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Design of a magnetic encoder using Hall effect

Diseño de un encoder magnético usando efecto Hall

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Abstract: We present the design of a magnetic encoder to measure angular position. The proposed encoder includes two Hall sensors in quadrature in a fixed platform. In addition, and over the sensors, there are two permanent magnets in a shaft. The relative motion between the fixed and the movable components generate a voltage variation in the sensors, which serve to generate the approximation of the angular position. We detail the acquisition process and the linearization method, because we consider that these are the most important contributions of this work. Lastly, we show the application of the encoder in the position control of a direct current motor to show the performance of the encoder estimating fast and slow angular position changes.

Keywords: Hall effect, Magnetic encoder, Position control, Position sensor.

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Resumen: En este artículo se presenta el diseño de un encoder magnético para la medición de la posición angular. El encoder está compuesto por dos sensores de efecto Hall en cuadratura en una plataforma fija. Además, sobre los sensores, y en el eje a medir se ubican dos imanes permanentes con magnetización axial. El movimiento relativo entre el componente fijo y el móvil del encoder genera una variación de voltaje en los sensores. Esta variación da lugar a la aproximación de la posición angular. Se detallan los procesos de adquisición y linealización de los datos, dado que son los aportes más importantes de esta propuesta. Para finalizar se muestra la aplicación del encoder en el control de posición angular del eje de un motor de corriente directa, con lo que se muestra el trabajo del encoder ante cambios lentos y rápidos de posición.

Palabras clave: Efecto Hall, Encoder magnético, Control de posición, Sensor de posición.

1. Introduction

Currently, and in order to improve the industrial processes, the physical phenomena related with magnetism are studied to design current sensors [1], magnetic field sensors [2], or position sensors [3-5]. An important goal of these studies consists in improving characteristics of the sensors such as precision, resolution and sensitivity. In any case, the operating principle of the sensors uses the changes in magnetic field thanks to the Hall's effect, as shown in [6-7], or the magnetoresistive effect, in [8]. In addition, looking for improvements in the quality of the

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sensors, many methods and algorithms have been studied to compensate the errors. In particular, the position measurement must focus on aspects such as 1) geometric orientation, for instance in [9], 2) polarity and magnet materials, in [10-11], and 3) the position of the sensor itself, in [12]. Once the measurements using the sensor are obtained, the output of the sensor should be linearized. This linearization process could be made using Artificial Neural Networks, for instances in [9] and [13], running polinomial approximations, in [14], or using other methods, such as the one described in [15].

There are many fields in the industry that require the measurement of angular position, for instance robotics, biomedicine, commuting, defense, among many others. The amount of possible applications makes relevant any improvement in the current technology to make measurements, such as the proposals in [16-17]. Current studies include the design and construction of encoders, which in addition to improve performance, precision, sensitivity, resolution and response time, should handle extreme weather conditions without losing the quality of the estimations, as presented in [18].

Among the conventional methods to measure angular position, the incremental encoder is the most popular. Therefore, this type of encoder has been studied for decades, which becomes in one of its main advantages. However, the incremental encoder may present errors due to vibrations and pollution. This sensor presents faults when used in places with gases or small remains of any material. Likewise, another problem with the incremental encoder is that it may occupy a large area for industrial applications. A final negative characteristic of these sensors

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is the fact that their output is relative to the initial measurement, and not absolute, given that their main component is a slotted disk.

In contrast to the incremental encoders, the magnetic encoders provide absolute measurement and they are contactless, which guarantee high performance in many environmental conditions. Thus, this paper focuses of the invention of a magnetic and absolute encoder.

The rest of the paper follows the next structure. Section 2 explains how a magnetic encoder works. Section 3 shows its construction. Section 4 details de acquisition and the signal processing. Section 5 presents the application of the built sensor to control the angular position of a motor. Finally, Section 6 reports conclusions and future work.

2. Principle of the Sensor Operation

The device presented in this paper estimates the angular position based on the variations in the magnetic field resulting from the motion of two magnets with respect to a fix position. The resulted field is measured by two Hall effect sensors located in quadrature. Thus, the voltage in the sensors generate a sine wave signal according to the angle of the shaft to be measured. In general, the output voltage of the sensor follows next expressions: $v_x = Acos(\theta)$ and $v_y = Bsin(\theta)$, where θ is the angle of rotation in radians, and A and B are the amplitudes of the signals, whereas v_x and v_y are the voltages in each sensor, respectively. Therefore, the approximations coming from the sensor are absolute in one turn, because each point in one revolution has its corresponding duple $\langle v_x, v_y \rangle$. Figure 1 presents the configuration of the magnets, denotated as N and S given their magnetic polarity North and South. The figure also shows the location of the Hall effect sensors.

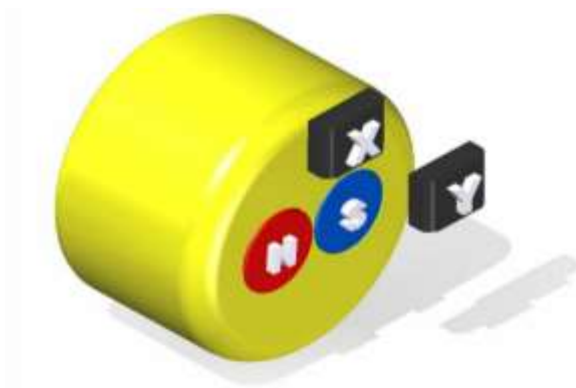

Figure 1. Two Hall effect sensors in quadrature and a couple of magnets. Source: own.

Given the configuration in Figure 1 and the outputs of the sensors, the angular position is obtained following the computation in Equation 1.

$$\theta = tan^{-1}\left(\frac{v_y}{v_x}\right) \quad (1)$$

3. Sensor Construction

An experimental procedure allows authors to select the magnet for the application, it is a neodymium NdFeB. These magnets have high concentrations of magnetic field and their surfaces are smooth. The best distance between magnets and sensors was defined also experimentally and it is equal to 10 mm. This distance produces variations in the voltage of the

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sensor with enough variation to get the best resolution out of the analog digital converter, as it is detailed later.

The sensor to measure the variations in the magnetic field is the DRV-5053 of Texas Instruments, which provides a rank of source voltage between 2.5 V and 38 V. On the other hand, the sensor has thermal stability between -40° -125° C, which is ideal for the application reported in this paper. The sensitivity of the sensor is +45 mV/mT, ±10%, according to the temperature, which is enough for most of the industrial applications without losing precision. However, if the temperature is a concern, it is important to check recommendations in [18]. That paper proposes a method to decrease the error caused by the changes in the ambient temperature.

The validation of the data coming from the sensor uses a protractor as the reference of measurements. In addition, the output of the sensor is compared with a goniometer. The protractor differentiates measurements every 1°, as shown in Figure 2.

Figure 2. Protractor and needle indicator. Source: own.

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The needle indicates an angle to the user, as shown in Figure 2, which permits running comparisons between the indication given by the protractor and the output of the sensor. The pointer has a needle at the end and a 3D prototyped piece to get attached to the shaft. The needle shape is especially important to calibrate the sensor. Figure 3 shows the final prototype of the sensor.

Figure 3. Absolute and angular position measurement prototype. Source: own.

4. Data Acquisition and Signal Processing

The data acquisition starts by the reading of voltage coming from the sensor using a Data Acquisition Card, the PCI-6024E. That card has 12 bits of resolution and processes data at 200 kS/s with adjustable input rank equal to ±10 V, ±5 V, ±1 V, and ±0.5 V.

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The first process that was made to the signal coming from the sensor consists in passing the signal through a first and low-pass filter. This sensor, in addition to filtering, should present a good approximation of the output sensor since the first measurement, instead of been initialized as zero as it is traditionally made using transfer functions. This requirement makes us to use the block diagram in Figure 4 and not the traditional transfer function block. The configuration in Figure 4 sets the initial condition of the integral equal to the initial input. Thus, avoiding fluctuations around the true measurement which may cause instabilities for the application of the sensor in control. The first gain in Figure 4 corresponds to the inverse of the constant time of the sensor, it is 1 ms. This constant time guarantees the noise cancelation and the normal operation of the sensor.

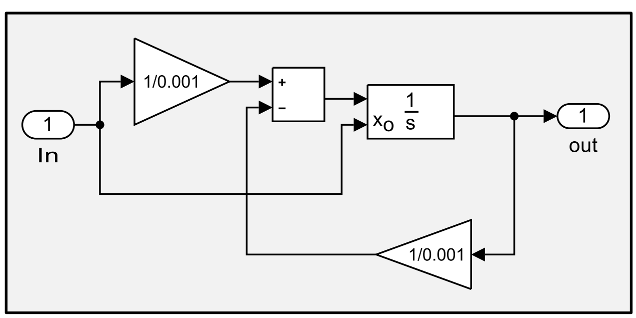

Figure 4. Low-pass filter to reduce the noise effect. Source: own.

On the other hand, once the filtering of the signal is done, the signals X and Y are normalized. The normalization eliminates any DC component and changes the amplitude of the signals to make them equal to 1. This is done subtracting the mean value, and then multiplying by the inverse of the maximum value. Figure 5 shows the result of the normalization, where the sinusoidal nature of the signals become evident.

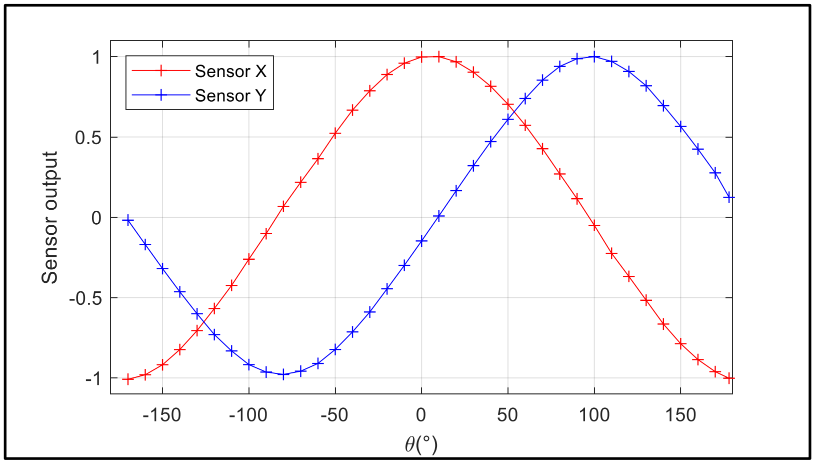

Figure 5. Sensor output including offset and amplitude adjustment. Source: own.

The signals in Figure 5 are the inputs of the expression in Equation 1, which provides the estimation of the angle in radians. Then, the signal processing changes radians into degrees. That signal in degrees enters a Neural Network to make the output of the sensor linear. However, and before entering the Network, the signal is normalized once more, dividing by 100. This normalization makes the whole variation of the sensor to get values close to 1, which is in general a recommendation to train Neural Networks.

The Neural Network to linearize the measurement is indispensable given that the estimations of the sensor in Figure 5 may have errors even higher that 5°. One of the reasons for such a big error is the difficulty in locating sensors and magnets exactly in quadrature. The design of the sensor started by running a polynomial linearization, but the error with the Neural Network

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was lower. In particular, the Neural Network is a Multilayer Perceptron, in this case with one hidden layer. The Network uses “tansig” transfer functions for the input and hidden layers, while the transfer function of the output layer is linear.

The selection of the best Neural Network was carried by an experimental process. We tested combinations from 2 to 16 neurons in the input layer and from 4 to 64 neurons in the hidden layer. In order to reduce the number of possible combinations we tested only inputs that match 2 to the power n, where n is a natural number. In other words, 2, 4, 8, 16 for the first layer, and 4, 8, 16, 32 and 64 for the second layer. The performance of the Network improves as the number of neurons grows, but a high number of inputs also requires high computation time during the running of the Network. Therefore, the number of neurons for the inputs was set to 8, and 4 for the hidden layer.

It is necessary to amplify the output of the Network 100 times, because the input was normalized dividing by 100. Thus, the output of the controllers covers the rank ±180°. We added an algorithm to extend the measurement rank to any number of turns. This algorithm observes the jumps that happened from -180° to 180° or vice versa, and properly subtracts or adds 360° to the estimation. Thus, the output of the sensor is smooth regardless the number of turns. The application of this algorithm does not mean that the sensor is absolute to any number of turns. It continues starting in an angle inside the rank ±180°.

Figure 6 presents a block diagram of the sensor, including the signal processing already mentioned. It includes the noise reduction, the normalization, the angle computation, the unit conversion, the normalization, the linearization, the re-scaling and finally the jump-avoidance algorithm.

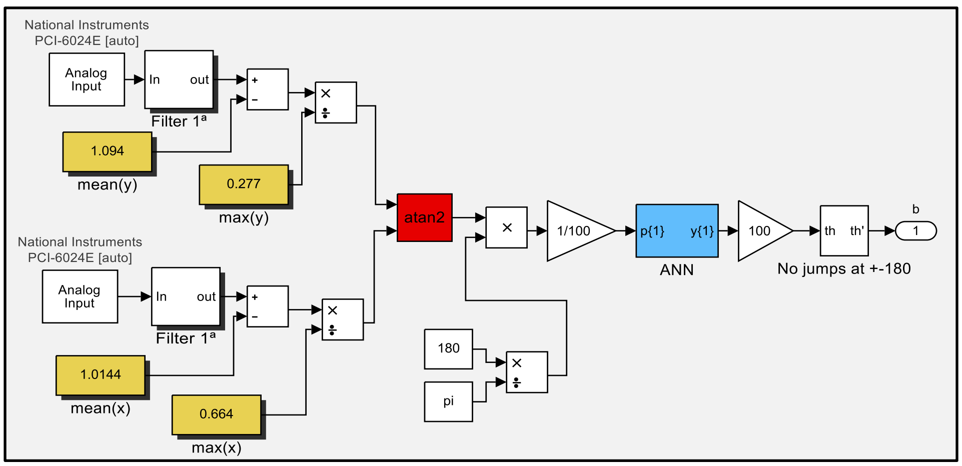

Figure 6. Block diagram for the signal processing of the sensor. Source: own.

As a result of the prototype construction we measured the error behavior of the sensor, as shown in Figure 7. The training stage for the Neural Network uses the mean squared error as a measure of performance. Figure 7 presents the results for the training of 200 Neural Networks. The error of the best among the Networks is shown in the upper part of the same figure.

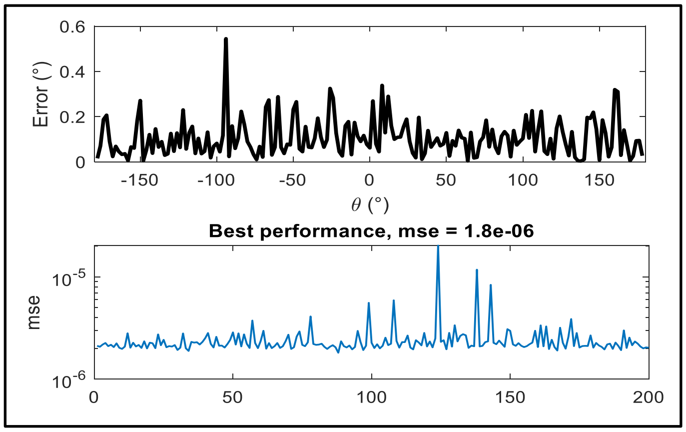

Figure 7. Neural Network performance, 8 neurons in the first layer and 4 in the second layer.

Source: own.

5. Application of the Encoder to Control the Position of a Motor

The validation of the sensor uses an experiment in which a controller leads the angular position of a shaft. This is a traditional application for encoders. The experiment serves to verify that the sensor properly measures a dynamic rotation of a shaft and not just that the sensor provides a stationary measurement as was already shown.

Consider a traditional PID controller with gains Proportional, Integral, and Derivative with respect to the error. In this controller the proportional action serves to control plants that are already stable, but this type of controller may generate big steady-state errors. On the other hand, the integral action (I) produces an output of the controller proportional to the accumulated error. This type of controller eliminates the steady-state error but makes the system slower. Lastly, the derivative action (D) predicts the behavior of the error, which make the control action faster. A disadvantage of the derivative component regards the amplification of the noise, which could make the system unstable. The union of the three actions (P+I+D) generates a better control action than the individual possibilities. This combination is stable, eliminates the steady-state error and it is faster than the PI option. The final version of the controller is shown in Figure 8 according to its implementation in Simulink.

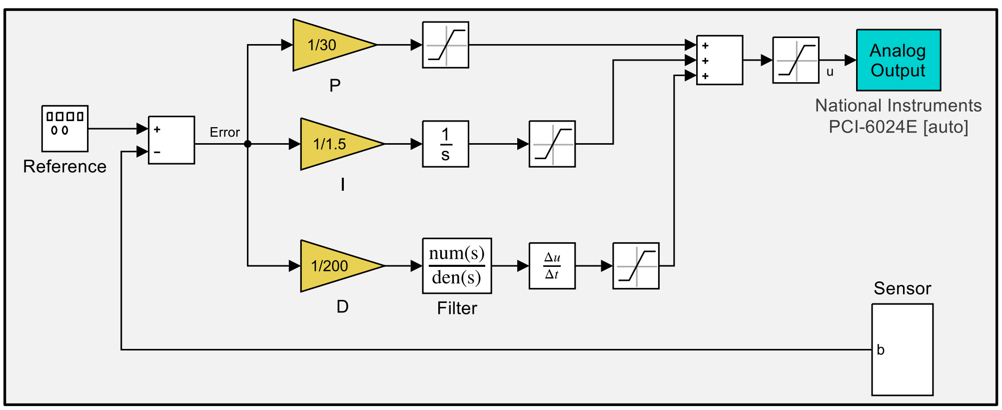

Figure 8. PID controller to regulate the position of a DC motor. Source: own.

The PID algorithm that was implemented works in the same way as the controller reported in [17], but this time the nominal current is 500 mA. That value of current requires the implementation of a power amplifier, this amplifier keeps the actuating signal, u, according to the definition in Figure 8, and amplifies the current to the value required by the motor. The power amplifier allows changes in the sign of the actuating signal, which result in the control of the rotation in both senses: clock wise and counter-clock wise. The amplifier is shown in Figure

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9. This power amplifier was build using LM386 operational amplifiers, because these amplifiers use dual sources, which facilitates the connections of the circuit.

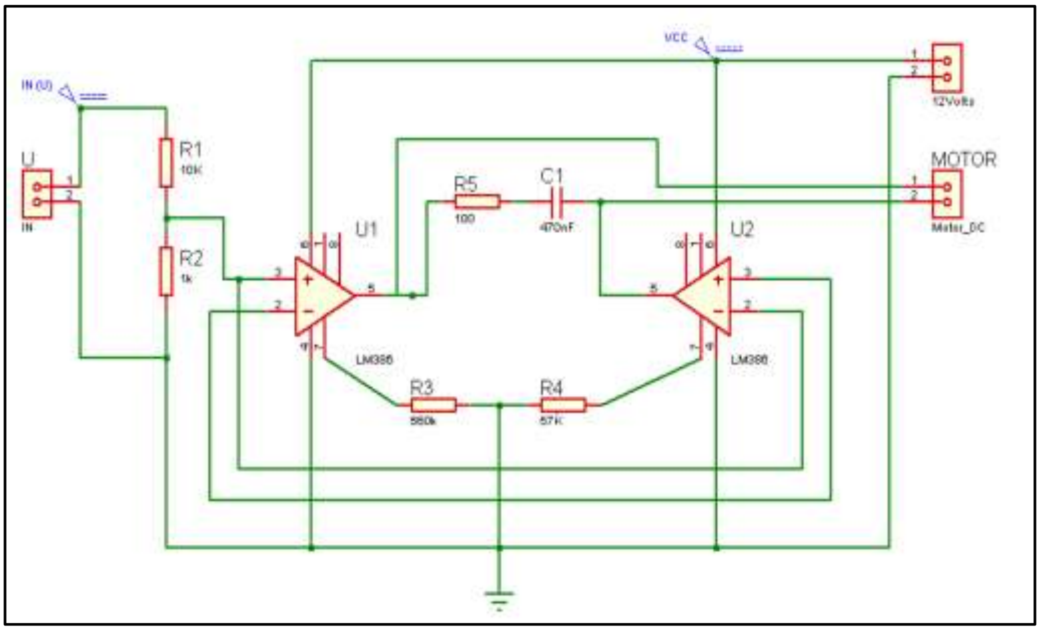

Figure 9. Power amplifier in bridge configuration. Source: own.

The reported application requires that the motor tracks a reference signal, r, using the information coming from the designed encoder as the feedback signal. The motor properly tracks the reference signal as shown in Figure 10. However, the behavior between 2.5 and 3 s requires more attention. The controller does not have enough time to set the position of the shaft in that section and it falls under the reference. The main reason for this behavior is the dead zone. This nonlinearity makes that the motor only overcomes inertia and friction after a threshold, when the integral of the controller accumulates enough error to move the motor. The effect of the dead zone makes the control of this motor a hard problem, it is a consequence of the building of the motor and not of the building encoder.

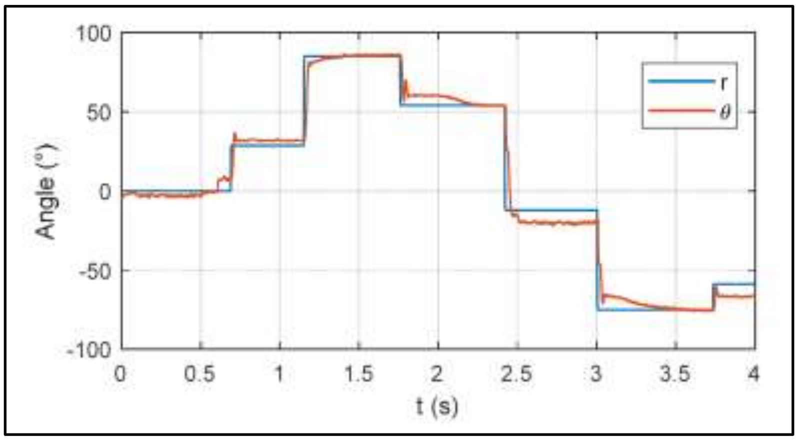

Figure 10. Position control of a motor. Source: own.

6. Conclusions

In this paper, we presented the building of an absolute magnetic encoder, which required two permanent magnets in quadrature with axial magnetization. The maximum error does not pass 0.5° during the whole measurement rank, which equals one turn. It was possible to demonstrate the utility of the designed measurement method with low cost and simple to build. The sensor was tested during the tracking of a reference signal corresponding to the angular rotation of the shaft of a DC motor.

The search of better precision, and improvements in sensibility and resolution should include the study of other methods to locate the sensor, as well as other magnetization schemes, and improvements in the signal conditioning. In addition, it is also important to increase the speed of the data acquisition and the time response of the encoder. It could be interesting to work with other configuration of sensors, different than quadrature.

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