DEPARTMENT OF ELECTRICAL
AND ELECTRONICS
ENGINEERING

EE491 / EE492 PROJECT REPORT

Hall-Effect Angular Encoder

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ABSTRACT

The project is designed to encode angular position of a diametrically magnetized disc by using hall-effect sensors. Hall-effect principle is used to determine angular position of the disc. Magnetic field of the disc is detected by two hall-effect sensors. According to these sensors' output and the known angles of the magnetic disc, a proper look-up table is determined. Look-up calibrated system is used to provide required accuracy of the project. Arduino Uno is used as a processor which is used for analog-to-digital conversion and controlling the stepper motor.

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ABBREVIATIONS

ADC : Analog-to-Digital Converter

SNR : Signal-to-Noise Ratio

coV : Corona Virus

LUT : Look-up Table

LSB : Least Significant Bit

MSB : Most Significant Bit

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1. INTRODUCTION

Hall-effect sensor is a sensor that measures the magnetic field. The output of a hall-effect sensor is affected by polarity and magnitude of the magnetic field. Hall-effect is an effect of magnetic field on a thin plate of conductive material which carrying a current. Magnetic field applied conductive material, such as copper plate, a small voltage difference is observed across the plate. The magnetic field should be measured in steady state conditions which provides proper results. The sensor's output does not only depend the magnitudes but also depend on the polarity. [1]

1.1. Hall-Effect Sensors

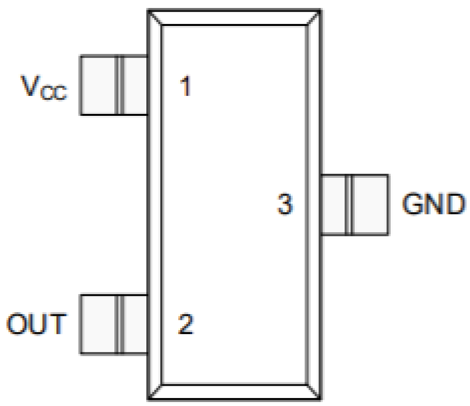

Figure 1: DRV5055 Pin Configuration

In angle measurement applications with 2-pole magnetized disc, difference between 0-degree and 180-degree cannot be distinguished by one sensor. Then, two hall-effect sensors are placed next to magnetized disc. Hall-effect sensors will be place 90-degree apart from each other's that provides the efficient results for two sensors in look-up table calibrated system. Magnetized disc doesn't have to be oriented in systems with two sensors. 90-degree is not obligatory for the look-up table calibrated systems but most efficient results are observed in 90-degree. Also, 90-degree phase difference generates quadrature signals. Bipolar and unipolar hall-effect sensors could be used in project. However, bipolar sensors are usually more practical than the unipolar sensors because bipolar sensors respond both north and south poles of a magnet which makes it usable for wider-angle applications. The system works with Arduino. So, output of the sensors' range must not exceed 5V. Then, high-accuracy, ratiometric, 3V or 5V, bipolar linear hall effect sensor DRV5055 provides the necessary conditions. [2] The DRV5055 produces unique voltage between V_{cc} (supply voltage) and 0.2V according to magnetic flux density. Output of the sensor is half of the supply voltage without any magnetic field. Additionally, ratiometric architecture is nothing but an architecture that eliminates error from V_{cc}. Operating temperature range relies on -45 to 125 (in C^{o}). [3]

1.2. Look-up Table Calibrated System

Look-up tables use reasonable amount of data in the memory in order to reduce processor load. Uncalibrated systems are not enough for designed accuracy conditions. The accuracy required in project could be provided by using calibrated system. There are three common methods for calibrated systems that are peek calibrated, look-up table calibrated and hybrid systems. Look-up table calibration is a solution for reducing processor load by using reasonable amount of data in flash memory. [4] In a look-up table calibrated system, sensor voltage data will be recorded for known angels.

Accuracy of the system is calculated by using the spaces between calibration points that means high accuracy depends on the number of calibration points used. Spacing between calibration points could cause unpredictable errors, if it will be greater than 30°. [2]

$$Accuracy \approx {}^{Spacing}/_{8} \quad (1)$$

1.3. Arduino Uno

Arduino Uno is one of microcontroller board released by Arduino. It has 14 digital input/output pins, 6 analog inputs, a 16 MHz ceramic resonator, a power jack, a USB port, a reset button and an ICSP header. Also, ATmega328p is included as a controller inside the Arduino Uno. ATmega328p is an 8-bit microcontroller with maximum 20MHz clock frequency. ADC resolution of Arduino UNO is 10 bits. [5]

1.4. Analog-to-Digital Conversion

ADC is a signal conversion from analog signals to digital ones. Analog signals make sense in digital systems thanks to ADC. Resolution is a term to explain how many levels that we have in determined range of output. It is given by number of bits. The smallest change in voltage required to guarantee a change output level is called least significant bit (LSB).

1.5. Stepper Motor

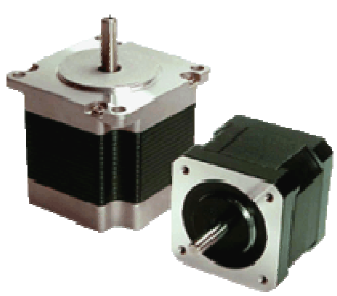

Figure 2: Stepper Motor [5]

A stepper motor is a rotary actuator works with high precision and torque. It rotates a specific number of degree according to step size. Determined angular position application is one of the areas where stepper motors are use. Magnetized disc centralized on top of the unipolar stepper motor. There are two configurations of stepper motor that are unipolar and bipolar stepper motors, both have their own applications and advantages. Bipolar stepper motor is the most popular configuration; it provides higher torque values with respect to unipolar stepper motors just because entire windings are used in applications. On the other hand, sides of each winding can be controlled with a single transistor in unipolar stepper motors. Half of the winding is energized at a time. Polarity of the motor can be easily changed just by using the other outer end of the winding. [6]

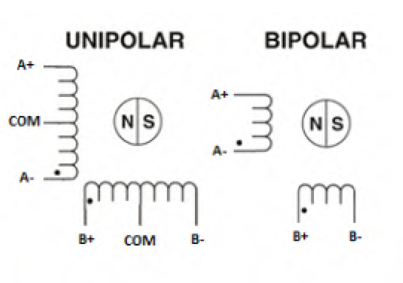

Figure 3 : Unipolar vs Bipolar Configuration [10]

Unipolar stepper motor has center taps which means there are three connections for each coil. Each sides of coils are activated to determine direction of the magnetic field and that sides are connected to IC. [9]

1.6. Linear Regression

Linear regression is a linear approximation for a data set. One dependent variable and one or more independent variables are used for modeling. If the independent variables are more than one, the approach is called multiple linear regression. To generate a linear line, offset and slope have to be known. The offset and the slope are calculated by using the data set which is occurred from independent and dependent variable.

2. PROBLEM DEFINITON

The angular position of a diametrically magnetized circular disc can be found by utilizing magnetic field. Related theory explained in introduction is hall-effect. Arduino Uno derives a stepper motor with 2-degree step. The disc centered on the stepper motor has a unique magnetic flux density for every position around it. This magnetic flux density changes according to angular position of the disc. Two hall-effect sensors are placed next to the disc and quadrature sensors' outputs are used for generating the look-up table calibrated system. Sensors' outputs are analog signals which have to converted into digital signals. For the conversion, ADC of the Arduino Uno shows up. ADC operations are done by ATmega328p (Arduino Uno). To get proper results, average of many ADC outputs is used. Averaged ADC outputs and known angles of the disc are matched to generate look-up table. At the end, angular position encoder using hall-effect sensors is implemented with look-up table calibrated system.

The accuracy requirement of the system has to satisfied. One of the most important criteria for accuracy is the applied method for encoder. Calibrated systems have better accuracy except systems with large number of hall-effect sensors. Designed project has to be implemented with two hall-effect sensors. Required accuracy cannot be provided with uncalibrated systems just by using two hall-effect sensors.

Unwanted current flows could be occurred in stepper motor derivation. To avoid this, ULN2003A IC is used as a motor driver.

ADC resolution of a microprocessor can be improved diversely. ADC requirement systems usually use off-chips to increase resolution. However, higher resolution is reachable without resorting to expensive off-chip ADCs. Oversampling and averaging is a method that is used to improve ADC resolution. Also, cost and complexity of system could be reduced by using oversampling and averaging. Oversampling reduces noise and improves SNR. Even so, there is a trade-off between resolution and throughput. The system's throughput is reduced, if the oversampling method will be applied. Throughput is a term to explain number of data words obtained per unit time. To improve resolution, we have to tolerate the reduced throughput.

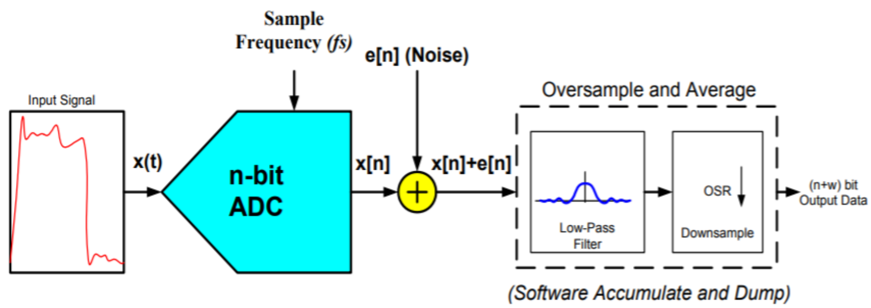

Figure 4: Oversampling and Averaging to Increase Measured Resolution by "w" bits [8]

Resolution requirement depends on system parameters that are the smallest significant change and the range of output. Relation between least significant bit and the range determines the required resolution. Before oversampling, Nyquist Theorem has to satisfied. Nyquist Frequency calculation is shown below:

$$F_{Nyquist} = 2 \times F_m \qquad (2)$$

$$F_s \geq F_{Nyquist} \qquad (3)$$

Where F_m is the highest frequency component of input signal. Sampling frequency has to higher than the Nyquist Frequency. Oversampling provides higher sampling frequency rates to increase the resolution. Oversampling frequency is related to the effective additional number of bits by a factor of four:

$$F_{os} = 4^w \times F_s \qquad (4)$$

Where “w” refers to desired additional bits of resolution, “F_s” refers to sampling frequency which satisfies the Nyquist Criteria, and “F_{os}” refers to oversampling frequency.

At the end, the project statements are followed,

1. Linear Hall-effect sensors generate output according to magnetic field. Sensors are placed 90-degree apart from each other which provides quadrature outputs and more efficient results.
2. Stepper motor with centralized diametrically magnetized disc on top is driven by Arduino Uno. Step size of the motor is 2-degree.
3. Output of the sensors is sampled and transmitted to digital signals via Arduino Uno. Samples is taken under steady-state conditions.
4. Around 255 sampled sensors’ outputs are used to create calibration data.
5. Look-up table is generated by using ADC output and known angle of the stepper motor. Piecewise-linear function helps to spread the results for all angles.
6. Look-up table will be used to determine angular position of the disc just by using the sensors’ output.

3. PROPOSED SOLUTION

Accuracy improvement is the most important part in solution. In most projects, there is always at least one study to improve the accuracy. Here, the methods applied in project are clarified.

3.1. Accuracy Improvement

As mentioned before, Arduino Uno has ADC with 10-bit resolution. ADC can be examined in two ways which are resolution and accuracy.

Accuracy is a term to explain the relation between observed results and true value. Accuracy can be improved by using averaging method. In method, more than one sample should be taken. Then, samples are added and the total is divided by number of sample. In the project, hall-effect sensors' outputs are sampled 256 times and averaging follows it. Average of the 256 sample generates the accurate result for ADC. In pseudo-code:

```
set sum to 0
set counter to 0
set limit to 255 times to read ADCout
while counter not equal to limit
  read the ADCout
  add the ADCout to the sum
  increment the counter
end of the while
average = total/limit
```

Resolution is an explanation of number of levels in known range of output. Resolution can be improved to reach more accurate and detailed result. 10-bit resolution provides 1024 levels in digital. We have 5-volt reference voltage.

$$\Delta V_{LSB} = \frac{V_{ref}}{2^N} \quad (5)$$

12-bit resolution is required for desired accuracy. Resolution is increased by using oversampling and averaging method. Resolution of the Arduino Uno is 10-bit without any operation. Oversample frequency is calculated accordingly Equation4.

Ratiometric architecture helps to eliminate the errors caused from power-supply voltage tolerance. The hall-effect sensor is selected with a ratiometric analog architecture. So, the error is reduced and the accuracy is improved just by choosing right components.

Low-pass filter can be used to improve SNR and overall accuracy just buy applying output of the hall-effect sensors. Sensing bandwidth of the DRV5055 is 20-kHz. The filter is applicable, if the full 20-kHz bandwidth is not needed.

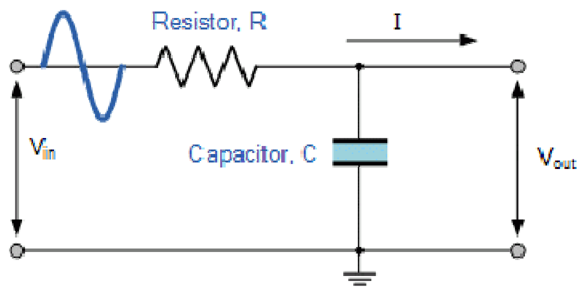

Figure 5: Low-Pass Filter

Design is done according to specifications of the sensor which are 5V power-supply voltage, -1 to 1 mA output current.

To create calibration points, known angle of the stepper motor and the hall-effect sensors are used. Output of the sensors are sampled for different angles of magnetized disc on top of the stepper motor. Sampled output values when the magnetized disc is in motion are not significant. So, samples are taken when the system is reached steady-state conditions.

Linear regression is used to linearize the nonlinear ADC outputs. Hall-effect outputs are assumed as cosine and sine signals. After digitalized cosine and sine waves, the digital values are compared to achieve approximately linear output. Selected signal is recorded for each level. Then, the Equation6 is applied to linearize the system.

$$Y = a + b \times x \quad (6)$$

Where,
a represents offset,
b represents slope,
x is shifted output of the ADC,
y is the angle,

$$b = \frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2} \quad (7)$$

$$a = \frac{\sum y(\sum x^2) - \sum x \sum xy}{n(\sum x^2) - (\sum x)^2} \quad (8)$$

n is the number of data is used.

4. RESULTS AND DISCUSSIONS

Results could not have observed because the project is done in COVID-19 situation. Simulations are also not possible. So, sine and cosine waves are used instead of the output of the hall-effect sensors. Cosine and sine waves are not linear signals and that makes the results inappropriate. To get linear result, selection is made between digitalized cosine and sine signals via ADC of Arduino Uno. Also, linear regression helps to get a linear approach according to selected ADC output. Operations for the linear approach are shown step by step in pseudo code.

```
Setup:
        set thetaDesired according to stepper angle
        set error1 and error2 to 0
        set nData to 128 according to number of level
        set sumTheta, sumTheta2, sumValue, sumValue2 to 0
Loop:
        read R from ADC0 cosine signal (cos(thetaMeasured))
        read Q from ADC1 sine signal (sin(thetaMeasured))
        mapping for R and Q from (0,4096) to (0,1)
        error1 = thetaDesired - 90*mappedR
        error2 = thetaDesired - 90*mappedQ
        if error1 > error2
                value=Q
        else
                value=R
        shift Value by 7-bit (shiftedValue = value >> 7)
        mapping for value from (0,4096) to (0,1)
        //Linear Regression
        for i=1 to nData
                sumTheta += 90*mappedValue
                sumTheta2 += (90*mappedValue)^2
                sumValue += shiftedValue
                sumValue2 += shiftedValue^2
                sumThetaValue += 90*mappedValue * shiftedValue
        end of the for loop
        b = (nData * sumThetaValue - sumTheta * sumValue) / (nData * sumValue2 -
        sumValue * sumValue)
        a = (sumValue2 * sumTheta – sumValue * sumThetaValue) / (nData *
        sumValue2 – sumValue * sumValue)
```

360-degree is divided 4 quadrants. According to angle, selection is made between sine and cosine wave. Each quadrant is divided 32 intervals by using 5 most significant bit (MSB) of the selected ADC output. Oversampling and averaging is applied to ADC which means there is 12-bit resolution. So, 5 MSB is used for addressing and then 7 bits are remaining. 7 least significant bit (LSB) divides each interval which occurs 128 points. Linear regression is used to generate two LUT. Slopes and offsets are stored in LUTs which will be used to calculate the angle.

ADCout (5MSB)	Offset	Slope
00000	0.0003	0.0345
00001	4.4173	0.0344
00010	8.8236	0.0343
00011	13.2087	0.0340
00100	17.5619	0.0337
00101	21.8728	0.0333
00110	26.1311	0.0328
00111	30.3264	0.0322
01000	34.4486	0.0316
01001	38.4878	0.0308
01010	42.4343	0.0300
01011	46.2786	0.0292
01100	50.0114	0.0282
01101	53.6237	0.0272
01110	57.1069	0.0261
01111	60.4517	0.0250
10000	63.6518	-0.0250
10001	60.4519	-0.0261
10010	57.1063	-0.0272
10011	53.6232	-0.0282
10100	50.0108	-0.0292
10101	46.2780	-0.0300
10110	42.4337	-0.0308
10111	38.4872	-0.0315
11000	34.4479	-0.0322
11001	30.3257	-0.0328
11010	26.1304	-0.0333
11011	21.8722	-0.0337
11100	17.5612	-0.0340
11101	13.2080	-0.0343
11110	8.8229	-0.0344
11111	4.4166	-0.0345

Table 1: Look-up Table for Slope and Offset

5. CONCLUSIONS

Hall-effect is used in many applications. Some of the applications are proximity sensing, speed detection, current sensing, and position detection. The reason is that the system is highly reliable, wide temperature range, and handle high-speed operations. Also, they are not affected by environmental conditions, such as dust, humidity, and vibrations. There isn’t any frictional force between sensor and the rotary element. On the other hand, Hall-effect principle is related to magnetic field and it does not need any magnetic field change which means it can measure zero speed or a positions.

Encoding of the angular position is done by utilizing the hall-effect. Look-up table is a good solution to avoid unnecessary processor load but the trade-off is using reasonable amount of data in flash memory. Accuracy can be improved by several methods which are detailed under proposed solution title. ADC resolution is improved without using any external device.

At the end of the project, Look-up table is generated by using sine and cosine signals instead of hall-effect sensors’ output and known angular position of the diametrically magnetize disc. The sine and cosine signals are digitalized by ADC in Arduino Uno. Then, the nonlinear signals are linearized by made a selections and using linear regression methods.

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APPENDIX

```
clear all
clc
nInterval=32;           %number of intervals
nPointInterval=128;     %number of points in one interval
nPoint=nInterval*nPointInterval; %total points in one quadrant
a=zeros(1,nInterval);
b=zeros(1,nInterval);
%%Selection and mapping operations
for i=1:nPoint
    if i<(nPoint/2)                                      %sin selected 0-
45degree
    mappedValue(i)=sin((pi/180)*(i-1)*90/nPoint);        %radian to angle
conversion
    else                                                 %cos selected 45-
90degree
    mappedValue(i)=cos((pi/180)*(i-1)*90/nPoint);        %i normalized 0-1024
to 0-90
    end
end
%%128 steps are declared for each interval
%90-degree is divided 32 interval
for i=1:nPointInterval
    LSB7(i) =i-1;
end
%%Linear Regression is applied for each interval
%Data set is occured 128 points for each interval
for k=1:nInterval
    sumY=0;
    sumY2=0;
    sumX=0;
    sumX2=0;
    sumXY=0;
    for i=1:nPointInterval
      sumY=sumY+90*mappedValue(i+(k-1)*nPointInterval);
      sumY2=sumY2+(90*mappedValue(i+(k-
1)*nPointInterval))*(90*mappedValue(i+(k-1)*nPointInterval));
      sumX=sumX+LSB7(i);
      sumX2=sumX2+(LSB7(i)*LSB7(i));
      sumXY=sumXY+90*mappedValue(i+(k-1)*nPointInterval)*LSB7(i);
    end
    a(k)=(sumX2*sumY-sumX*sumXY) / (nPointInterval*sumX2-sumX*sumX);
    b(k)=(nPointInterval*sumXY-sumY*sumX) / (nPointInterval*sumX2-sumX*sumX);
end
```