage dividers were utilized. Since the specific resistor values that produce exactly 1V were unavailable, a potentiometer was used and tuned to generate 1V. Additionally, a LD1117AS33 voltage regulator was used to generate the 3.3V supply for the PCB.

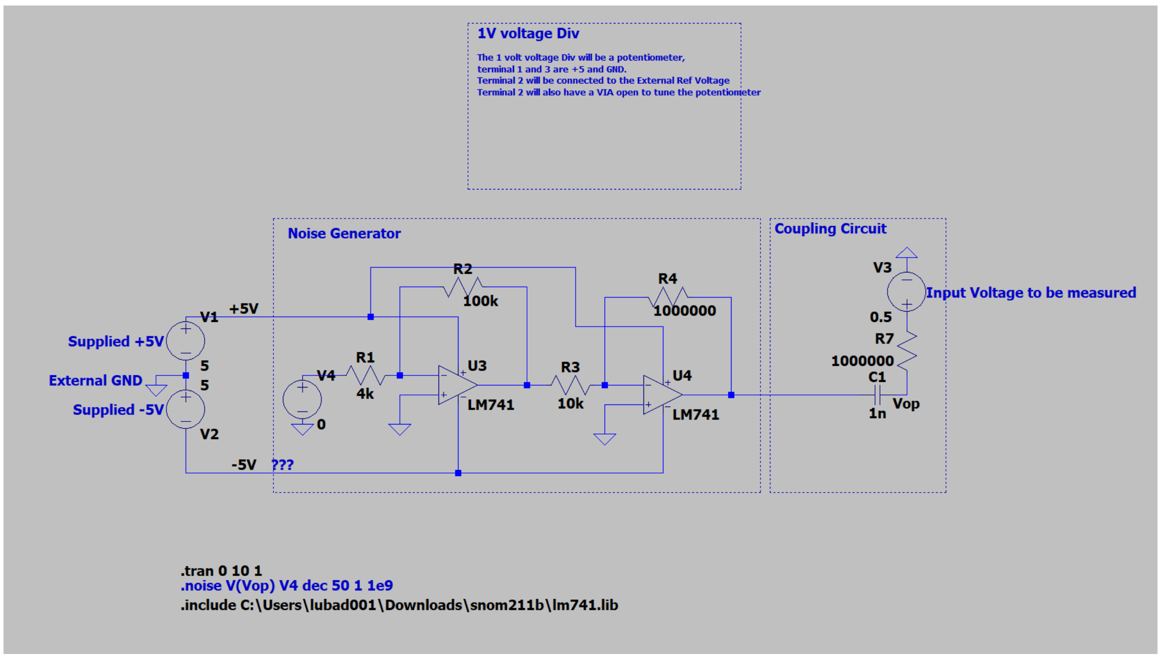

Figure 1: Noise Generating/Coupling Circuit

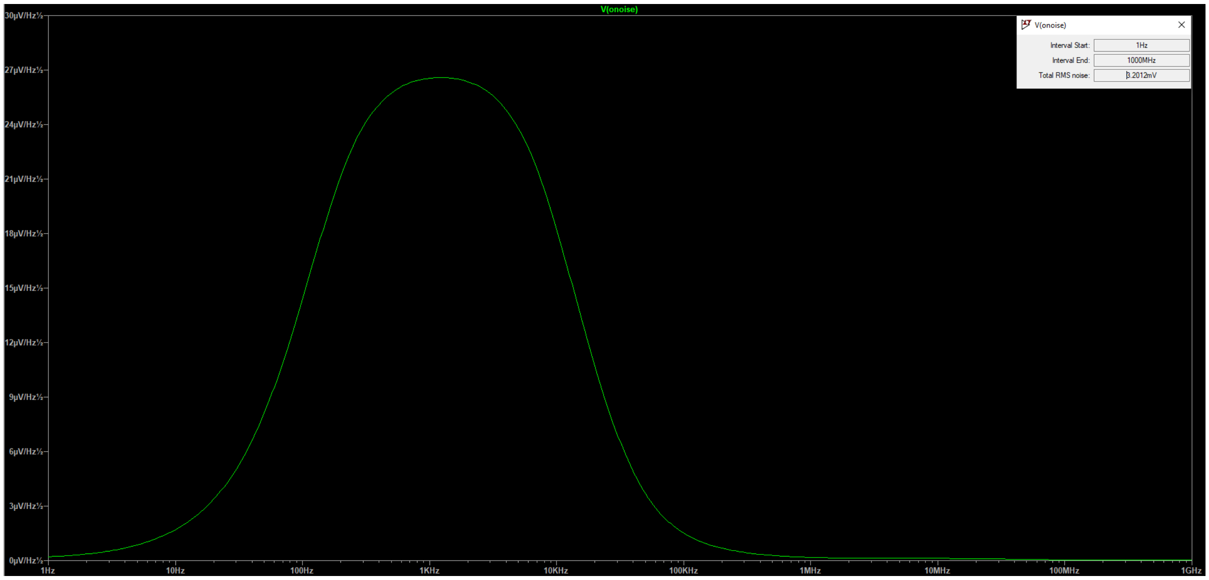

Figure 2: Noise Generated from LTspice Simulation

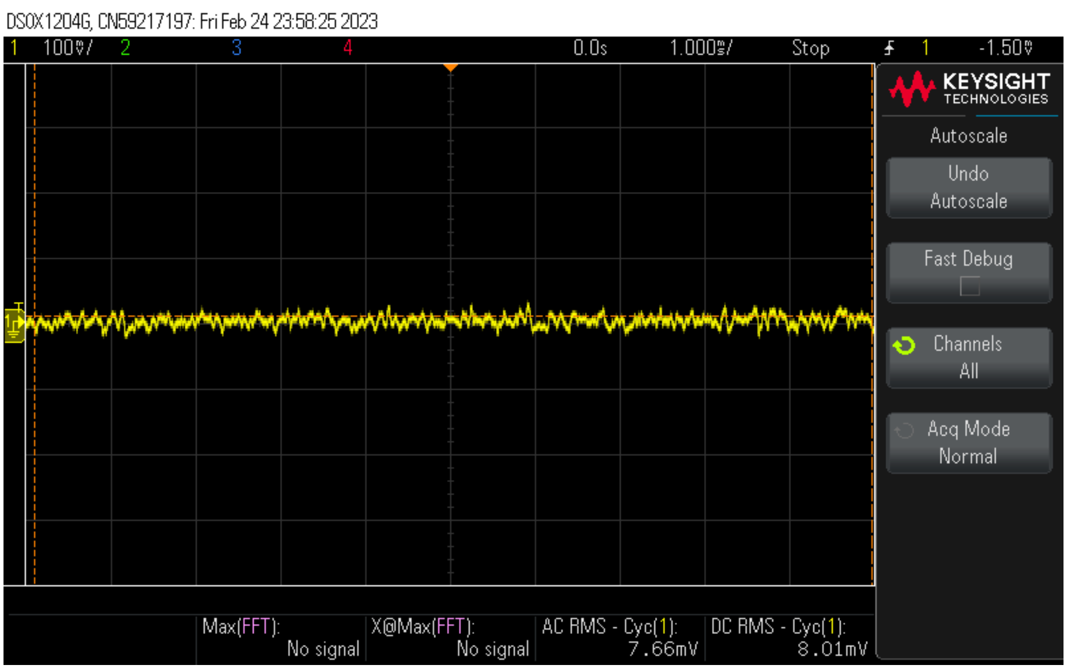

Figure 3: Noise Sampled

Through simulation, the RMS of the noise voltage was found to be 3.2012 mV, which is in close proximity to the required 3mV. Furthermore, the noise generated by the breadboard was determined to be 8.01 mV, which is a reasonable amount given the involvement of op-amps.

When it comes to programming the PIC24, configuring the ADC is a simple task. The microcontroller's datasheet was referenced to configure the right control registers and modes of the ADC to what we desire. The following is the setup that was done for configuring the ADC in the PIC24.

```
void adc_init() {
    TRISAbits.TRISA0 = 1;
    TRISB = 0;
    TRISBbits.TRISB15 = 1; // set AN9 to input
    AD1PCFGbits.PCFG9 = 0; // Analog Input Pin Configuration Control bits
    AD1CHSbits.CH0NA = 0;
    AD1CHSbits.CH0NB = 0; // negative input set to Vr-
    AD1CHSbits.CH0SA = 0b1001; // select channel to read from pin AN9
    AD1CSSLbits.CSSL9 = 1; // input scan select set to pin AN9
    AD1CON2bits.CSCNA = 1; // scan inputs
    AD1CON2bits.ALTS = 0;
    AD1CON2bits.VCFG = 0b001; // 0b001 --> voltage reference set to external Vref + pin
    AD1CON3bits.ADCS = 0b00; // A/D Conversion Clock Period Select bits. 0b01 --> 2*Tcy
    AD1CON1bits.SSRC = 0b111; // Trigger Events. 0b111 --> Auto-conversion
    AD1CON3bits.SAMC = 0b01; // Auto-Sample Time bits. 0b01 --> Tad
    AD1CON1bits.FORM = 0b00; // Data Output Format bits. 0b00 --> integer

    AD1CON1bits.ASAM = 1; // A/D Sample Auto-Start Mode bit. 1 --> Sampling begins immediately after last conversion
                          //completes; SAMP bit is automatically set

    AD1CON2bits.SMPI = 0b00; // Sample/Convert Sequences Per Interrupt Selection bits. 0b00 -->  Interrupts at the
                             //completion of conversion for each sample/convert sequence

    AD1CON1bits.ADON = 1; // A/D Operating Mode bit. 1 --> ADC on

    _AD1IF = 0; // interrupt flag
    _AD1IE = 1; // enable bit
}
```

Figure 4: Code of PIC24 for ADC

```
int getAvg() {
    int i = 0;
    unsigned long int average;
    unsigned long int sum = 0;
    for(i = 0; i < 256; i++) {
        sum += storagebuffer[i];
    }
    sum >> 4;
    average = sum / (256);
    return average;
}
```

Figure 5: Code for Averaging values in buffer

Based on LTspice simulation, figures 6, 7, and 8 show our schematic and PCB designs.

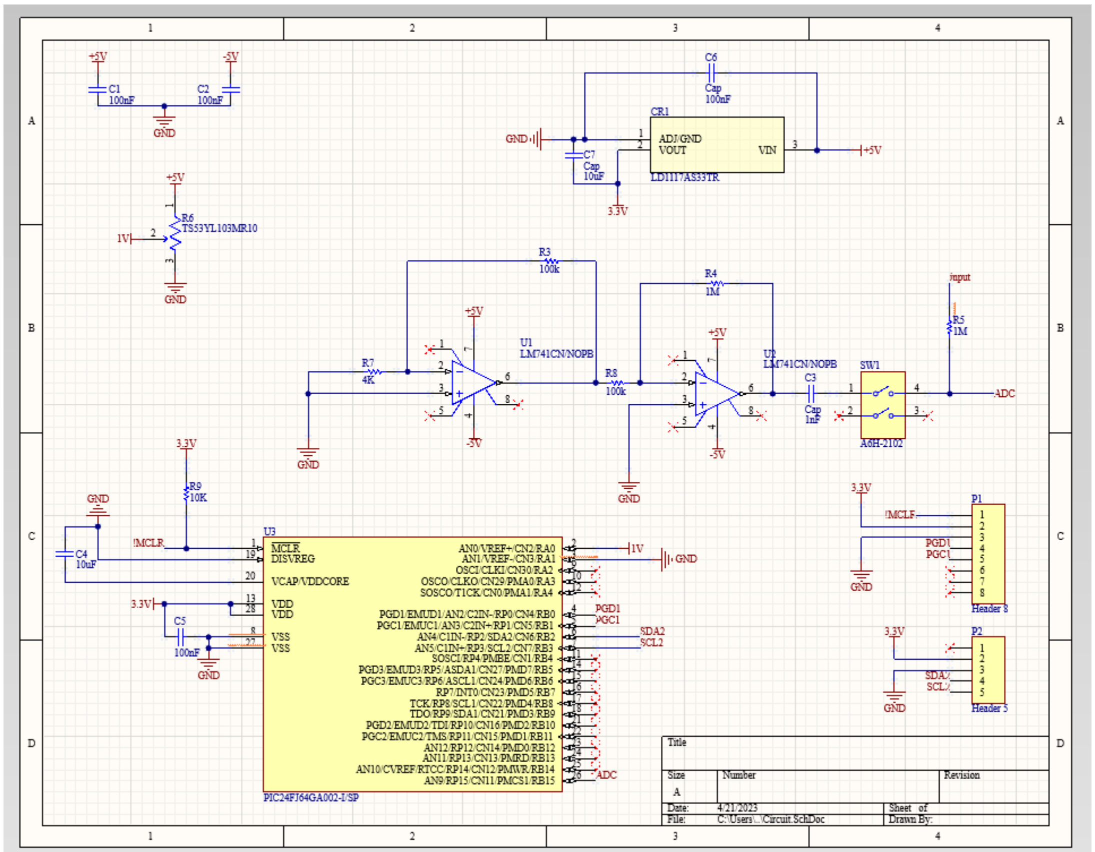

Figure 6: PCB Schematic in Altium

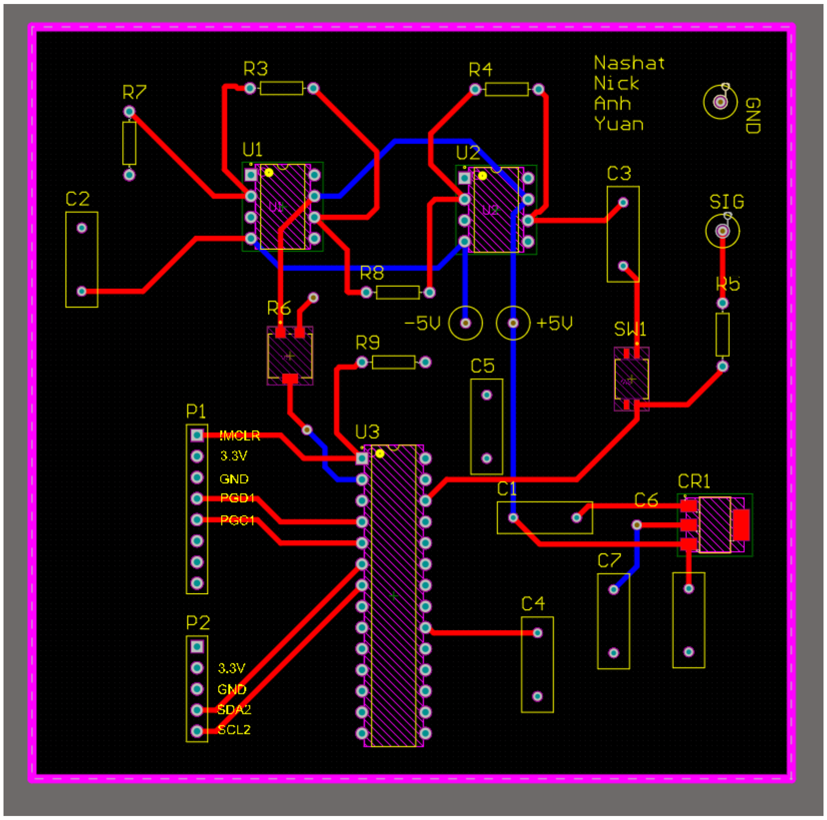

Figure 7: PCB Layout in 2D

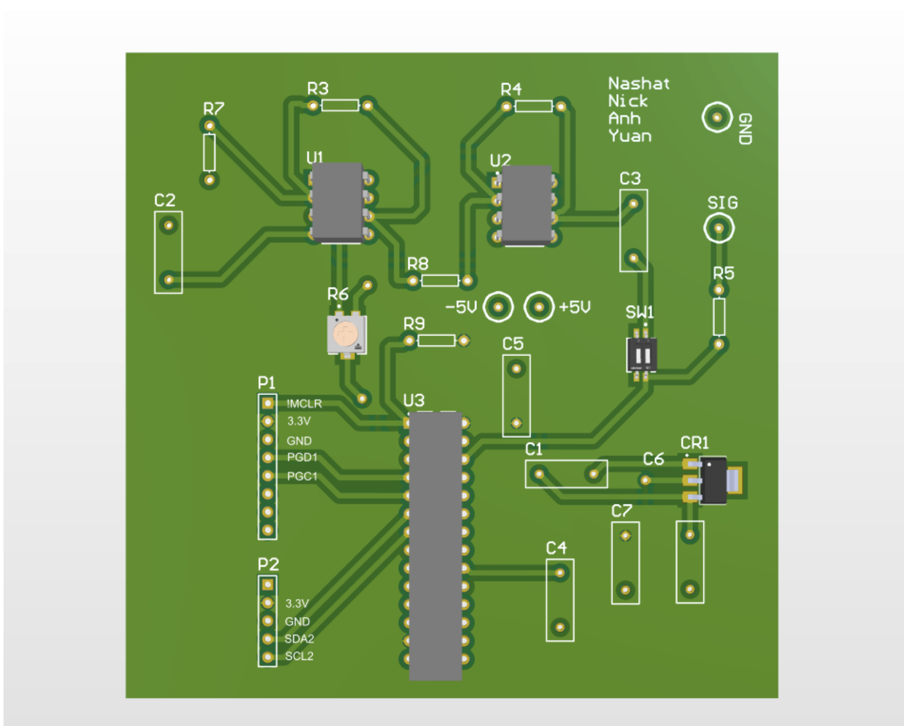

Figure 8: PCB Layout in 3D

When testing the voltages on our PCB, we encountered the problem that the 3.3V voltage divider from our original design outputs 1.2V, which was not enough to run the LCD screen or the PIC24. We desoldered the system and modified the box to use a potentiometer, but this did not work as the potentiometers would undersupply voltage then at a certain point suddenly bump it up to 5V. This is likely because we reached the end of the potentiometer's range. After modifying the circuit to connect the 3.3V net (also GND and 5V) to a breadboard, many different combinations of voltage dividers were tried. Eventually, 77 ohm (on the top) and 1Mohm (on the bottom) were used to generate 3.5V. However, this was still inadequate, so a design for a 3.3V voltage regulator was eventually found and implemented on the PCB. These issues likely arise from the power consumption of the PIC 24, as the power draw would cause the 3.3V net to drop.

After packaging the PCB into the Bud 750-1015 enclosure, the project met the requirements specifications by ensuring high accuracy of measurement with a 14-bit resolution for a randomly selected DC voltage between 0 and 1 volt. The input voltage range is set between 0V to 1V and the PIC24 operating voltage of 3.3V is achieved by using a voltage regulator.

Finally, we randomly chose 8 values of test voltage between 0V and 1V when the switch is on to compare 14 bits voltage on LCD display (actual) with voltage value on the oscilloscope (expected). The measurements taken are recorded in table 3 with their corresponding error. Then, the experiment was done again with the same V_{test} values with the switch off to compare whether or not noise has an impact on accuracy. By requirement, all error values should not be greater than 100 microvolts (10%).

	Noise On		Noise Off	
V_{test} (V)	$V_{display}$ (V)	Error (%)	$V_{display}$ (V)	Error (%)
0	0	0	0	0
0.05	0.05450439	9.00878	0.05548095	10.9619
0.10289	0.10449218	2.553911081	0.10485839	2.913328099
0.25	0.25379003	1.516012	0.25476074	1.904296
0.35245	0.35302734	0.1638076323	0.3538208	0.3889346007
0.5005	0.50238037	0.3756983017	0.50299072	0.4976463536
0.6501	0.6506958	0.09164743886	0.65264892	0.3920812183
0.90103	0.89990234	0.1251523	0.90228721	0.1395303153

Table 3: Voltages with and without noise

From table 3, all of the errors with switch on are less than 100 mV (10%), which satisfied the project requirement. Upon comparison of the percent error with and without noise, it is evident that the addition of noise resulted in a higher voltage resolution and increased accuracy for the

14-bit ADC. At the same time, the errors are at its largest for both cases when V_{test} is smaller (0.05V in the table), which may come from more actual voltage biases coming from the oscilloscope when the voltage is small.

Taking the data from table 3, two coordinate diagrams were created in Excel. The predicted line coefficients were found to be 0.9964 with noise and 0.9985 without noise, indicating a close correlation between the tested and displayed voltage readings. Overall, the 14-bit ADC has proven to be highly successful and accurate in its design.

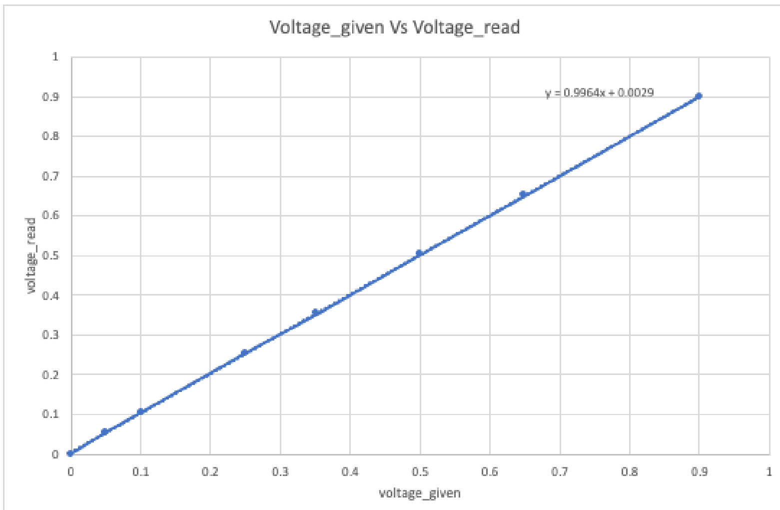

Figure 9: V_{test} vs. $V_{display}$ with Noise (switch is on)

Budget:

Component	MFG PN	Quantity	Unit Cost ($)
LM741	LM741CN/NOPB	4	0.91
PIC24FJ64GA002	PIC24FJ64GA002	1	5.00
LCD	SSCI-014052	1	8.37
Switch	AH6-2102	1	2.99
16 Header Pin	629-2012	2	0.73
Banana Plug	108-0906-001	4	1.38
1MΩ Resistor	MBB0207VD1004BC100	2	1.34
100k Resistor	CF18JT100K	2	0.10
10k Resistor	CF14JT10K0	1	0.10

2k Resistor	CF18JT2K00	2	0.10
12k Resistor	CF14JT12K0	1	0.10
24k Resistor	CF14JT24K0	1	0.10
10k Potentiometer	TS53YL103MR10	1	1.77
1000pF (1nF) Capacitor	FA18X7R1H102KNU00	1	0.27
100nF (0.1uF) Capacitor	300-1069 (ECE Depot)	4	0.08
10uF Capacitor	300-1084 (ECE Depot)	2	0.56
3.3V voltage regulator	LD1117AS33TR	1	0.90
Box	Bud 750-1015	1	7.56
		TOTAL	$42.30

Table 4: Materials needed and their costs

Conclusion/Summary

ADC on the PIC24 can be increased from 10-bit accuracy to 14-bit by adding noise and oversampling, but careful consideration must be given to noise levels and methods to reduce their impact. To achieve a noise level of 3mV, we use two LM741 op-amps to generate and amplify the necessary noise. Next, the resistor's Johnson noise is coupled to the voltage that the ADC should measure, and the original information retention of the analog signal is improved by oversampling (noise is spread over more samples, noise has less impact on the digital output and higher effective resolution and SNR are obtained) and low-pass filtering (prevents noise from overlapping when being sampled). At the same time, based on input DC voltage +5V, the operating voltage of 3.3V obtained by a voltage regulator and the reference voltage of 1V obtained by potentiometer dividing are connected to the microcontroller PIC24. The PIC24 is responsible for receiving the input samples, filling them into a circular buffer, and then calculating its mean over the number of bits desired. After working on the PCB design on Altium, the designed circuit board is to be packaged in a Bud 750-1015 enclosure, with one switch, LCD display, and four inputs: 5V, -5V, Vtest, GND. The PIC24 is programmed with the ADC code and then we randomly choose 8 values of test voltage between 0V and 1V when the switch is on/off to compare 14 bits voltage on LCD display (actual) with the voltage value on Oscilloscope (expected). All recorded values shown in table 3 has its corresponding percent error which then is graphed to see the linearity. According to the results, we found that all of the errors with the switch on/off are less than 100 mV (10%). With the noise switch on the error is less compared to when the noise switch is off. This shows that the designed 14 bits ADC has a high resolution and is more accurate with noise. The project is very successful in increasing the resolution.