Hand Level for Measurement of Angle

Zishu, Wu, wuz78, 400089778, Lab03

***Abstract*—In this paper, we introduce a system can be used to measure the angle by only using an accelerometer, Esduino and PC. The user can control a 3-centimeter square accelerometer by hand, to get a accurate measurement of the angle. The data will simultaneously be processed, transmitted from the Esduino, then displayed on the PC and represented by LEDs in two modes. The device can measure a single axis from 0 to 90 degrees or 360 degree, or measure and display xy axis on the same graph. This device provides a hand-level solution for people to measure the angle with small error. The aim of the paper is to provide an overview of the system, show the testing result and discuss about some limitation and performance of the device.**

I. Introduction

IN real-world applications, a large amount of information needs to be collected, recorded and then be analyzed. Therefore, engineers need to acquire a huge amount of data from the real world into computers simultaneously. The data acquire technology can detect, record and convert data at the same time, so that the future analysis has higher efficiency, accuracy and reliability. In the data acquisition system, Analog-to-digital converter is the core of the system, which converts analog signals to digital form and transmits it to the computer. This technique is widely in many fields such as music recording, heart pacemaker, scientific research and so on.

One example of real-world application is in civil engineering, the engineer needs to measure the size and angle of the building structure. Equipment such as tapeline and protractor might cause a large unavoidable human error in measurement. Nowadays, new techniques help to decrease human error as much as possible, many monitoring and measurement equipment are used by civil engineers in many stages of civil projects. For example, EDM is a machine from LANDEC ENGINEERS company, which can measure the angle and the distance by using light. The data are processed to the microcomputer to generate graph and coordinate file for future designing.

For an unprofessional application, this device introduced in this paper provides a cheap, portable and simple hand level solution to measure the angel. It calculates the angle by measuring the acceleration of gravity and transmits the data to the computer simultaneously. All data can be recorded in the computer for future use.

In the next section, we discuss the design of each part of in the system. The third section shows the test result of parts in section 2 and the entire system. In the fourth section, we have some discussions about the system feature limitation, frequency limitation and performance of the systems.

Zishu Wu is with McMaster University, computer engineering and management, 1280 main street west, ON, L8S 4L8 Canada (e-mail: wuz78@mcmaster.ca)

Design Methodology

This section introduces each component of the system and data flow from the transducer to the PC and LED display including the process from the real-world data, transducer, signal-conditioning circuit, A/D converter and computer. Each section explains the design in terms of hardware setting by using schematics and pin assignment map, as well as program logic using flowcharts.

A. *The Final Pin Assignment Map*

Refers to **Fig. 1**, the pins that are used is labeled. For the input, AN5 is connected to the x-axis pin from the accelerometer. AN6 is connected to Y or Z-axis for other functions. The button is connected to IOC0 and the switch is connected to PS2. For the LED display, the most significant digit, which represents the mode is output to the pin PT4. The bits for tens digit are labelled in brown-yellow color, which are from PT3(MSD), PT2, PT1, PP5(LSB). The bits for single are labelled in blue, which are PP4(MSB), PP3, PP2, PP1(LSB)

Jumpers need to be moved as labelled in the diagram in order to access channels. The operating voltage can be selected as 5V or 3.3V by the jumper. The detail can be found in the document "EsduinoXtreme User Guide"

The 3.3V is the supply voltage for the accelerometer. The 5V source is connected to the button.

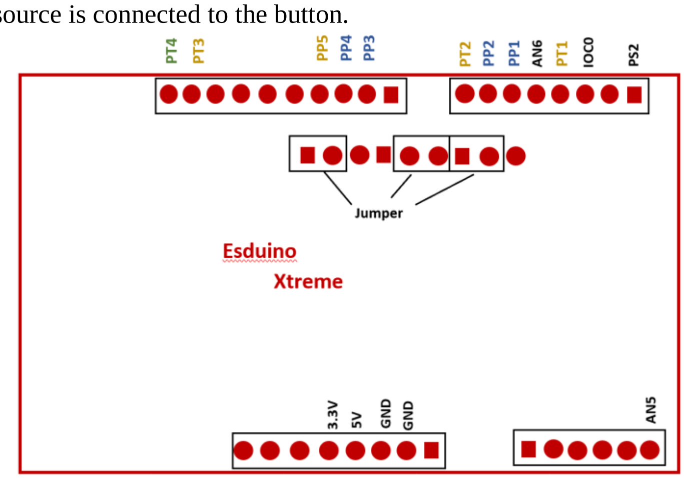

Fig. 1: the pin assignment map on Esduino

B. *Quantity Signal Properties*

In this device, the angle measurement is performed by accelerometer ADXL337. It can measure 3-axis acceleration including acceleration of gravity and dynamic acceleration, then output analog signal that are proportional to acceleration in total.

The output signal range and sensitivity of the sensor is proportional to supply range which is between 1.8V to 3.6V. The sensitivity of the output is 360mV/g at Vs = 3.6V. The output sensitivity is 195mV/g at Vs = 2V.

The horizontal position provides a voltage that is approximately half of the supply voltage. There might be self-bias inside the accelerometer because of the temperature change. In Figure 2, the plot shows that the output voltage of zero-g point is not stable when the temperature increase.

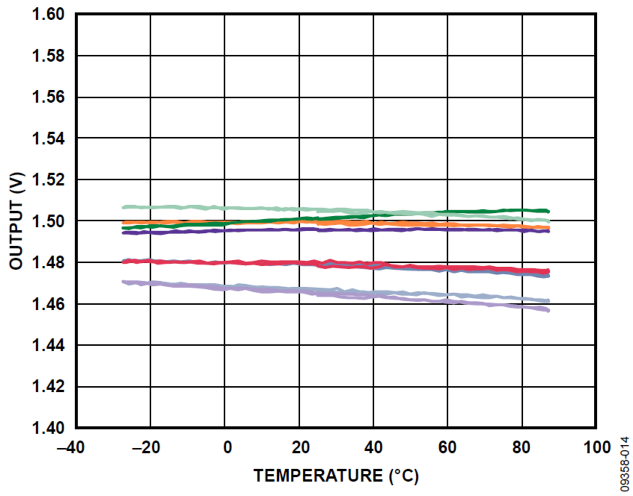

Figure 2: zero-g output voltage versus temperature

The output signal has noise, which is distributed by white Gaussian noise. Increase supply voltage results in a lower noise density. Another way to decrease noise is to apply a low pass filter (refers to **(1)**). The user can limit the bandwidth by adding capacitors at pin Cx, Cy and Cz (**Table 1**).

$$rms\ Noise = Noise\ Density \times (\sqrt{BW \times 1.6}) \quad \textbf{(1)}$$

Bandwidth (Hz)	Capacitor (μF)
1	4.7
10	0.47
50	0.10
100	0.05
200	0.027
500	0.01

Table 1:Filter Capacitor Selection

The typical output frequency of the ADXL337 is greater than 500Hz. The user needs to make sure the ADC sampling frequency is two times larger than the signal frequency, which should be equal or bigger than 1 KHz. Otherwise, aliasing error will occur when reconstruct the signal. The sampling frequency which refers to the PC plot sampling frequency should also be considered. In this case, it is set to be 20Hz. Consider that the user will not rotate the accelerometer at a very high speed. The result input signal frequency in the real world should be lower than 500 samples/second. It is not necessary to set the lowest sampling frequency as 1KHz. The test shows that 2Hz sampling frequency can give a good performance for normal use.

C. Transducer

The pins and wires connection is labelled in the **Fig. 3**.

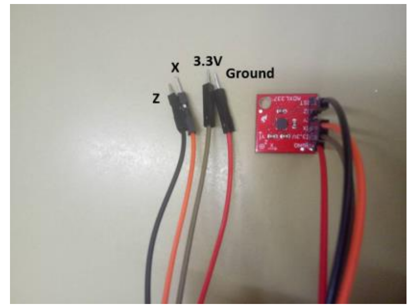

Figure 3: picture of accelerometer with wire connected to the pin

The output of the accelerometer is the projection of the gravity vector that points to the ground on the direction vector. (**Fig. 4**) Therefore, the output is maximum when the angle is -90° and is minimum when the angle is +90° (**refers to (2)**)

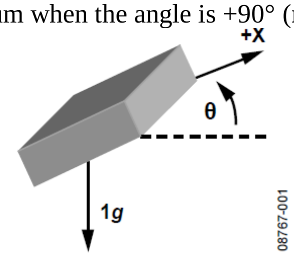

Figure 4: accelerometer

$$A_{X,OUT}\,[g] = 1\,g \times \sin(\theta) \quad \textbf{(2)}$$

In degree measurement, the derivative of the output acceleration versus angle is close to 0 as the angle approaches -90 and +90 degree (Figure 5). Therefore, to convert the voltage data to the angle, the inverse sin function can be used to calculate the angle in radians.

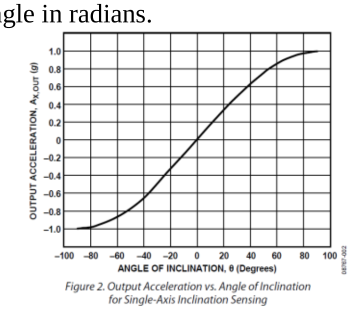

Figure 5: Output acceleration vs. Angle for Single-Axis

The resolution of degree is not constant, and it is worst at ±90 °. When the range is narrow in the middle of the full range, a linear approximation can be applied to calculate the angle. For this application, a range of 0° to 90° need to be covered. Therefore, the linear approximation is not reliable at the terminal end. The inverse sinusoidal function can give an accurate result.

Since there are no trigonometric functions and floating number on ESDX, the data, which is used to display on LED can be obtained by receiving processed data from PC component. Therefore, the approximation will be almost the same as the reverse transfer function of the accelerometer. The X -axis is always assigned to channel AN5. the Y or Z-axis (depend on the function needed) is assigned to AN5.

D. *Precondition circuit*

The amplification is needed when the output voltage range from the transducer is not suitable for ADC. In this device, the amplification is not needed

E. *ADC*

An A/D converter can accept electric voltage and convert the information into the desired data format.[1]

The ATD clock should be set two times larger then the input signal frequency. In this device, the prescaler is set to be 2. Therefore, the ATD clock = $\frac{6\,MHz}{2*(2+1)} = 1MHz$

The Esduino accept 8,10 and 12 bits of ADC resolution. In this device, the ADC resolution uses 12 bits. The conversion uses the successive-approximation method, which converts the analog signal into an n-bit code in n steps Since the input/output relationship is not linear, there is quantization error exists in the process. The example of quantization error is shown in **Fig. 6**.

The maximum quantization error = the resolution of ADC is $\frac{Vdd}{2^n} = \frac{3.3}{2^{12}}$ =8.0566E-4

The average conversion error is $\frac{Vdd}{2^{n+1}} = \frac{3.3}{2^{13}}$ =4.028E-4

On the Esduino, AN channel 5 and 6 are used for x-axis and y/z-axis. In the main function code, the AN channel 6 is not set as input. The functions of display XY axis and 360 degrees are in the separate project file.

The setting of the register can refer to the "HCS12 Instruction Set Reference"

	linear approximation	Actual Voltage	predicted voltage	error	%
0	2080	1.66	1.676190476	0.01619	1.619048
20	1930	1.57	1.555311355	0.014689	1.468864
30	1870	1.52	1.506959707	0.01304	1.304029
45	1790	1.457	1.442490842	0.014509	1.450916
60	1718	1.395	1.384468864	0.010531	1.053114
75	1679	1.366	1.353040293	0.01296	1.295971
90	1660	1.3575	1.337728938	0.019771	1.977106

Fig. 6: Quantization error for sample angle

F. *LED display MODE 0 (BCD) & MODE 1 (Bar)*

In this project, 9 LEDs are used to represent the value of the angle in two modes. Generally, LED is ON means that the bit value is 1. LEDs turns OFF means that the bit equals 0. The display mode is determined by the input value of a toggle switch. The 1st LED shows the mode that is operating at present.

In mode 0, each decimal digit is represented by 4 bits. The tens digit is displayed by the 2nd to the 5th LEDs. The next 4 LEDs display the value of the single digit of the angle. For example, 36° should be displayed by LED like 000110110. The detail of each digit vs the value of output is in the **Table 2**.

tens	PT4	PT3	PT2	PT1	PP5	PP4	PP3	PP2	PP1	ones
1	0	0	0	0	1	0	0	0	0	1
2	0	0	0	1	0	0	0	0	1	2
3	0	0	0	1	1	0	0	1	0	3
4	0	0	1	0	0	0	1	0	0	4
5	0	0	1	0	1	0	1	0	1	5
6	0	0	1	1	0	0	1	1	0	6
7	0	0	1	1	1	0	1	1	1	7
8	0	1	0	0	0	1	0	0	0	8
9	0	1	0	0	1	1	0	0	1	9

Table 2: the value of output pin vs the decimal value in BCD mode(Mode 0)

In mode 1, the 1st LED is ON. the angle is rounded to the nearest ten's integer (eg, 10,20,30) from 0° to 90°. Then, the angle is displayed in a linear bar format. For example, 24 degrees is expressed as 110000000.

To achieve two modes, the basic idea is to build a look-up table. For mode 0, the tens digit and single digit of angle is separated by using "divide"(/) and "remainder"(%). The output of LEDs is determined by the value of each part by looking up the table (**Table 2**).

For mode 1, the output of LEDs is determined by which range that the angle is in. For example, in the range from 15° to 24°, the output should all be 110000000.

Nine outputs (PTT[1:4] and PTP[1:5]) are used to display the angle. The most significant digit is PTT[4]. The tens digit of the angle is expressed by PTT[3,2,1] and PTP[5] from the most significant bit to the least significant bit. In the same order, the single digit is expressed by PTP[4,3,2,1].

G. *Data Processing*

The main calculation of angle is done in the MatLab. The Esduino's main task is to transmit the data out and in. Based on the principle of the accelerometer, the angle can be obtained by using the inverse sin function **(3)**. The idea of calculating the parameter in the arcsin function is explained in **Fig 7**. The Esduino read the output from the accelerometer as 2080 when the degree is 0, as 1660 as the degree is 90. Assume CO = 2080-1660 = 420. When the degree is maximum, it is 420 smaller than the 0 degrees. The degree can be calculated by $\sin^{-1}\frac{AB}{AO}$. AO equals to CO as 420. AB is the distance between 2080 and present output Esduino reads. Therefore,

$$\text{angle} = \sin^{-1}\frac{(2080-intput)}{420} \quad \textbf{(3)}$$

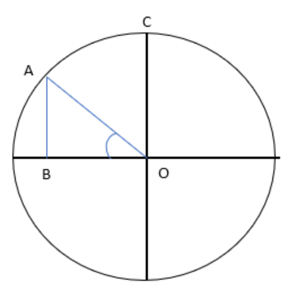

Figure 7: graph to explain the equation of inverse sin function

The data is processed between both Matlab and Esduino. After the Matlab calculate the accurate angle, it transmits the data back to the Esduino for LED display.

Matlab is set to read 16bit as a single data by using char (which is faster) to transmit the data every two times. The data flow is explain in the flowchart (**Fig. 8, Fig. 9)**

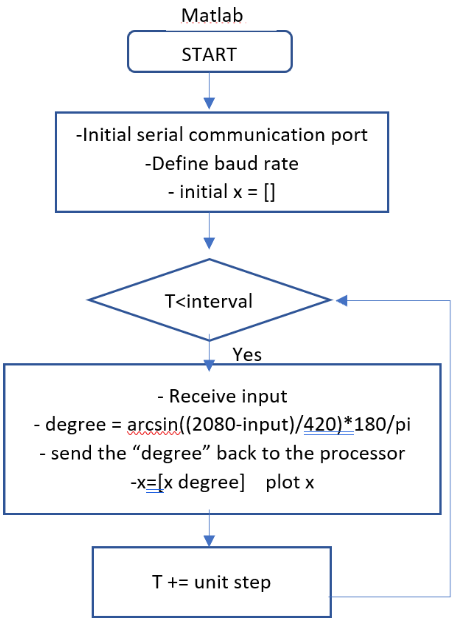

Fig. 8: flowchart of PC

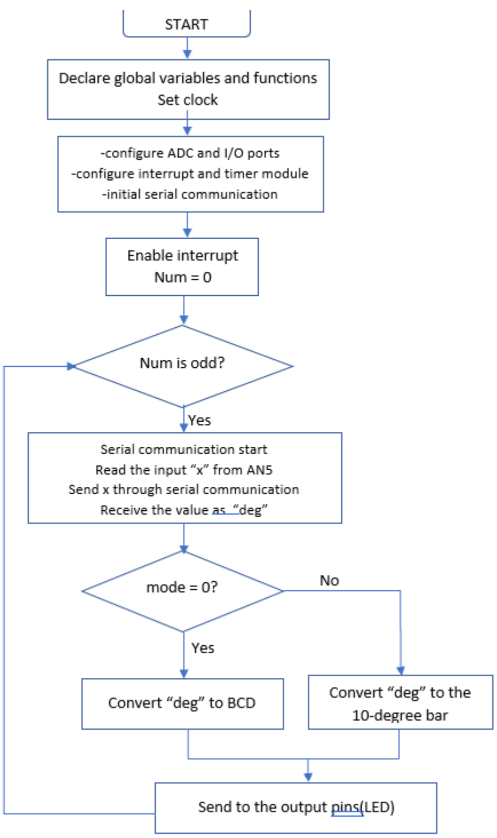

Fig. 9: flowchart of program

H. *Control/Communicate*

This device required a bidirectional serial communication. The bus speed for this application is 6MHz. To set the E-clock, the internal 1MHz signal is set as the source clock. The detail is shown in the *Setclk()* function.

Baud rate is selected as 14400 based on the calculation and trade-off between error and speed **(4).**

$$\text{Baud rate} = \frac{\text{F(e-clock)}}{\textit{Baud Divisor}*16} \quad \textbf{(4)}$$

From **table 3**, the minimum error and maximum speed is chosen, which is 14400 baud rates with 0.16% error. Although the baud rate 38400 has 2.4% error which is lower than the 6% error requirement. The main specification of device is performance a accurate angle measurement. A higher error probability will affect the accuracy of data. If the baud rate 38400 is chosen, the error will be increased by 15 times as the speed is only increased by 2 times.

The serial communication is started or stopped by a interrupt driven momentary switch. When the serial communication is started, the ESDX transmit the data to the PC first and then wait to accept the data. Data that received is processed to a different form to determine the LEDs depends on the mode.

E-clock	baud Rate	SBR (Baud Divisor)	round(SBR)	error
6000000	300	1250	1250	0
	600	625	625	0
	1200	312.5	313	0.16
	2400	156.25	156	-0.16
	4800	78.125	78	-0.16
	9600	39.0625	39	-0.16
	14400	26.04166667	26	-0.16
	19200	19.53125	20	2.4
	38400	9.765625	10	2.4
	57600	6.510416667	7	7.52
	115200	3.255208333	3	-7.84

Table 3: calculation for choosing the baud rate

I. *Full System Block Diagram*

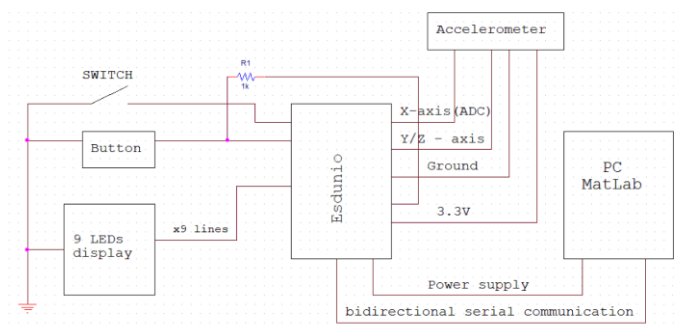

Fig. 10: system block diagram

J. *Full System Circuit Schematic*

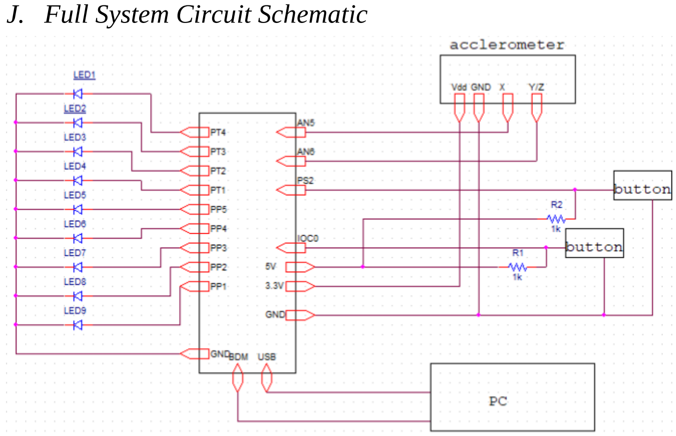

Fig. 11: system circuit schematic

II. RESULT

This section contains the test and result of each component in the system separately. The first test is to validate the internal clock is set correctly. The second test is to verify the factor that affect the quality of accelerometer output signal. The third test tests the full voltage range of accelerometer output signal. The forth test tests the ADC by comparing the output from PC plot to the oscilloscope result. The fifth test tests the display of the LEDs in two modes. Then the entire system is tested. The last two subsections are tests for two extra functions: x-y axis display and 360 degrees display

A. *Verify the Clock and Delay Function*

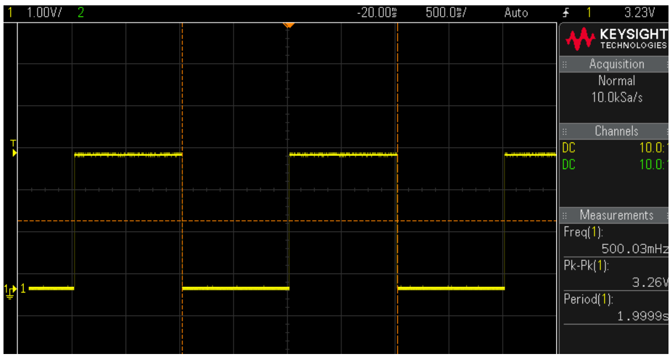

Fig. 12: oscilloscope picture of delay 1 second

To test the setting of the clock speed, the direct way is to create a 1-second delay. From the graph of the oscilloscope (Figure 12), the delay period is about 2s in total with 50% duty cycle. Therefore, the clock speed and delay loop matched the requirement.

B. *Test of The Signal Property*

The first property to be tested is the noise in the output. In the figure, the degree is decreasing from 90 to 0 degrees. When the angle is stably changing, the white gaussian noise is small and the average value is zero in time domain.

If the hand control is a little bit unstable, the noise will be significantly large like it is shown on the left of the figure13 due to dynamic acceleration.

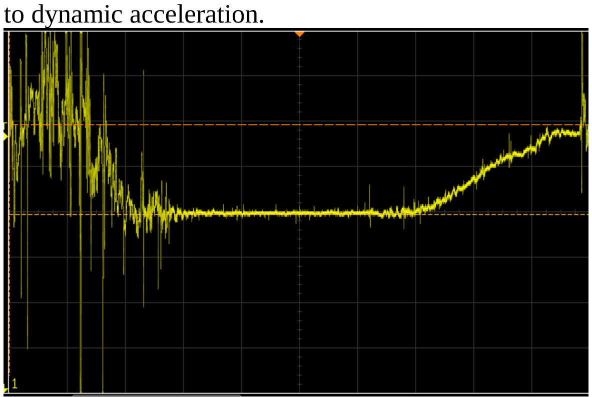

Fig. 13oscilloscope picture of rotating x-axis from 0 to -90°

From measurement, the 0-degree output is 1.66V, which is 0.01V higher than the theoretical value from the datasheet ($\frac{Vss}{2} = \frac{3.3V}{2} = 1.65\ V$). This difference might come from the temperature situation.

C. *Test the Performance of the Transducer*

The maximum value of the output signal is achieved when the angle is -90°， which is about 1.9524V. The minimum value of the output signal is 1.35750 when the angle is 90 °.

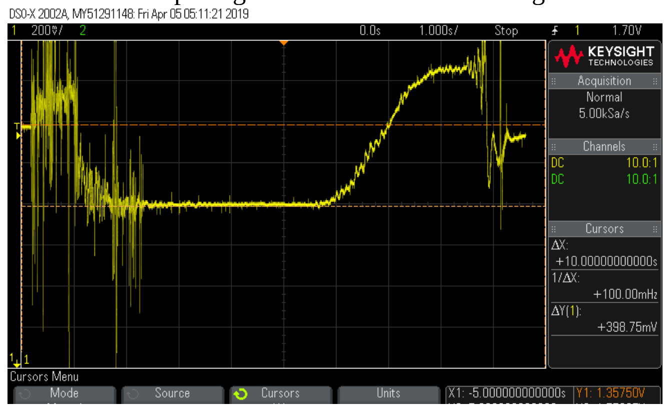

Fig. 14: rotate the accelerometer from -90° to 90°

D. *Test ADC*

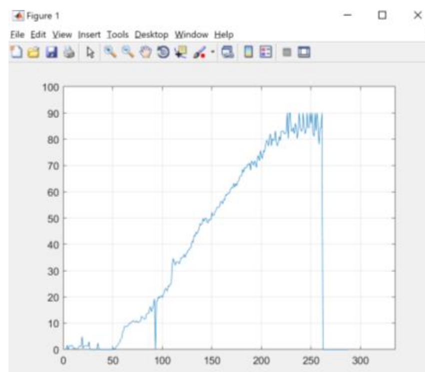

Fig. 15: MATLAB plot of rotating the x-axis from 0 to 90°

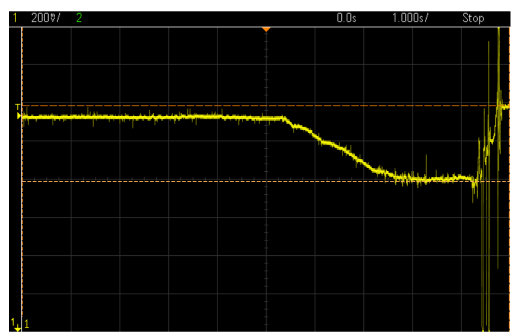

Fig. 16: oscilloscope screenshot of rotating the x-axis from 0 to 90°

Compared two figures (Figure 15, Figure 16), the screenshot from oscilloscope shows the detail of noise. The MATLAB plots the sample point and line them up, so it cannot show the noise but a single line. There is quantization error in ADC conversion, so some noise component is eliminated in the process of A/D conversion.

E. *Test the Mode 0 and Mode 1*

The green LED is the most significant digit. The next 4 LED represent the tens digit of the angle. The rest represent the single digit of the angle.
Mode 0:

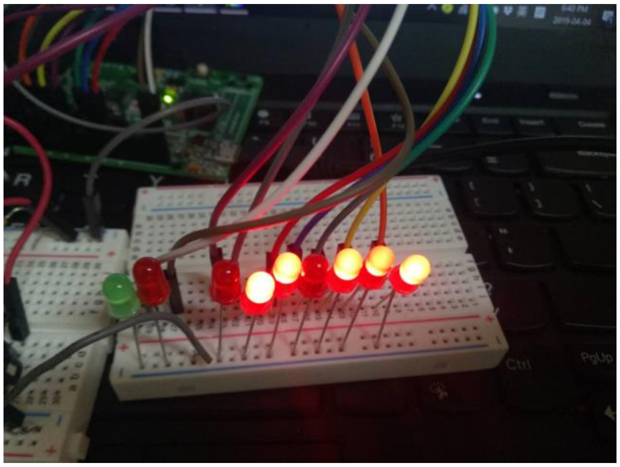

Fig. 17: Mode 0 LED display when the angle is 39°(Fige 18)

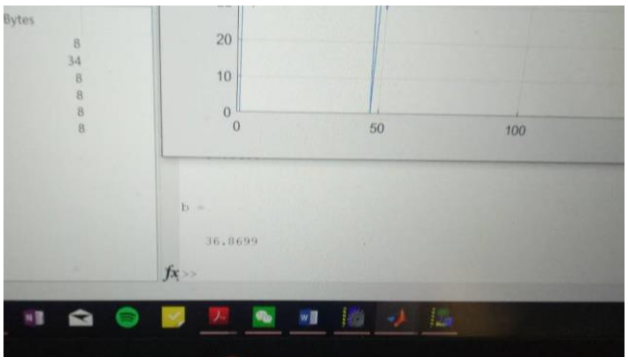

Fig. 18: MATLAB output of same angle as Fig 17

Mode 1:

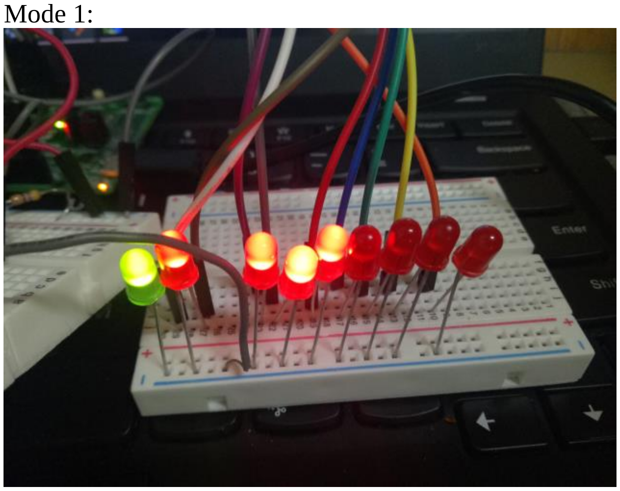

Fig. 19: Mode 1 LED display when the angle is 46°(Fig 20)

```
b =

    46.3699

>>
```

Fig. 20: Matlab output when the angle is same as Fig 19

F. Test the Entire System

After the button on the left is pressed, the serial communication starts. When the button on the right is pressed, the LEDs display the angle in Mode1. After the button on the left is pressed again, the serial communication will stop. The LED will not change the state anymore, and the x-axis(time) in MATLAB plot will stop moving.

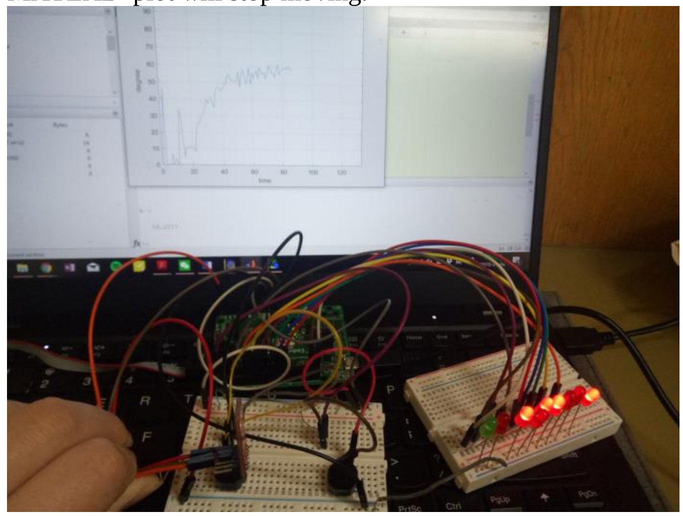

Fig. 21: Entire System

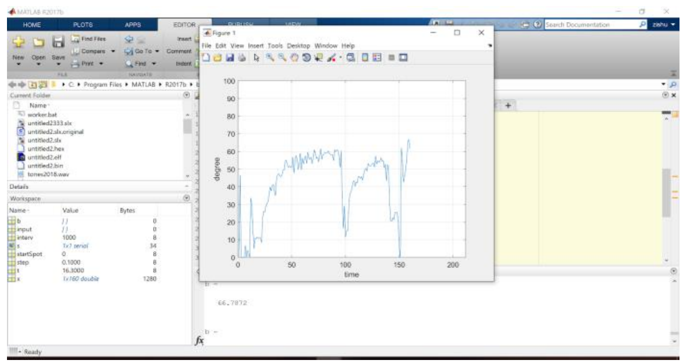

Fig. 22: screenshot of PC display

G. Test xy axis

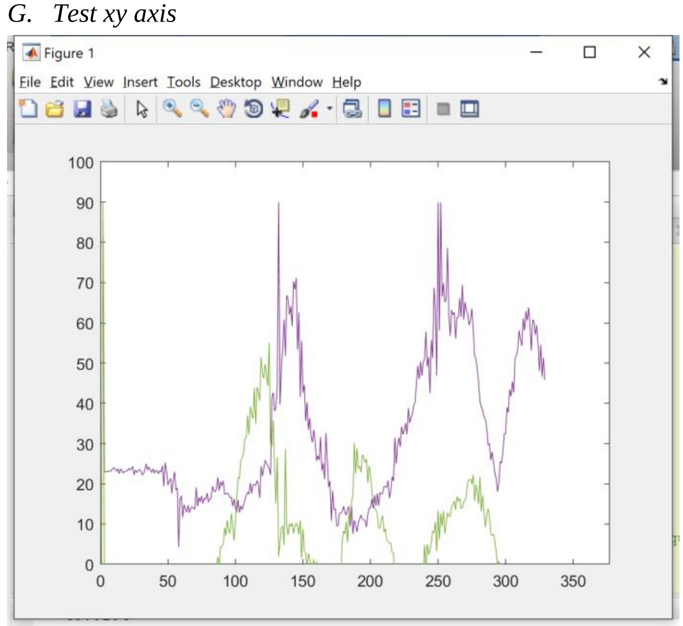

Figure 23: plot x and y axis on the same graph

H. Test 360° plot

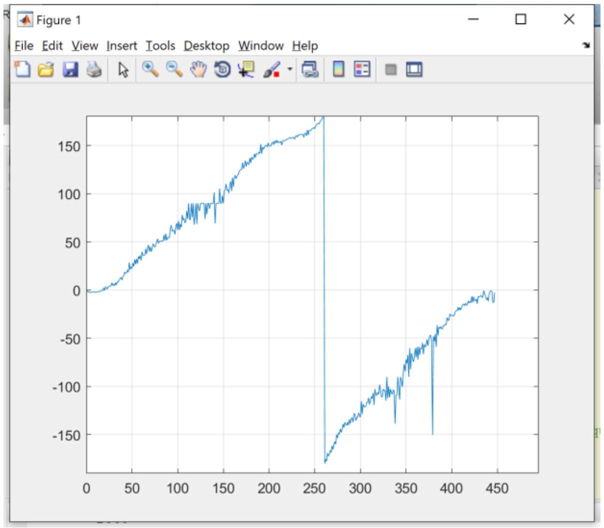

Figure 24: full degree measurement of x-axis

There will be a jump between -180° and +180° since they are accurate the same angle.

III. DISCUSSION

This section discusses some problems and limitation that need to be solved or discussed when develop this program. We also compare two result from the oscilloscope and PC. At the end of the section, we discuss the idea of the future development.

A. Floating Point and Trigonometric Function

The ESDX use C language to program the function. To overcome the error caused by the floating-point capability in ESDX. the device uses bidirectional serial communication. The main calculation is done in the PC program. MATLAB is a strong mathematics tool that can give precise results what can perform the trigonometric functions and give decrease the error caused by the floating value.

B. Quantization Error

Despite the error from the calculation, there is quantization error exist in A/D conversion since the number of bits we use is finite. The relationship of analog to digital is not perfectly linear. The maximum quantization error is the resolution. The detail of calculation is in the section 2.E. The maximum error is equal to $\frac{V_{FS}}{2^{12}}$. V_{FS} is the full-scale voltage range. Therefore, the maximum error is 8.0566E-4.

C. Limit of the Serial Communication rate

The serial communication rate is another critical factor of the device performance. The maximum standard serial communication rate is 14400. The error should be lower than 6%, 14400 has only 0.16% error. 38400 has 2.4% error. When measuring the degree, the correctness of the data is important. The error is 15 times larger when the speed just increased by 2 times. Compare the trade-off between speed and correctness, 14400 is a better option. The full calculation is in **Table 3.** The test uses the serial communication rate as 19200, the right data cannot be transmitted properly (Figure 23).

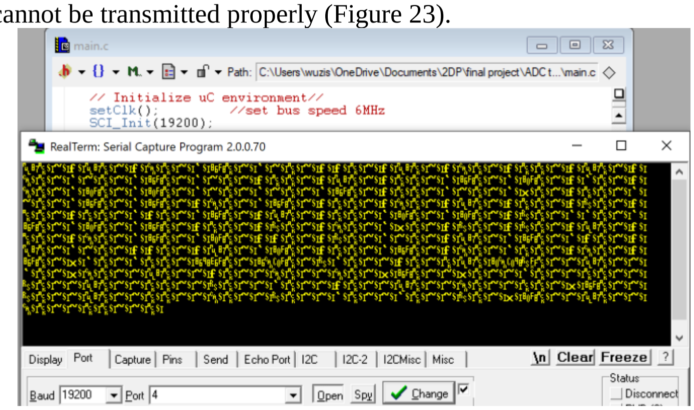

Fig. 25: output when use 38400 as the baud rate

D. Limitation of the Speed

For every system, there is a limitation on the speed. The primary limitation for this limitation comes from the bus clock and the process of serial communication. The bus clock is the highest speed the device can reach. In this program, the smallest delay time is set as 1ms. Therefore, the highest sampling frequency for plotting is 1KHz. To obtain a higher frequency, the user needs to change the period variable (which is 6000 default) in the delay function. The serial communication function (SCI) is another critical factor that will lower the speed of the program. The total delay is the conversion time from ATD plus the SCI function time at 14400 bps plus the defined delay function. The function SCI_OutDec will convert bits into ADCII character. The function SCI_OutChar converts the number into 8-bit, which will take less time to transmit. In this program, the data need to be transmitted twice.

$$conversion\ time = \frac{(12+2+2)}{1\ MHz} = 16us$$

Therefore, the total delay is related to the bus clock and SCI function feature.

E. Limitation of the Analog Signal Frequency

Another error that might occur is when the sampling frequency is too low. The error is called aliasing error. From the sampling theorem, the sampling frequency should be equal or larger than 2 times the input signal frequency. Therefore, the maximum frequency of the analog signal is half of the sampling frequency which is called the Nyquist frequency. When the input signal frequency exceeds the limitation, the aliasing error will occur which cause the signal distortion.

F. Sharp Transition

When the analog input signal has sharp transitions, the signal can be reproduced only when the signal frequency is very low or the sampling frequency is much higher. Assume the input signal is square wave with 50% duty cycle and 2Hz (2 sample/second). If our sampling frequency is 1 kHz, the reproduced signal will have almost the same shape because most sample point from analog signal is “captured” by sampling.

When the analog signal frequency increases, the reproduced signal will be smooth out because the sampling frequency is not fast enough to catch the edge point (sharp point).

G. Discussion of the Result

To verify the data processing and transmission is correct, the accelerometer can be placed in a fixed angle. The MATLAB output should be same as the angle. To verify the sampling frequency is reasonable, the test can be performance by human hand to show that the output plot has variation caused by hand-controlled rotation. This proves that the sampling frequency is good enough to catch the small change and reproduce the overall analog signal.

Compared to the validation results, the sensitivity is not optimal when the degree exceeds 85 since the resolution of degree is not constant. The PC plot cannot show the noise because it only plots one point at a time.

H. Limitation and Problems

The first limitation is the loss of noise detail on the PC plot. This limitation is mentioned in section 2.d and 3.g.

Some noise points are plotted as the true angle value. This causes another problem that the noise might affect the judgment. If the user fixes the accelerometer at an angle, the plot is still not stable.

Another limitation is the speed of the device. Since the sampling frequency of plotting is defined by delay function. The system is not free during the delay period. When the device needs to be developed to perform more functions, the delay period is a waste of time.

I. Future Improvement

The interrupt feature can increase the efficiency of the program. After the PC receive a data, it can send a signal edge to the ESDX. The interrupt can catch the edge and start another serial communication. Using interrupt can save the time period which is used as a delay in the present program.

IV. Conclusion

The paper introduces a device that can provide a hand-level solution for angle measurement. It explains the method and rationale of each component and the entire system. User can record all data in MATLAB or csv file for future analysis. In view of these results, the device can provide a accurate angle value as long as the hand control is stable. For future development, this program needs to be developed as an interrupt-driven program. The energy and work efficiency will be increased. The device can perform more function at the same time.

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