FIRAT UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
TÜRKİYE

IMPLEMENTATION OF QUALITY CONTROL SYSTEM USING MAGNETIC IMAGE SENSOR

Ahmed Saeed MOHAMMED

Master's Thesis

DEPARTMENT OF COMPUTER ENGINEERING
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THESIS APPROVAL

This thesis, which was prepared according to the thesis writing rules of the Graduate School of Natural and Applied Sciences, Fırat University, was evaluated by the committee members who have signed the following signatures and was unanimously approved after the defense exam made open to the academic audience.

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DECLARATION

I hereby declare that I wrote this Master's Thesis titled “Implementation of Quality Control System Using Magnetic Image Sensor” in consistent with the thesis writing guide of the Graduate School of Natural and Applied Sciences, Firat University. I also declare that all information in it is correct, that I acted according to scientific ethics in producing and presenting the findings, cited all the references I used, express all institutions or organizations or persons who supported the thesis financially. I have never used the data and information I provide here in order to get a degree in any way.

02 July 2021

Ahmed Saeed MOHAMMED

PREFACE

Showing magnetic field as an object put into a two-dimensional image will make that important especially with low cost, power and easy to use, unlike some costly sensors even though sensor is not very accurate but it gives good results and could be used for getting and measuring magnetic data in real time. All this done by using a set of unexpansive magnetic sensors combined together.

Ahmed Saeed MOHAMMED
ELAZIG, 2021

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ABSTRACT

Implementation of Quality Control System Using Magnetic Image Sensor

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This research depicts an overview and special technique for the recognition, detection and measuring the quality of magnetic on materials. It is based on the Hall Effect principle of and signal converter. The board is small but it gives good results in addition to ease of use, less cost and low power. The magnetic field emitted from the material to be checked is converted to a visual spectrum. This means that magnetic fields can now be seen in real-time, the magnetic sensors used on the tile are some of the most highly sensitive.

Hall effect sensors and the matrix layout were simulated in the MATLAB Simulink and the results were put in the thesis.

Visualizing things that are very difficult to normally seen. Because there is so much around that just cannot easily perceive, and how much more interesting bits of science we would be able to get done if only could easily see them as naturally as seeing things like color. Magnetic field detection in an object into a two-dimensional image will make that cool and very interesting especially with low cost, power and easy to use, unlike some costly sensors.

In the thesis, the results of the matrix array of sensors are obtained then the performance is discussed.

Keywords: Sensor, Magnetic Field, Hall Effect, Magnetic Imaging, Quality Control System.

ÖZET

Manyetik Görüntü Sensörü Kullanılarak Kalite Kontrol Sisteminin Uygulanması

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Bu çalışma, malzemeler üzerindeki manyetik kaliteyi tanımak, saptamak ve ölçmek için genel bir bakış ve özel bir teknik tasvir etmektedir. Çalışma Hall etkisi prensibine dayanmaktadır. Çalışmadaki kart küçüktür fakat kullanım kolaylığı, daha az maliyet ve düşük güç ile iyi sonuçlar vermektedir. İncelenecek olan materyalden yayılan manyetik alan bir görsel spektruma dönüştürülür. Bu da manyetik alanların artık gerçek zamanlı olarak görülebileceği anlamına gelmektedir ve karo üzerinde kullanılan manyetik sensörler en yüksek hassasiyete sahip olan sensörlerdendir.

Hall etkili sensörlerin ve bunların matris yerleşımin içeren yapının MATLAB Simulink ortamında sımulaıyony yapılmış ve sonuçlar tezde sunulmuştur.

Normalde görülmesi çok zor olan şeyleri görselleştirmek de zordur. Çünkü çevrede kolayca algılanamayacak kadar çok şey vardır ve onları renkler gibi doğal olarak görebilirsek, bilimin daha ne kadar ilginç bulgular çıkaracağı bilinmemektedir. İki boyutlu bir görüntüde bir nesnenin manyetik alanın tespiti, bazı pahalı sensörlerin aksine, bunu özellikle düşük maliyetli, güçlü ve kullanımı kolay olan, faydalı ve ilginç bir uygulama haline getirecektir.

Tezde bu matris dizilimli sensörün ölsün sonuçları verilmiş performanın tarlışilmıştır.

Anahtar Kelimeler: Sensör, Manyetik Ala, Hall Effect, Manyetik Görüntüleme. kalite kontrol sistemi.

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SYMBOLS AND ABBREVIATIONS

Symbols

B	: Flux Density
B	: Magnetic Field that has been created by Magnet or Current-carrying conductor
d_H	: Thickness of the Hall plate
E	: Electric field
F_{hall}	: Output Hall Voltage B
F_L	: Entire electromagnetic force (Lorentz force)
GND	: Ground pin
H	: Magnetic Field Strength
I	: Current
k_H	: Sensitivity of the Hall generator
q	: Particle's electric charge
R	: Distance from the center of the current conductor
R_H	: Hall coefficient
V	: Voltage
Vcc	: Positive voltage (usually 5 volts)
Vdd	: Voltage applied to the Drain of the transistors
V_H	: Hall Voltage
Vout	: Output voltage
μ0	: Permeability of free space

Abbreviations

ADC	: Analog to Digital Conversion
AMR	: Anisotropic Magneto Resistors
CW	: Continuous Wave
DC:	: Direct Current
GMI	: Giant Magneto Impedance
GPS	: Global Positioning System
GSM	: Global System for Mobile Communications
HTS	: High-Temperature Superconductors
IC	: Integrated Circuit
MAD	: Magnetic-anomaly Detection
MEMS	: Micro Electro Mechanical Systems
MO	: Magneto Optical Sensor
P	: Polarity
SDT	: Spin-Dependent Tunneling
SOI	: Silicon On Insulator
SQUID	: Superconducting Quantum Interference Device
UXO	: Unexploded Ordnance

1. INTRODUCTION

The magnetic characteristics of materials will give various information to other material characteristics because of ferromagnetism's nature. as an example, the measurements of magnetic-hysteresis parameters space that are affected by the microstructure of the material and by residual or applied stresses. Recently, hard work has shown that magnetic hysteresis and also Barkhausen effect may be used to test the state of the materials by using various non-destructive appliances [1].

The capacity to measure and image magnetic fields allows for the evaluation of the magnet's performance, allowing for quality control of a permanent magnet, magnetic assembly, or piece of equipment that uses magnets. Much of the technical information on magnetic fields that is routinely published and taught at the university level refers to magnetic fields produced by electromagnets or active coil products. Electromagnet coils and units are more closely related to electrical engineering units than permanent magnets. Permanent magnets have a fundamentally different nature than active coils in terms of creating a net external magnetic field [2].

Normal magnetic influx leakage signal should be processed in every channel in the array data of the magnetic, which increased the complexity of the processing system. This study will introduce a processing system for a magnetic image, these processes may include some image processing, signal processing operations and field colorizing [3].

Here are several literature surveys that have been studied early:

When a current-carrying conductor is held in a magnetic field, the field gives some power to the charge streaming on the conductor in a lateral way. The presence of a magnetic field initiates all Hall Effect machines. Polarity and flux density are two of the most important aspects of a magnetic field. Many Hall Effect sensor digital switches are designed to shut down if there is no magnetic field present (open circuit at the output). The switch will be engaged if it is simply exposed to a magnetic field with sufficient density and direction [4], [5].

A two-dimensional hall sensor array can calculate the orientation of a magnet matrix by filtering harmonic elements. For filtering out an arbitrary amount of harmonic signals, a 1D sensor array is suggested, which is then expanded to a 2D sensor array for magnet matrix location calculation. A 2D hall sensor array screening both fundamental and 2nd harmonic components of the magnetic flux, as well as its conditioning circuit board, is installed to compute the location of the magnet matrix for a planar motor. Finally, an XY linear motion stage is utilized to measure the location of the magnet matrix and test the efficacy of filtering harmonics. The suggested 2D hall sensor array is a work in progress [6].

A Mobile Hall Sensor Array is used to determine the shape of ferromagnetic materials buried in walls or the ground. The Magnetic Flux Leakage Theory is used to describe the form of the ferromagnetic material in the Mobile Hall Sensor Array device. Magnetic flux is generated by two permanent magnets. When a ferromagnetic material is moved closer to permanent magnets, the magnetic flux distribution is disturbed, and the changes in the magnetic flux distribution are detected by the 1-D array of the Hall sensor array arrangement. A signal processing device conducts magnetic imaging of the magnetic flux distribution prior to displaying the real-time artifacts on a netbook. A signal processing application software is being created to gather and analyze 1-D Hall sensor array data in order to construct a 2-D array matrix. The magnetic representation of ferromagnetic material is generated utilizing the voltage signal and magnetic flux distribution of the processed 1-D Hall sensor array data. The findings demonstrate how magnetic representations derived from the specimen's voltage signal and magnetic flux distribution may be used to determine the form of square, circular, and triangle-shaped specimens. Magnetic images of actual ferromagnetic objects are often used to demonstrate the form identification capabilities of the Mobile Hall Sensor Array system. The results demonstrate that the Mobile Hall Sensor Array device is capable of performing magnetic imaging in order to differentiate between various ferromagnetic materials [7].

Another study was done for the permanent magnet force. Regulation of completely automated apparatus, data collection and analysis, computational integration according to permanent magnet models, visualization of performance, simulation of dynamic outcomes, swift simulations using cluster are the main use is the study. The calculation of a magnetic field with high precision was made possible by a fully automatic apparatus. Models of magnets focused on computational integration is remarkably accurate as compared to the experiment. Parametric diagrams were used to visualize the determined and measured magnetic field, although other more descriptive approaches such as flux density vectors or lines were also used. [8].

Another method is used for detecting both the electric and magnetic fields using a single sensor. The proposed methodology is simple and allows the frequency range of sensors used to monitor electric and magnetic fields in the same space location to be extended below 100 kHz. When the magnetic antenna's shield is used as an electric field monitor, both the E and H components of the electromagnetic field can be calculated with a single unit (shielded magnetic antenna). The authors' approach is easier and less expensive than the approaches currently used for concurrently calculating E and H, but it is less precise. In general, high-frequency E and H measurements are conducted with a single sensor, but This type of sensor (sensor for E and H at the same point in space) can be expanded to frequencies below 100 Wz using the techniques proposed. No one has mentioned such a solution in the literature as far as we know, and the sensor (instrument) we create can be used to monitor electric and magnetic interference fields [9].

A harmonic expansion is used to describe the representation of a two-dimensional magnetic field in a current-free area. For cylindrical components, the expansion is derived and then applied to Cartesian components. A dynamic field is often used to classify the Cartesian elements. The expansion coefficients are transformed according to the rules for different forms of coordinate transformations. The vector and complex potentials are used to investigate the association between a given current distribution and the corresponding field harmonics [10].

Magnetic materials' biomedical uses are a hot subject of today's research. Design and construction of suitable instrumentation receive special consideration. A magnetic device made up of an equidistant series of commercial permanent magnets (6 × 4 assay) was suggested, planned, and tested for future use in cell cultivation experiments. By using a gauss-meter, the magnetic field distribution was determined in three axes: OX, OY, and OZ. The data are evaluated statistically. Near the middle of the XY plane, the magnetic field was generally homogeneous, but at the margins, a strong magnetic field gradient was found. The magnetic field intensity was found to decrease as the Z gap was increased. Since the obtained parameters of a constructed device are satisfactory, it can be suggested for cell cultivation experiments that include the application of an external magnetic field [11].

A real-time magnetic imaging device was designed utilizing an array of magnetic sensors to detect magnetic objects by arranging the magnetic sensor array, which consists of 16 HMC5883L sensors in a 44 arrangement in the scanning field with a 6 cm gap among the sensors. The bicubic interpolation method was used to reconstruct magnetic field representations from magnetic particles. This imaging method was used for a variety of applications, including one-object experiments, multiple-object experiments, and the magnetic object experiment in various positions. Magnetic objects such as miniature staples, big staples, paper clips, nuts, and nails were used in the experiment. The findings of the experiment demonstrate that the device is capable of detecting the magnetic field of a magnetic source and generating an image from it. This device can also sense variations in the magnetic object's location, whether it's near to the sensor or far away [12].

As a conclusion of the previous studies, we found that all of them depended on the principle of working with the hall sensor and how it deals with the magnetic field in terms of intensity and intensity, although each one of them used a special sensor that he used either to measure the magnetic field or to show its image significantly by the human eye. Some of them used a single sensor, and some of them used a group of sensors as an array (as is the case with our study). As for the data analysis, it was done by reading the data released through the sensor or showing it in the form of a chart or data. In the case of our sensor, we used DRV5053 Analog-Bipolar Hall Effect sensor to display the field in the form of a two-dimensional matrix and show the measurements and analyze them. All this using an inexpensive sensor integrated on the board with a circuit and displaying the data on the PC.

There are are some issues that we had in the research, the board that we used in the research is small board with very tight-pitched components is a bit challenging to assemble (in case of the hall sensor). Also, Magnetic properties that has been applied should be relatively strong. Another problem is that the object has to be close to the board to get best result. At last, it's not very accurate because of low image resolution.

Using a simple and cheap device for quality control implementation and visualizing the magnetic field with showing its measurement in real-time is very important and useful today especially with the industry nowadays.

As human beings, it is easier for us to understand what appears to be a visual image than to be translated in codes or numbers, so the basic feasibility of this work is to convert the magnetic field into optical colors on a screen that can be seen clearly using some simple tools like a special sensor and analog to digital converter.

2. MAGNETIC SENSORS AND THEIR TECHNOLOGIES

Various types of sensors are used for measuring the magnetic field and using this data to directly or indirectly measure various parameters. At present, technological changes, in particular the mixing of technologies in compasses or new technologies of magnetic field sensors, are dictated by new needs and are being developed thanks to consumer electronics.

Magnetic field sensors are used to detect the speed of movement or rotation of different objects, as well as their location and angle of rotation. The sensors operate on the basis of a proportionate change in the output voltage or resistance of the sensor caused by an external magnetic field. Before discussing magnetic fields and sensors, it is necessary to understand the concept of proportional change [13], it’s necessary to talk a briefly about magnet and how the field surrounded by it.

2.1. Magnet Types and Applications

Magnets are available in a variety range of shapes and sizes, including discs, spheres, horseshoes, and other unusual shapes. Larger magnets are usually stronger. Different materials may be used to strengthen the power of small magnets. The magnet's form. The shape of each magnet has an impact on how it is used. It defines how the magnetic field lines outside of the magnet are arranged as well as the magnet's pull power [14].

2.1.1. Magnet

To put it simply, a magnet is a body that can attract iron. Or: a magnet is an object made of a specific material that creates a magnetic field, Figure 2.1 shows a sample of natural magnet.

Figure 2.1. Natural magnet with the property of attraction.

Millions of molecules are clustered together to form magnets, which are referred to as fields. Each domain has a north and south pole, similar to a mineral magnet. The power of the domains is combined because they have the same directionality, resulting in a greater magnet. There is at least one north (N) and one south (S) pole of each magnet [15].

2.1.2. Types of Magnet

As seen in Figure 2.2, there are three major groups of magnets which they are [16]:

- Permanent magnets: also called magnetic ores, when ores containing iron or iron oxides are cooled and magnetized by earth magnetism, a type of ore is created. And when there is no electric current, permanent magnets have a magnetic effect and their energies are still directed in one direction. Once magnetized, permanent magnets never lose their magnetism and maintain it.
- Temporary magnets: They are permanent magnets that align when placed in a strong magnetic field but lose their magnetic properties when the field is removed.
- Electromagnets: they are made up of a metal core and an induction coil that conducts an electric current.

Figure 2.2. Some types of magnets.

2.2. Magnetic Field

The magnetic field is the area that surrounding the magnet where external items are magnetically affected. While human sense organs are unable to perceive the magnetic field, assistive devices demonstrate that it occurs [17].

A magnetic force surrounds our planet. This has always been the case, at least since the dawn of earth. And all on Earth, including humans, creatures, and plants, is subject to the field's invisible lines of power. The human body, on the other hand, has its own magnetic field, which is caused by the influx of blood into the vessels. It will vary depending on the organ [18].

2.3. Overview about Magnetic Sensors

The magnetic sensor is the generic name given to sensors that detect the magnetic changes in the environment and generate signals. Magnetic sensors are also called “Field-Effect Sensors”. Magnetic sensors are composed of two types of materials: inductive and semiconductor material. Various types of sensors are used for measuring the magnetic field and using this data to directly or indirectly measure various parameters. At present, technological changes, in particular the mixing of technologies in compasses or new technologies of magnetic field sensors, are dictated by new needs and are being developed thanks to consumer electronics [19].

Magnetic sensors are used for contactless determination of the position of objects, even with a high switching frequency. They can detect magnets through the walls of materials such as non-ferrous metals, stainless steel, aluminum, plastic, or wood.

Magnetic sensors have existed for quite some time. The first sensor was a primitive compass that sensed the earth's magnetic field for navigational purposes using a lodestone, a magnetic rock. It is unknown when this practice began, although there are references to it dating back to the 12th century. Magnetic sensors have improved in sensitivity and sophistication since then. Hall effect sensors, induction coils, flux gates, magnetic force microscope tips, magneto-resistive sensors, and SQUIDs are some of today's magnetic sensors (superconducting quantum interference devices). Figure 2.3 shows a table of these sensors sensitivities [20].

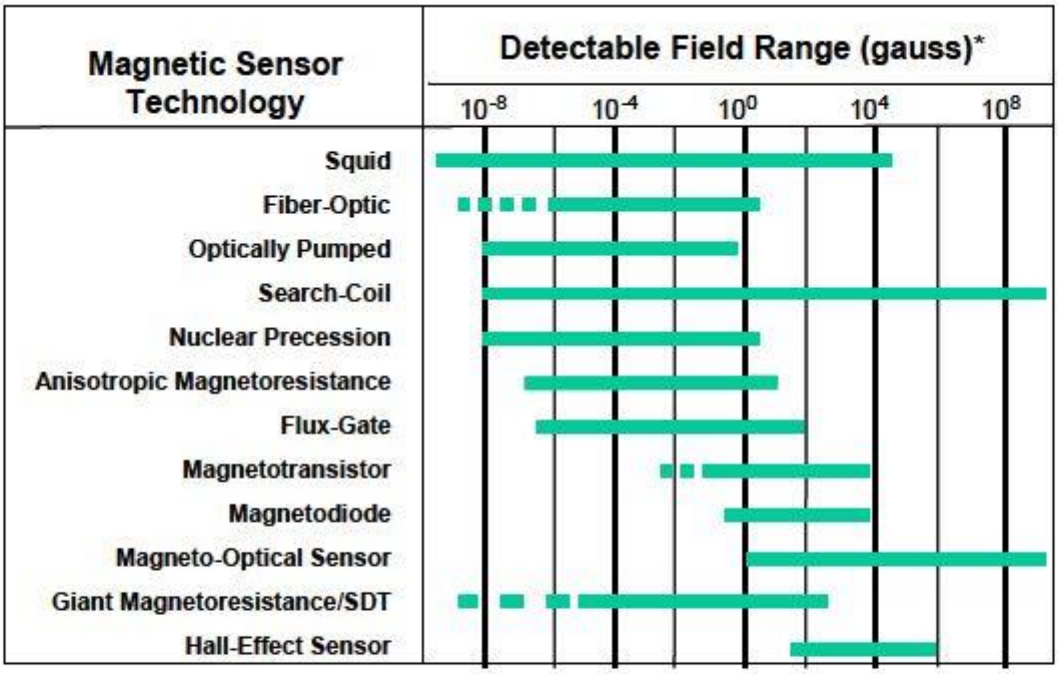

Figure 2.3. Popular magnetic sensor sensitivity. The solid lines reflect actual results, while the dashed lines represent expected performance[1]

For magnetic current imaging of integrated circuits, only SQUIDs and magneto-resistive systems are currently possible. The sensitivity and resolution of these sensors are the only differences. In a typical IC failure, currents are frequently less than 1 mA, and the sensor is isolated from the sample by more than 150 m. The sensitivity of the magnetic sensor has an effect on its ability to image weak currents at such a distance. Magnetic sensors with the highest sensitivity are SQUIDs.

They could be programmed to compute fields as low as 1 femtotesla (10-15 tesla), 40 billion times smaller than the Earth's magnetic field. SQUIDs' electronic fault isolation is typically built with a sensitivity of about 20 picotesla (10-12 tesla). Under normal operating conditions, this enables imaging of 500 nA of current at a distance of 400 m. The superior magneto-resistive sensors are less sensitive by 2-5 orders of magnitude, but they're easier to scale down to achieve resolution of less than 300 nm [21].

Everyone one these many types of sensors used for special work, and classified into many types. Figure 2.4 shows shortly those common types of magnetometers [22]:

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[1] Last updated by NVE 2004.

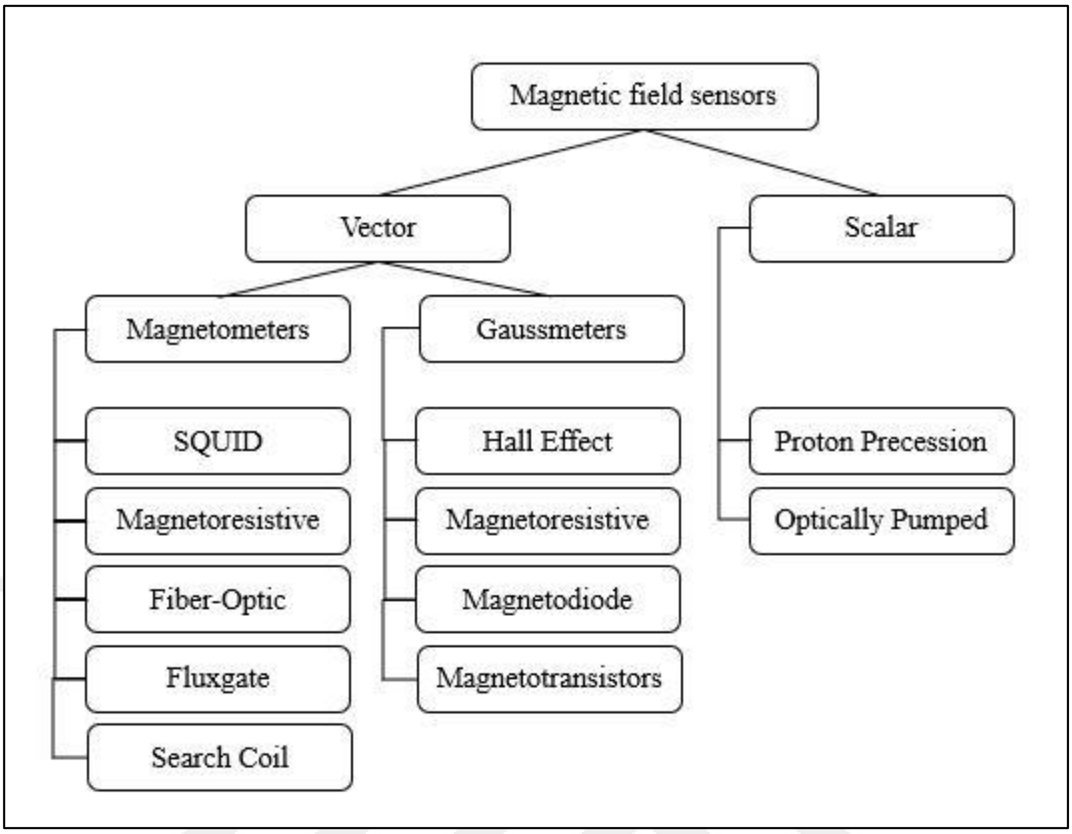


Figure 2.4. Types of Magnetometers

Magnetic inductive sensors are designed for contactless detection of the position of objects. Magnetic position sensors function without mechanical wear and have an advantage over inductive contactless sensors, since with the same dimensions they have a greater response distance. In addition, magnetic sensors can detect magnets through walls made of aluminum, wood, plastic, stainless steel or non-ferrous metals. The main types of magnetic sensors (magnetometers) are Vector Magnetometer and Total field (scale) Magnetometer [23].

2.3.1. Vector Magnetometer

Most vector sensors affected by some problems, commonly a lot of vector magnetometers devices have noise, especially the noise 1/f. Decreasing noise effects based on a device operating at the MEMS flux concentrator that extends the operating frequency above the dominant noise range. Another important problem in the vector magnetometers mentioned above is that the effect of the rotational vibration on them.

Search-Coil Magnetometer

Faraday's law induction is the base of the search-coil magnetometer. The voltage is equal to the rate of flux switch between the conductors as the magnetic flux passes through the coiled conductor. As the flux changes from the coil, the flux changes from the pulley, the lap rotates in a consistent area, or the coil passes through an irregular magnetic field in a magnetic field that changes over time, the lap rotates in a uniform area, or the coil passes through an irregular magnetic field in a magnetic field that changes over time.

Fluxgate Magnetometer

The sensor of the fluxgate magnetometer is a core (iron core) made of a high permeability magnetic material wound with opposite primary and secondary coils. Measuring instrument that measures magnitude of magnetic flux and its change. A method using a magnetic flux meter based on the principle similar to the gully coil and oscillation galvanometer or galvanometer has been used. Recently, due to the changing of the magnetic flux passing through the caller coil, the voltage generated in the coil is integrated by an integrator consisting of a capacitor, a resistor and a measuring amplifier, and the output voltage is displayed in an analog display or an analog-to-digital converter, voltage-frequency A magnetometer for digital display using a converter is often used. In addition to this, there is a flux-meter which displays a voltage generated by a magnetic flux change with a voltmeter, Figure 2.5 shows the illustration of Fluxgate.

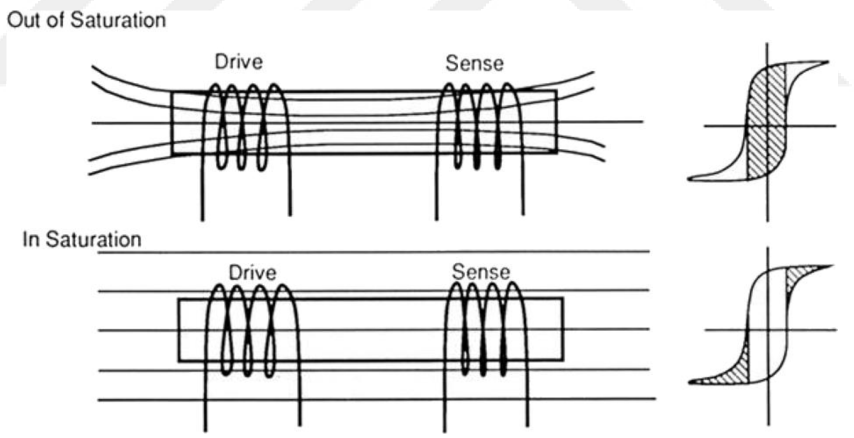


Figure 2.5. The operating principles of fluxgate magnetometers

Superconductor Magnetometers (SQUID)

It is an abbreviation for Interference Device (SQUID) and is a superconducting magnetic sensor with extremely high sensitivity. It the highly sensitive device for measuring the magnetic field at low frequencies (less than 1 Hz) as shown Figure 2.6.

Since SQUID can measure extremely weak magnetic field which could not be measured with conventional sensors, it is expected to be applied in a wide scope of applications like application of geophysical applications and material evaluation. In medical applications, magnetoencephalography that measure minute magnetic signals generated from nerve cells of the brain, and magnetocardiography that can measure magnetic signals generated from the heart of the fetus of the womb are being put to practical use. In geophysical applications, the use for exploring underground resources such as metals is currently being studied. In materials evaluation applications, food foreign matter inspection equipment has been developed, and research on material diagnosis for new elements such as hydrogen tanks and glass fiber reinforced plastics, and equipment diagnosis research has been done.

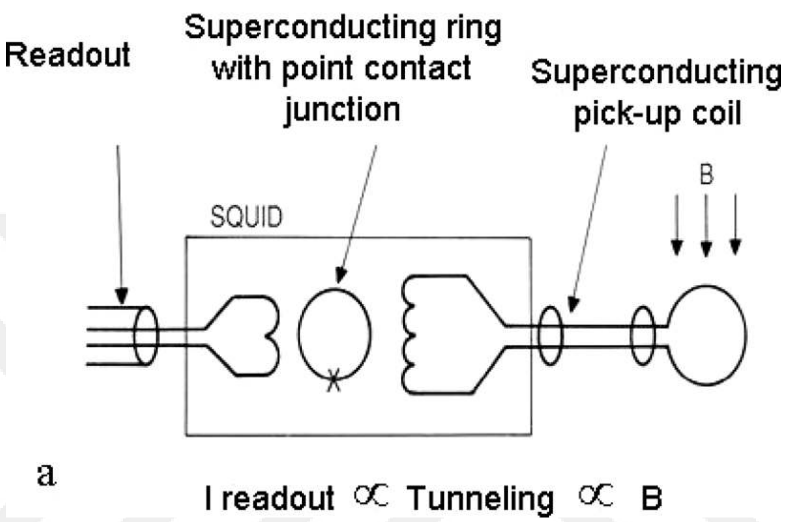


Figure 2.6. Schematic of SQUID

The Hall Effect Sensor Magnetometer

The Hall sensor is a magneto-electric instrument named after physicist Hall, who discovered the theory from which it was later created.

The Hall effect is a sensor used for measuring the strength of a magnetic field. The output voltage is equal to the frequency of the magnetic field that passing through it.

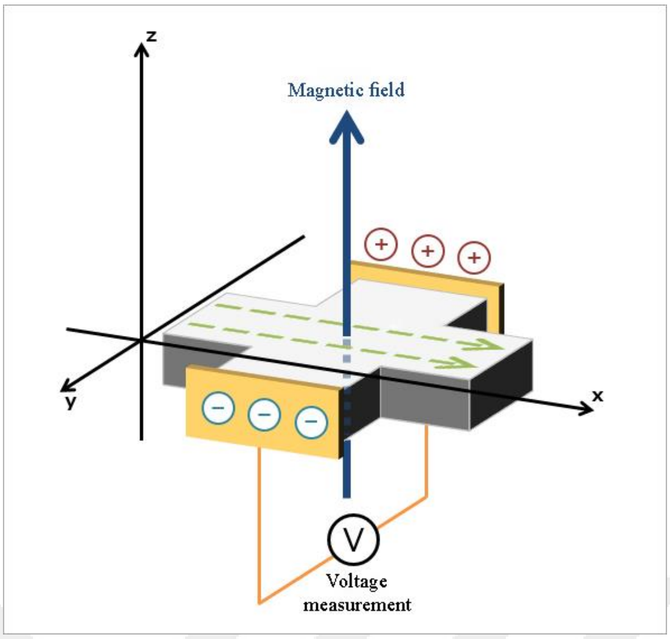


Figure 2.7. Hall effect sensor working

The cross-shaped object at the center of the Figure 2.7 is the Hall element. When a magnetic field is applied in z direction while the current is flowing in x direction, a Lorentz force is applied and the direction of the charged particle advancing in the y direction is bent. As a result, a surface that is charged to the + side and a surface that is charged to the - side appear. By measuring the potential difference between these surfaces, it is possible to assess if a magnetic field is produced and its strength.

GMI Magnetic Sensor

GMI refers to the phenomenon that the AC impedance of a material changes with an applied magnetic field. At present, it is the frontier of scientific research, and its future is better than giant magnetoresistance.

The behavior of giant magneto-impedance (GMI) in amorphous materials has been caused by the attention of the scientific community and the magnetic heads in their application prospects in micromagnetic sensors.

Magneto-diode

Sensitive magnetic diode. It is a magnetically sensitive element with a pin structure with extremely small intrinsic region. The recombination region is formed by diffusing the impurity serving as a recombination center or special processing of the side surface of the region. When a forward voltage added, the sides of holes, electrons from the side is injected into the region current flows as in the vertical direction to the current field when a such, holes and electrons are both and flows towards the recombination region while being more inclined. In the recombination region, holes and electrons decrease due to recombination, so the resistance in the region increases and the current decreases. When the magnetic field direction is reversed, the current increases, the structure shown in Figure 2.8. It has higher accuracy than Hall element and magnetoresistance effect element, and it is applied to magnetism detection, acoustic element, control apparatus using magnetism, etc.

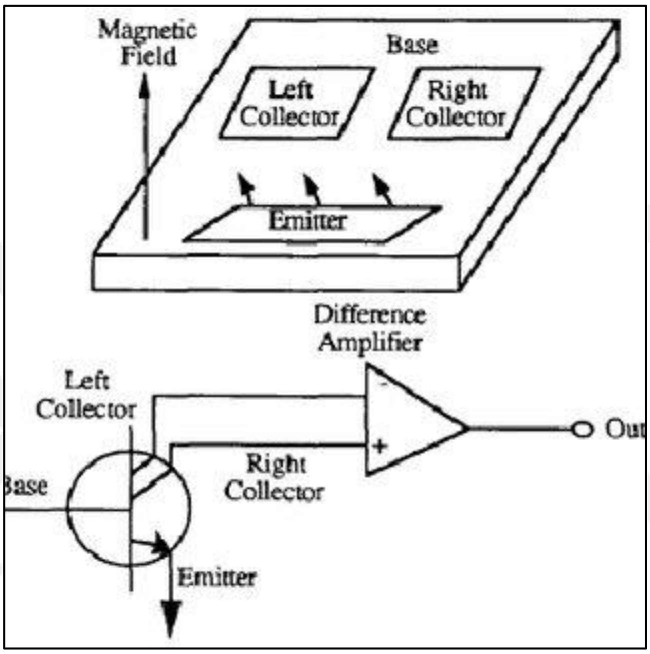


Figure 2.8. Structure of magneto diode

Magneto-transistor

It is made in the form of a metal or ferrite rod with a coil. The peculiarity of this solenoid is that its ends extending beyond the coil are made pointed. The maximum magnetic flux of this solenoid is determined, among other things, by the cross-sectional area of the core. Moreover, this stream ALL goes beyond the limits of the solenoid into the outer space through pointed ends. At the ends, the concentration (focusing) of the magnetic flux occurs without reducing its intensity.

Magnetooptical Sensor

Magneto-optic sensor technology is an imaging inspection method that can be used for magnetic field distribution measurement and non-destructive measurement.

It can be used for magnetic field analysis of different magnetic materials, MO sensors with several measuring ranges and sizes are available.

s phenomenon called Faraday effect is a phenomenon in which the linearly polarized light propagating in the magneto-optic sensor is rotated (rotated) by the influence of the magnetic field from the outside.

It happens when the magnetic field is perpendicular to the direction of polarized light transmission and only the plane of polarization spins at the same frequency.

The optical rotation angle is given by the following equation.

$\beta = V \cdot d \cdot B$

The optical rotations of different angles obtained by the strength of the magnetic field can be converted into the light intensity by passing it through the analyzer, so it is possible to image the intensity distribution of the magnetic field in the sensor surface directly, in real time can do it. Figure 2.9 shows principle of MO sensor.

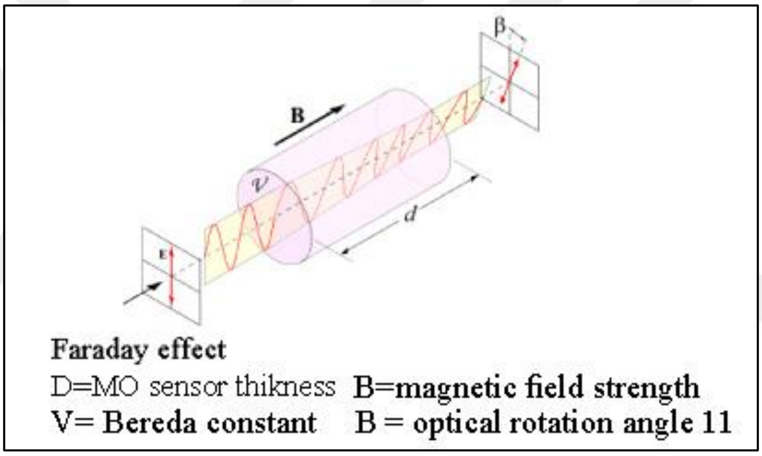


Figure 2.9. MO Sensor

MEMS Based Magnetometers

MEMS is from the acronym of Micro Electro Mechanical Systems. Its technology is to add high value to a wide range of products in a wide range of fields, such as accelerometers used in printer heads, automobile airbags, mobile phones and game machines, and mirror devices that control light with projectors, Safety, etc.) as an indispensable device to support it, as shows in Figure 2.10.

As the technical scope of MEMS, it refers to a device in which mechanical element parts, sensors, actuators, and electronic circuits are integrated on one silicon substrate, glass substrate, organic material and so on. Due to constraints on other device construction methods, differences in materials, etc., the mechanical structure and the electronic circuit may become different chips.

Although the main part is made from semiconductor integrated circuit fabrication technology, it will be MEMS until it includes the sacrificial layer etching process to form three-dimensional shape and movable structure.

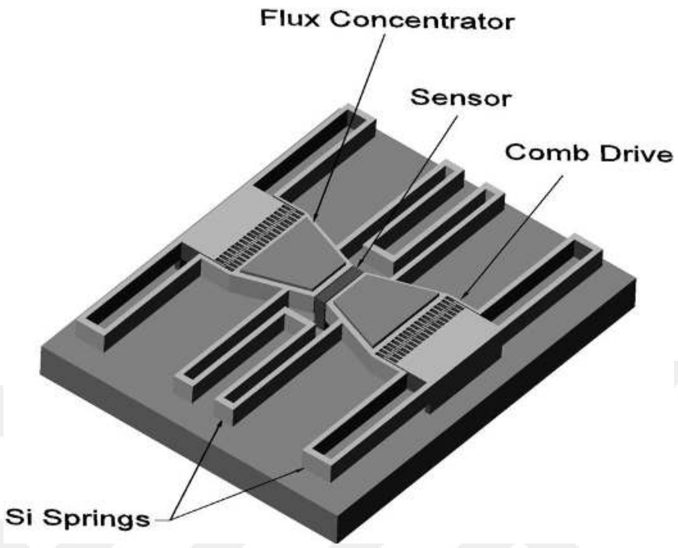


Figure 2.10. The concepts of MEMS flux concentrator

2.3.2. Total Field (Scale) Magnetometers

The overall magnetic field is characterized by an important feature of being insensitive to rotational vibration. The full magnetic field benefit from the fact that the division between several levels of nuclear energy or electron is proportional to the size of the magnetic field through a sufficient magnetic field to measure the magnetic force. To obtain high sensitivity, it is needful to use resonance with a fine line with a long lifetime. Such a line limits frequency sampling. Therefore, the sensitivity of those magnets is sharply reduced at frequencies higher than 10 Hz.

Optically Pumped Magnetometer

Quantum magnetometer - a device for measuring the strength of magnetic fields, based on quantum phenomena. Such phenomena are the free ordered precession of nuclear or electron magnetic fields, to cable transitions between the magnetic sublevels of atoms, as well as quantum changes in the magnetic flux in the superconducting circuit. Optically pumped magnetometer using optical pumping technique measures total magnetic force and is superior to measurement sensitivity and continuous measurement compared with proton magnetometer. Figure 2.11 illustrates the Optically pumped magnetometer.

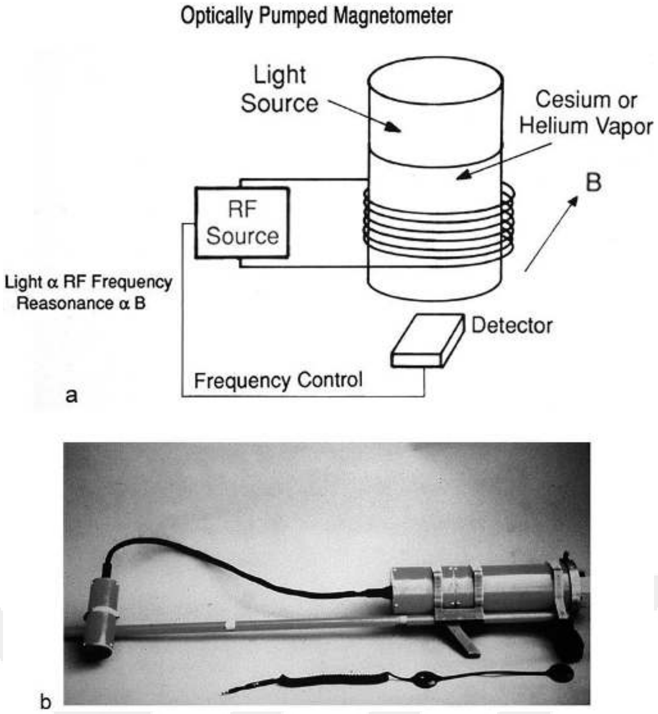


Figure 2.11. The Optically pumped magnetometer, (a) A schematic, (b) Hardware example

Optically pumped quantum magnetometer is more sensitive and expensive, consume an order of magnitude more electricity, less durable, require some caution in handling, operate in a narrower temperature range, used mainly to remove magnetic anomalies maps, then detect and identify GPS's.

Nuclear-Precession Magnetometer

Also called proton magnetometer, it is the main instrument of the Earth's geomagnetometer, used for the measurements of the Earth's magnetic field performed on the Earth's surface. It consists of a small rectilinear solenoid (coil) that contains inside a cylindrical glass vessel a strongly hydrogenated liquid (typically, chemically pure water), which can be seen as a sort of proton solution, equipped with magnetic moment. This sensor is arranged with its axis approximately in the local East-West direction and in the coil a continuous electric current is sent for a few seconds, which generates a rather intense polarization magnetic field (a few hundred times more intense than the Earth's magnetic field), which orients (on average) a certain part of the protons parallel to the axis of the coil as seen in Figure 2.12.

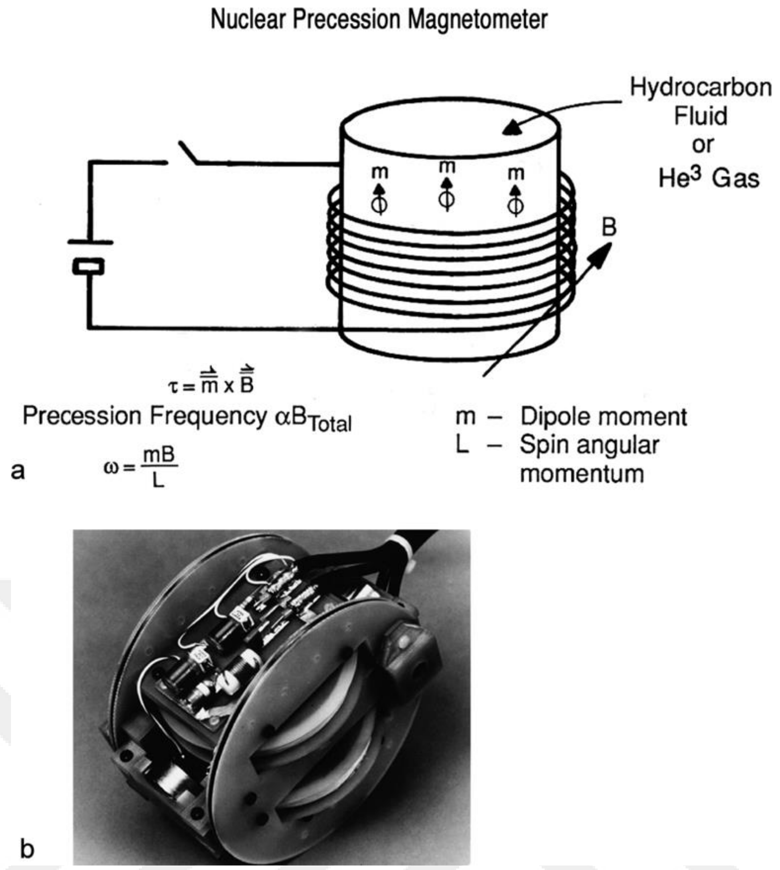


Figure 2.12. Nuclear precession magnetometer: (a) schematic; (b) hardware example

Overhauser Magnetometer

Overhauser magnetometer is a portable high-sensitivity magnetic field inclinometer. It is designed for magnetic measurement at the survey point, exploration of resources and remains, observation of long-term geomagnetic change, volcano / earthquake research and so on. An example of Overhauser magnetometer is GSM - 19. GSM - 19 secures 0.01 nT sensitivity and 0.2 nT accuracy within the operating temperature range for earth magnetic field measurement. The GSM - 19 has a powerful function with a built - in microprocessor, enabling high - capacity measurement values to be recorded. Synchronous measurement with base station (up to 2 Mbytes) is possible, and correction for day-to-day change of geomagnetism is done automatically. Measurement results are gathered in computers, data recording devices by serial communication format. Online transmission and data transmission after observation is also possible. In the state of the magnetic field inclinometer specification, for the inclination value detection, measurement of the two magnetic fields is performed continuously by controlling the accurate measurement interval. The measured value is high precision and it is irrelevant to the diurnal change of the magnetic field [24].

2.4. Magnetic Sensor Applications

Many applications are in our life using magnetic sensors. For example:

- General Physics.
- Medical physics.
- Robotics.
- Automotive industry.
- Measurements and magnetic explorations of the terrestrial field.
- Aeronautical Industry.

The high-accuracy magnetic sensor is the basis for measuring the magnetic field. The magnetic sensor consisting of a sensor, an analog circuit and a single-chip microcomputer has an accuracy of $\leq 0.1\%$ and has temperature error compensation [25].

The magnetic brush is also called a magnetic roller, and the magnetic roller is composed of a magnetic strip. Select a magnetic field uniform magnetic strip to assemble a magnetic roller with good performance. Main working principle First, the internal magnetic brush of the copier enhances or weakens the process of magnetic powder (magnetic ink). Specific operation: After the paper enters the copier, the paper is finely counted into countless lines, and the number of dots in each line is scanned by the camera. Finally, the computer controls the magnetic roller to absorb magnetic powder or does not absorb magnetic powder according to whether there is a valid point [26].

2.4.1. Magnetic sensor applications categories

Almost all applications of magnetic sensors could be classified into four main categories. The difference between the first three categories is specified by according the use of the current of the magnetic field of the earth. The fourth group is biological (medical) area. Table 2.1 shows the first three groups and everyone has a list of the important applications and that are most commonly using sensors [27].

Table 2.1. Categories of magnetic sensor applications [28]

Category 3 High Sensitivity app.	Category 2 Medium Sensitivity app.	Category 1 Low Sensitivity app.
Definition	**Definition**	**Definition**
• Measuring field gradients or differences due to induced (in Earth's field) or permanent dipole moments	• Measuring perturbations in the magnitudes and/or direction of Earth's field due to induced or permanent dipoles	• Measuring fields stronger than Earth's magnetic field
Major Applications	**Major Applications**	**Major Applications**
• Brain function mapping • Magnetic anomaly detection	• Magnetic compass • Munitions fuzing • Mineral prospecting • Traffic control	• Noncontact switching • Current measurement • Magnetic memory readout
Most Common Sensor	**Most Common Sensor**	**Most Common Sensor**
• SQUID gradiometer • Optically pumped magnetometer	• Search-coil magnetometer • Flux-gate magnetometer • Magnetoresistive magnetometer	• Search-coil magnetometer • Hall-effect sensor • Magnetoresistive magnetometer

Low Sensitivity Apps. (Current Sensing)

AC current sensor that shows up in Figure 3.1 is an example of this classification of sensors applications. The AC current sensor creates an output of voltage that is corresponding to present going over the sensor. A shut circle strategy utilizing an attractive center and criticism curl can be executed to adjust the attractive motion from the current that have been detected. The most widely recognized plan utilizes Hall Effect sensor rided inside a covered attractive center. The Hall sensor's ability to fit through a small hole framed in the visually appealing center is related to the way it reacts to the field opposed to its surface [29].

Medium Sensitivity Apps. (Magnetic Compassing)

Magnetic compassing is the process of finding the orientation of the sensor with respect to the Earth's magnetic field lines. Measurements of magnetic fields must be taken on a horizontal plane. This is often accomplished via the use of a deflection mechanism that allows gravity to orient the sensor mechanically, or through the use of overlay sensors and applying the orientation in an electrically controlled way. Magnetic anomalies, such as bridges and mineral storage, have a significant impact on earth navigation positioning accuracy [30].

High Sensitivity Apps. (Magnetic Anomaly Detection)

Magnetic sensor applications that have been thoroughly studied (MAD). This involves detection at a distance from the object of ferromagnetism (for example, an aircraft, mine, ship, or tank ship). The dipole of a ferromagnetic object's magnetic characteristics dipole has two capacities. One of them is a persistent dipole moment. And this results in a magnetic tape effect, in which the solid iron becomes magnetized, which most ships minimize. The other is the initiated moment of magnetic dipole of ferromagnetic material, which is the substance's reaction to the Earth's magnetic field. Magnetic permeability results in the formation of a magnetic dipole. Materials with a high magnetic permeability may be exposed to the magnetic field that surrounds them [31].

Medicinal / Biological Apps

Additionally, magnetic sensors may be used in biological and medical research. Magnetic labels, for instance, may be used to indicate the closeness of certain molecules. Magnetic microbeads were used as markers in a multi-analytic biosensor that detected DNA hybridization on a micro fabricated device. The movement of bodily components, such as the tongue's articulatory motions during speaking or the tiny mechanical vibrations of the eyelids. SQUIDS sensors are another example of biological uses. It is used to assess the weak magnetic fields produced by the brain and other medical testing [32].

2.4.2. Security applications of magnetic sensors

Magnetic sensors are widely employed in military and defense applications. Many traditional sensors, such as induction coils, resonance magnetometers, and fluxgates, will be replaced by new sensor types such as GMR, AMR, GMI, and SDT [33].

The basic sensor specifications in essential applications:

- Reliability and dependability.
- Higher sensitivity and affectability.
- Methods for self-test techniques.
- A few implementations necessitate a smaller size, lighter (weight), and lower power use.
- Best cost.

2.4.3. Ferromagnetic objects detection

DC magnetic finders frequently exploit the region of Earth deformation produced by ferromagnetic item permeability. Unless the item is purposely set separate by everlasting magnets, permanent polarization (hard components) of ferromagnetic material is feasible but not predictable.

With things that are far distant from the sensor, this strategy works effectively. The sensor is either moving through the covering item, such as (UXO), or it is fixed and detects a moving target, such as a vehicle. It is usually more radical to use an active field generator rather than a passive technique that depends on the Earth's field. If the discovered object is tiny and near the sensor [34].

2.4.4. Conducting objects detection with using eddy currents

The frequency range of the Eddy current metal detector operates in the frequency range of 1 kHz to 100 kHz. Magnetic field sensors that measure secondary magnetic fields induced by eddy currents are traditionally a modern AMR and induction sensors are used. The main task is to avoid large irritation field to measure small secondary magnetic fields. The pulse detector uses time separation: The measurement time starts after the excitation field decayed. The CW detector uses a gradient coil system or a vertical detection coil. A similar method is used in both detection frames for access control and portable metal detectors [35].

As shown in Figure 2.13, a scanning magnetic microscope for magnetic fields is the Tristan model SMM-770 Scanning Magnetic Microscope.

Figure 2.13. SQUID scanning microscope model SMM-770 with dc and ac biasing magnets.

This system is evaluated to identify magnetic fields over a flat surface with unmatched spatial resolution. Superconductor Magnetometers (SQUID) sensors may be used to picture things at room temperature, such as [36]:

- Traces on a circuit board or multi-chip module.
- Shorts to ground planes.

- Current distributions.
- Magnetic inks used in currency (shown in Figure 2.14).
- Insulators, ferrous and nonferrous metals to detect cracks, voids and corrosion.
- Nanoparticle distributions.
- Flux-motion in HTS materials.

Figure 2.14. Magnetic image of dollar bill section.

The SMM-770 can also be configured to detect [37]:

- Induced magnetization.
- Magnetic susceptibility.
- Eddy currents.
- Magnetic hysteresis.
- Micropaleontology.
- Magnetobiologic activity.

2.4.5. Local navigation and position tracking by using artificial field

These types of devices are used for accurate monitoring of local sites and the guidance of those objects that are important, for example, pilot helmets, indoor or underwater navigation. A fixed magnetic field, such as a long current connector or coils, is typically used in this commonly system. A collection of passive markers or magnetic sensors is carried by moving items [38].

3. FUNDAMENTALS OF THE STUDY

Prior to the advent of computers, electromagnets were constructed using analytical measurements or by computing representative voltage maps in electrolytic tanks and resistive sheets. Magnetic measurements on final magnets, as well as intermediate magnet models, were required at the time. It is now feasible to accurately assess the quality and intensity of magnetic fields. On the other hand, magnetic measurements on the completed magnet are the simplest and most accurate method to ensure that the desired field quality has been attained. Additionally, it is the most effective method for ensuring the effectiveness of serially manufactured electromagnets while simultaneously monitoring tooling wear. While the majority of measurement methods have remained essentially unaltered for a long period of time, equipment has continually improved [39].

3.1. Choice of Visualizing Method

The choice of visualizing and measurement method depends on several factors. The field strength, homogeneity and variation in time, as well as the required accuracy all need to be considered. Also, the number of magnets to be measured can determine the method and equipment to be deployed.

This study is based on the principle of Hall Effect and signal converter. The board is small but it gives good results in addition to ease of use, low cost and power.

The magnetic field emitted from the material to be checked is converted to visual spectrum. Which means that magnetic fields can now be seen in real time, the magnetic sensors used on the tile are some of the most highly sensitive.

3.2. Hall Effect Sensor Principles

Magnetic sensors are solid-state instruments that are gaining in popularity due to its efficiency in applications such as sensing location, directional movement and velocity. They are also a common choice of sensor for electronics designs because of their non-contact wear-free function, low maintenance, robust design, and immunity to vibration, dust, and water as sealed hall effect devices [40].

Magnetic sensors cause a great deal scope of positive and negative magnetic fields in many applications, and the Hall Effect Sensor is one kind of magnet sensor that output signal is a feature of the magnetic field density around it [41].

Tools that are powered by an external magnetic field are known as Hall Effect Sensors. A magnetic field has two main properties: flux density (B) and polarity (P) (North and South Poles). A Hall effect sensor's output signal is a feature of the magnetic field intensity around that instrument (as shown in Figure 3.1). When the magnetic flux density around the sensor exceeds a certain pre-set threshold, the sensor detects it and generates an output voltage called the Hall Voltage, V_H [42].

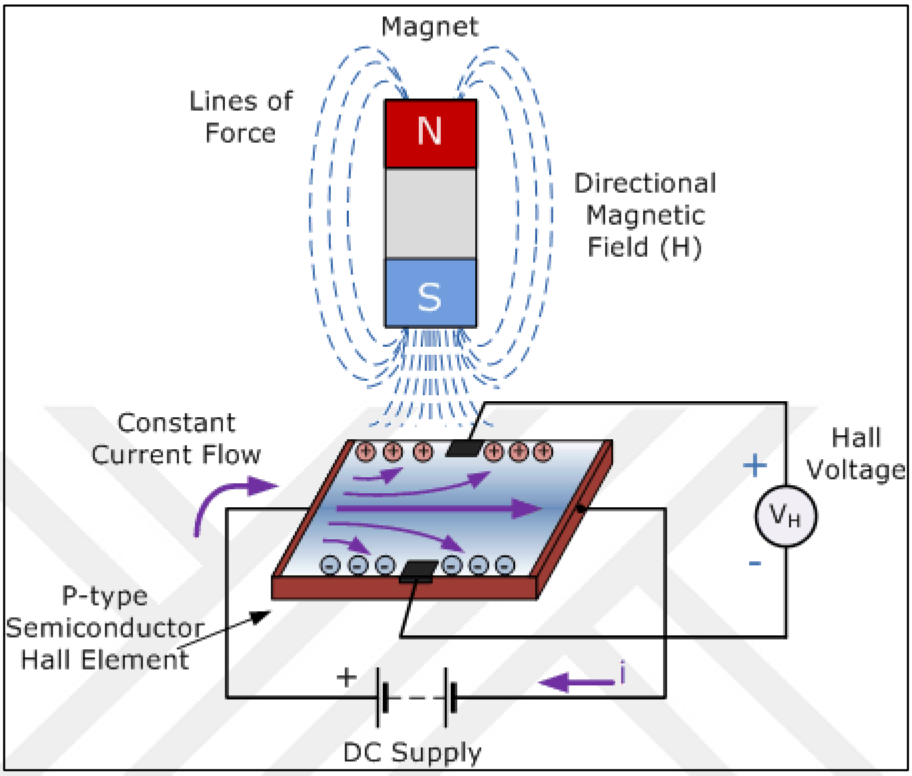


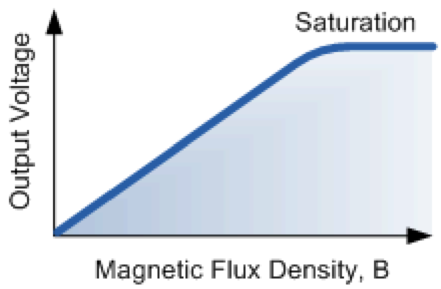
Figure 3.1. Hall Effect Sensor Principle

All Hall Effect Sensors are available into two types, which are either Linear or digital outputs. For linear (analogue) sensors, the output signal is taken directly from the operating amplifier's output, with the output voltage being proportional to the magnetic field flowing through the Hall sensor [43]. That output voltage of Hall sensor is given as equation 3.1:

$$V_H = R_H \left(\frac{I}{t} \times B\right) \tag{3.1}$$

Where:

Table 3.1. Hall Effect Principle and equation

• V_H = Hall Voltage in volts • R_H = Hall Effect co-efficient • I = Current flow through the sensor in amps • t = Thickness of the sensor in mm • B = Magnetic Flux density in Teslas	

The effect occurs due to how current flows in a conductor (shown in Table 3.1). Current is the movement of electrons or holes. When a magnetic field is applied perpendicular to the current, it produces a Lorentz force on the charge carriers [44].

3.3. Hall Effect Sensor Theory

For a 1 mA current, the Hall sensitivity of silicon sensors is normally 1 mV/mT. Thin-film InSb (typically 5 mV/mT) or InAs (typically 2 mV/mT) may achieve higher sensitivity. As compared to Si and InSb, InAs devices have a lower temperature dependency of the Hall voltage, and their working range is also superior: it exceeds C-to-C range needed for automotive applications. Using SOI technology, a promising Hall sensor was created: For an 80-wide, 50-nm-thick sensor, 1 noise was achieved [45], [46].

The transverse part of the flux density moving through the sensing element is linearly proportional to the Hall voltage output signal. Lorentz forces operate on charges passing across a magnetic field, causing the Hall effect.

$$F_L = q\,.(V \times B) \tag{3.2}$$

$$F_{hall} \propto B$$

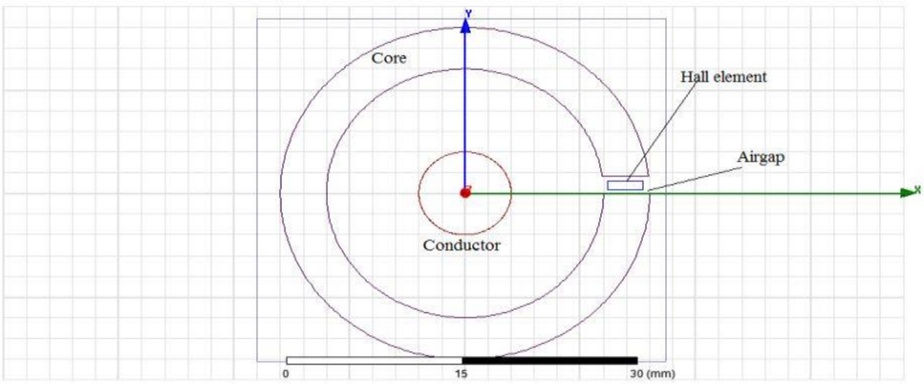


Figure 3.2. Two-dimensional of open loop current sensor [47], [48].

The 2D structure of an open loop current sensor as seen in Figure 3.2. Since the open loop current sensor has axis symmetry, it's easy to perform in 2D and the results are correct. Therefore, design is done in 2D (showed in Figure 3.3 and 3.4) [47], [48].

B-field at the center of Hall element is calculated by taking line integral using the following expression:

*B = Scl: * (Integrate (Line (Polyline1), ScalarY (< B_x, B_y, 0>)), 10000)*

B-field at the center of Hall element is calculated at a center point using the following expression:

*B = Scl: * (PointValue (Point (Point1), ScalarY (< B_x, B_y, 0>)), 10000)*

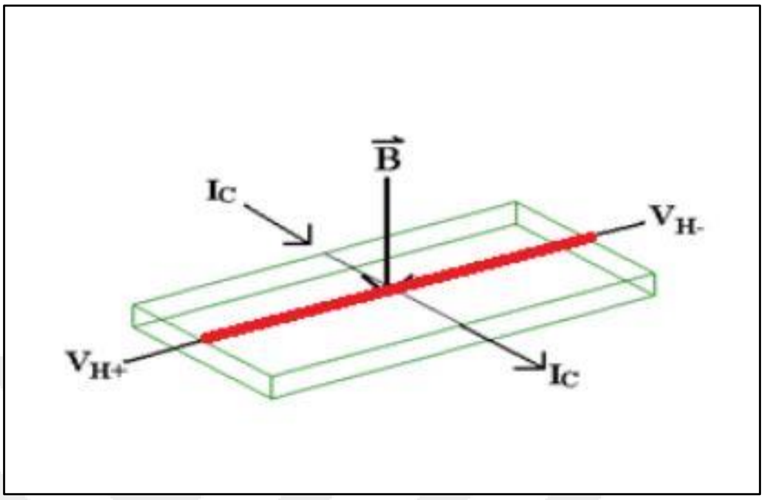


Figure 3.3. Line integral calculation of B Field [49].

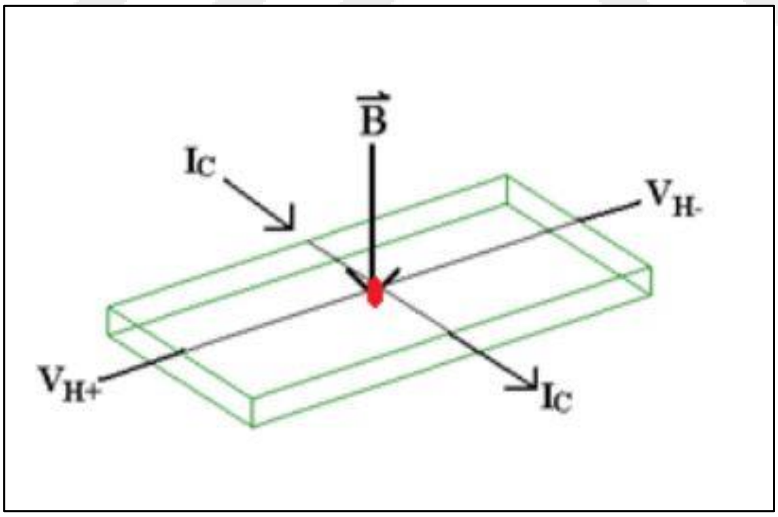


Figure 3.4. Point calculation of B Field [49].

Concentric magnetic field lines are created around a current carrying wire in general, and they can be estimated using the expression. [49].

$$B = \mu_0 I / 2\pi r \tag{3.3}$$

Where:

μ0 is the permeability of free space

I is the current

r is the distance from the center of the current conductor.

3.4. Hall Effect Sensor Working

In a Hall-effect sensor, a current is sent along a very thin strip of metal. In the presence of a magnetic field, the electrons in the metal strip are deflected toward one edge, resulting in a voltage gradient across the strip's short side (perpendicular to the feed current). Hall-effect sensors have an advantage over inductive sensors in that they can detect static (non-changing) magnetic fields, while inductive sensors react to a changing magnetic field generated by a coil of wire and resulting in voltage at the sensor's output [50].

The sensor functions as an analog transducer in its most basic form, returning a voltage directly. It is possible to calculate the distance between the Hall plate and a known magnetic field. The relative position of the magnet can be calculated using groups of sensors [51].

When charged particles travel through a magnetic field, forces act on them, causing the beam to deviate from its initial path. When electrons move over a conductor, they create a beam of charged carriers. When a conductor is placed in a magnetic field perpendicular to the direction of the electrons, it is deflected off its straight path. As a consequence, one conductor plane acquires a negative charge while the other acquires a positive charge. The Hall voltage is defined as the potential difference between these two planes [52].

When the electric field's force on charged particles matches the magnetic field's force, the separation of charges comes to a stop. While the current does not vary, the Hall voltage is a measure of the magnetic flux density. Hall-effect sensors are classified into two types: linear and threshold. The output voltage of linear Hall-effect sensors is proportional to the magnetic flux density. At a certain magnetic flux density, threshold Hall-effect sensors exhibit a significant drop in output voltage. This experiment was used to demonstrate that only negative charges are free to travel in a conductor. Previously, it was believed that positive charges moved in a current-carrying conductor. This experiment is referred to as the Hall experiment [53].

3.5. Magnetic Image Sensing

Although magnetic sensors (magnetometers) are sensing the magnetic field and measuring the field, human eyes cannot sense (see) that field. So, sometimes we need to visualize the field for some reason as required, for example detecting magnet in objects or biology deals. Some sensors do it directly i.e., capture the magnetic image, and some other sensors need a special method to do it (in the case of our Hall sensor), for example, converting signals generated from the field and convert it to a visual color to see using human eyes.

In this research a DRV5053 Analog-Bipolar Hall Effect Sensor has been chosen to visualize a magnet or magnetic field, it’s done using an array of 64 sensors, which means a matrix of 8×8 and analyzing the data that has been read from those sensors to implement quality control for it

4. HARDWARE AND SOFTWARE IMPLEMENTATION

The majority of sensors detect the presence of magnetic fields via the Hall effect; these sensors are referred to as Hall-effect sensors. A magnetic sensor's most basic component is the Hall-element. Typically, these sensors are placed in four-terminal housings with two controlled and two differential output terminals.

The control current is applied to the control terminals, and the differential output terminals are used to monitor the output. As shown in Figure 4.1, the magnetic field is transformed to an electrical signal using a simple Hall-effect sensor.

A magnetic system turns physical characteristics like position, speed, current, temperature, and so on into a magnetic field that Hall-effect sensors can detect.

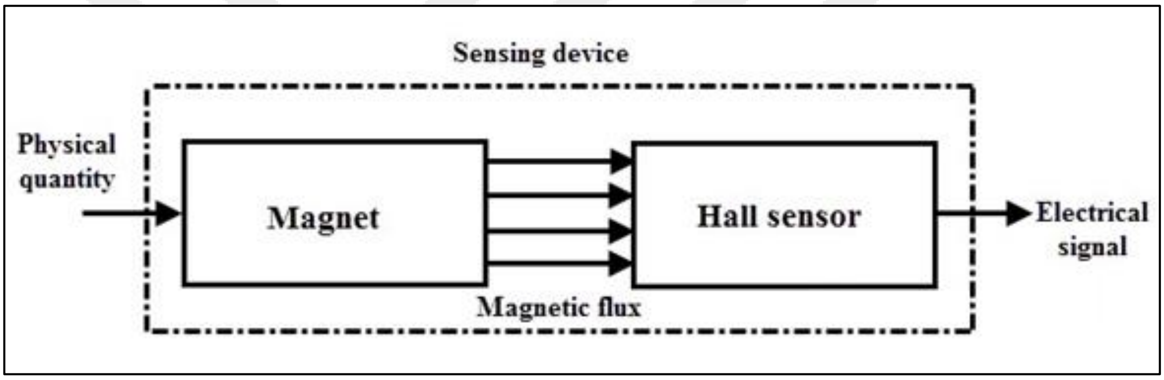


Figure 4.1. Hall-Effect sensor working strategy.

4.1. Hall-Effect Integrated Circuit (IC) Sensors

Integrated technology and the Hall-effect idea are used to create Hall-effect integrated circuit switches. Compared to optoelectronic or inductive sensors, Hall-effect integrated circuits are more effective, less costly, and efficient. The integrated circuit for Hall-Effect sensors is shown in Figure 4.2.

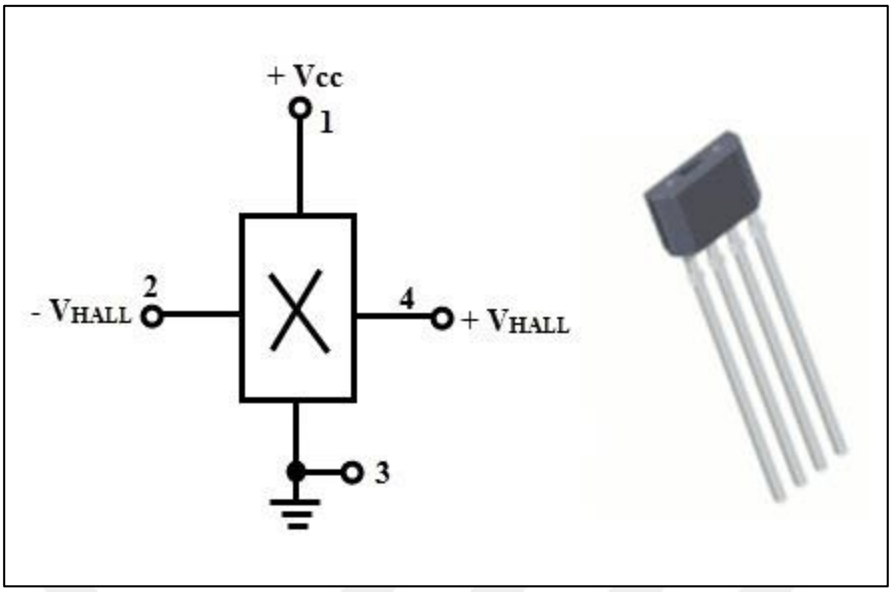


Figure 4.2. Hall-Effect Integrated Circuit (IC) Sensors [54]

4.2. DRV5053 Analog-Bipolar Hall Effect Sensor

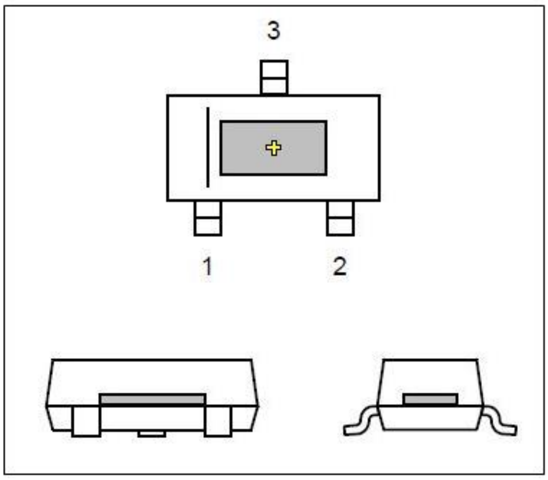
The DRV5053 is a chopper-stabilized Hall IC that offers an enhanced temperature sensitivity and built-in safety for magnetic sensing applications.

The 0- to 2-V analog output detects the polarity of magnetic fields and linearly reacts to applied magnetics flux density. The device's broad working voltage range of 2.5 to 38 V, along with protection against reverse polarity up to –22 V, making it suitable for a wide variety of industrial and consumer applications. The device's packaging and size are shown in (Table 4.1 and Figure 4.3).

Internal safeguards guard against reverse power supply, load dump, and output short circuit or overcurrent.

Table 4.1. Device Information

Part's number	The Package	Body-size (nom)
DRV5053	SOT-23 (3)	2.92 mm × 1.30 mm



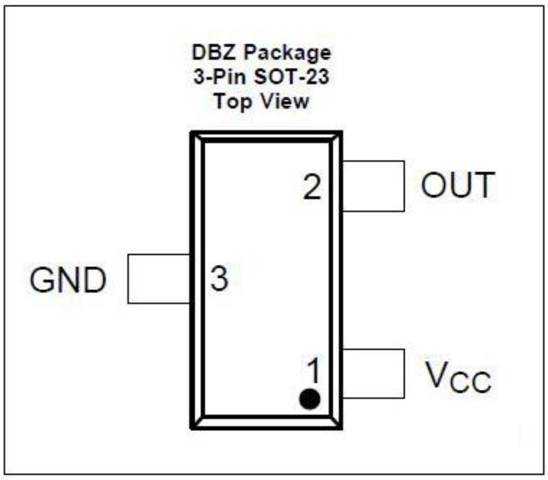


Figure 4.3. SOT-23 (DBZ) Package and Pin Configurations [54]

4.3. DRV5053 Features

Here are some of DRV5053 device features:

- Linear Output Hall Sensor.
- Superior Temperature Stability.
  - Sensitivity ±10% Over Temperature.
- High Sensitivity Options:
  - –90 mV/mT (VA), (seen in Figure 4.4).
- Supports a Wide Voltage Range.
  - 2.5 to 38 V.
  - No External Regulator Required.
- Wide Operating Temperature Range.
  - TA = –40 to 125°C (seen in Figure 4.4).
- Amplified Output Stage.
  - 2.3-mA Sink, 300 µA Source.
- Output Voltage: 0.2 ~ 1.8 V.
  - B = 0 mT, OUT = 1 V.
- Fast Power-On: 35 µs.
- Features of the Protection:
  - Protection Reverse Supply (up to –22 V).
  - It is Supporting up to 40-V Load Dump.
  - Output Short-Circuit Protection.
  - Output Current Limit.

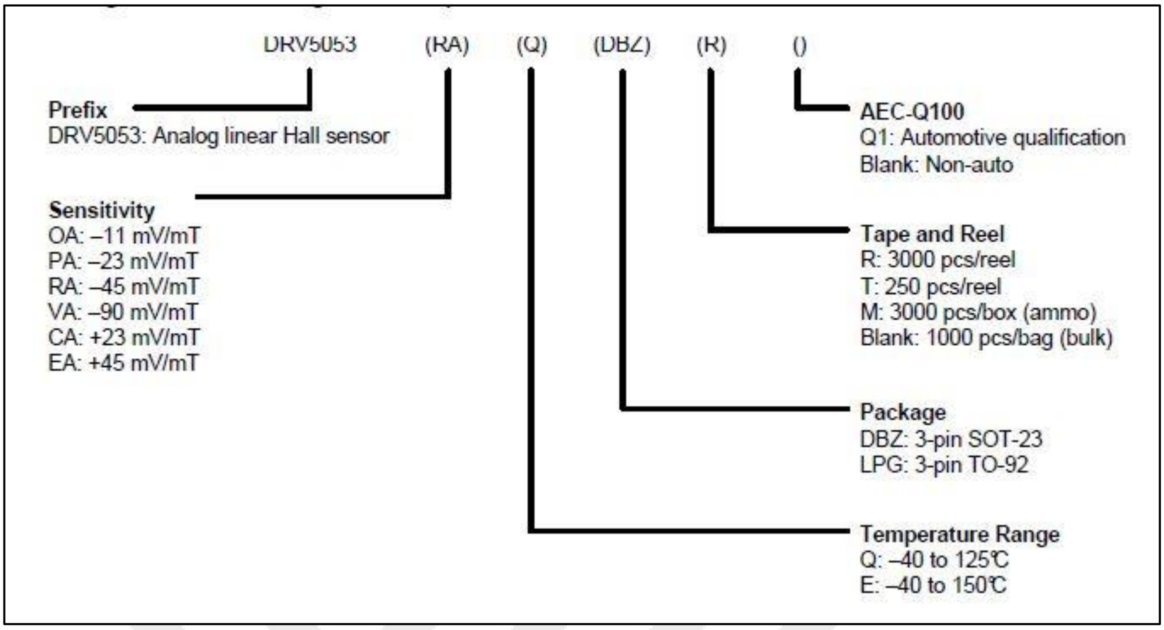


Figure 4.4. The legend of reading the complete device name of DRV5053 device.

Table 4.2 illustrates Pin Configuration and functions:

Table 4.2. Information of the device

Pin		Type	DESCRIPTION
Name	DBZ		
GND	3	GND	Ground pin
Vcc	1	Power	2.5 to 38 V power supply.
Out	2	Output	Hall sensor analog output.

And Table 4.3 shows the details of Magnetic properties:

Table 4.3. The Magnetic Characteristics

	PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT[1]
	DRV5053VA: –90 mV/mT					
s	Sensitivity	V_{CC} = 3.3 V T_A ≈ –40°C to 125°C	–140	–90	–45	mV/mT
V_N	Output-referred noise	V_{CC} = 3.3 V; R_{OUT} = 10 kΩ; C_{OUT} = 50 pF T_A ≈ –40°C to 125°C		44		mV_{pp}
B_{SAT}	Input saturation field	V_{CC} = 3.3 V T_A ≈ –40°C to 125°C		9		mT

Typical characteristics of DRV5053 device are shown in Figure 4.5:

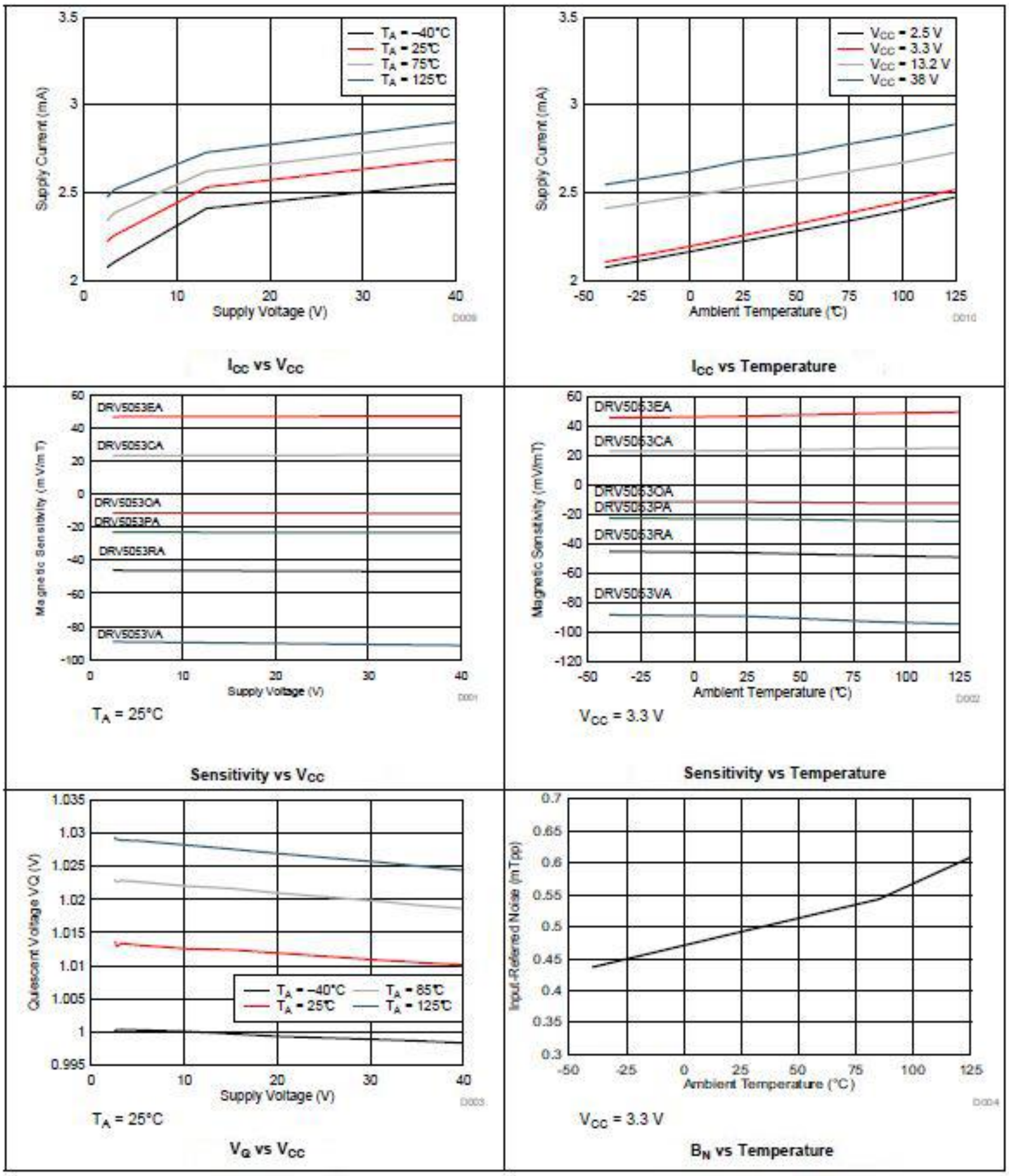


Figure 4.5. Typical characteristics of DRV5053 [54]

4.4. Functional Block Diagram

The DRV5053 is a magnetic sensing device featuring a chopper-stabilized Hall sensor and an analog output. A supply voltage of 2.5 to 38 V can be used to power the DRV5053 device, and it can withstand continuous reverse battery conditions of –22 V. When about –22 to 2.4 V is applied to V_{CC}, the DRV5053 device will not operate (with respect to GND). In addition, as demonstrated in Figure 4.6, the device can sustain supply voltage up to 40 V for brief durations.

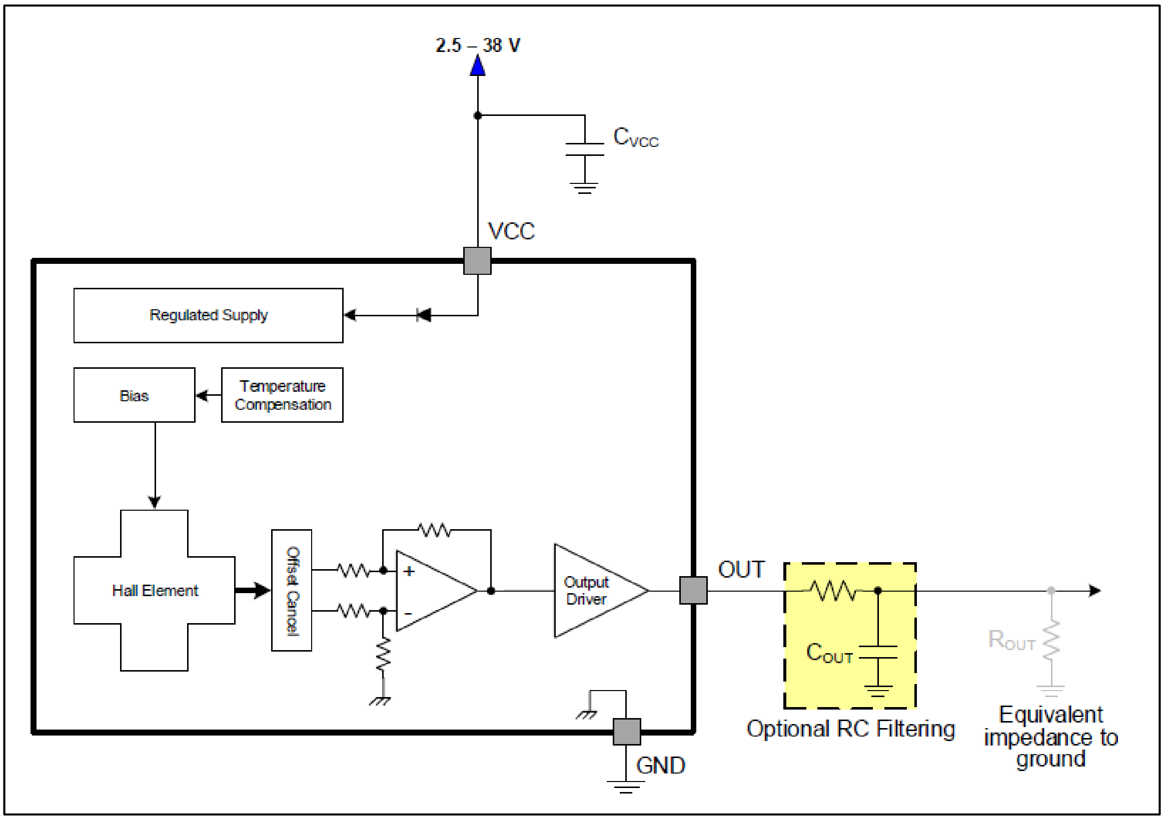


Figure 4.6. Functional Block Diagram

The magnetic field perpendicular to the package dictates the output voltage. Without the presence of a magnetic field, OUT=1V is obtained. When a magnetic field is present, the output voltage varies linearly with the magnetic field.

Polarity of a magnetic field is defined as follows: On the stated side of the container, a positive magnetic field has a south pole. A negative magnetic field arises on the designated side of the package's north pole.

For devices having a negative sensitivity (DRV5053RA: –40 mV/mT), a south pole causes the output voltage to fall below 1 V, while a north pole causes the output voltage to rise beyond 1 V.

For devices with a positive sensitivity (DRV5053EA: +40 mV/mT), a south pole causes the output voltage to increase beyond 1 V, while a north pole causes it to fall below 1 V.

In Figure 4.7 we can see the definition of field direction:

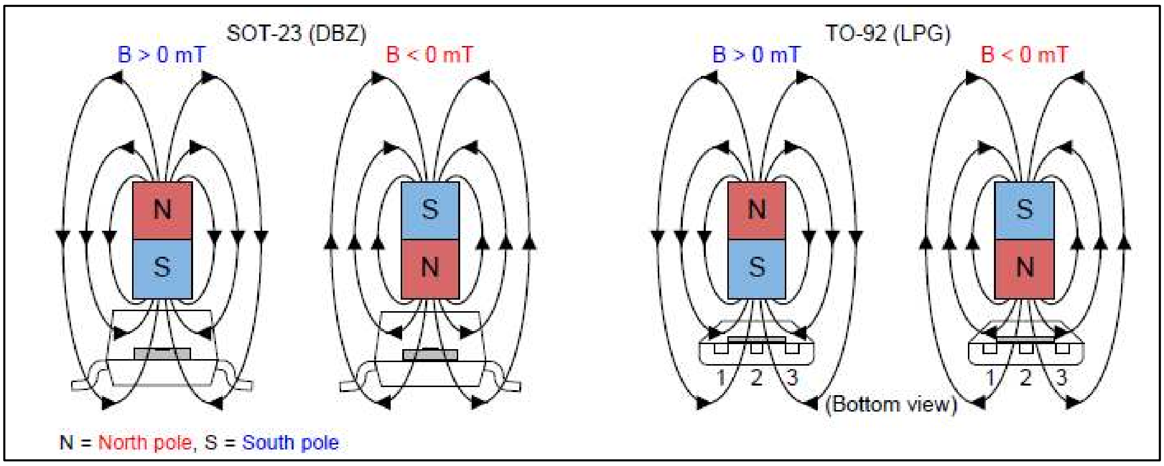


Figure 4.7. Field Direction Definition [54]

4.5. Device Output

As illustrated in Figures 4.8 and 4.9, Negative sensitivity (–45 mV/mT, RA) and positive sensitivity (+45 mV/mT, EA) are described for the DRV5053 device output.

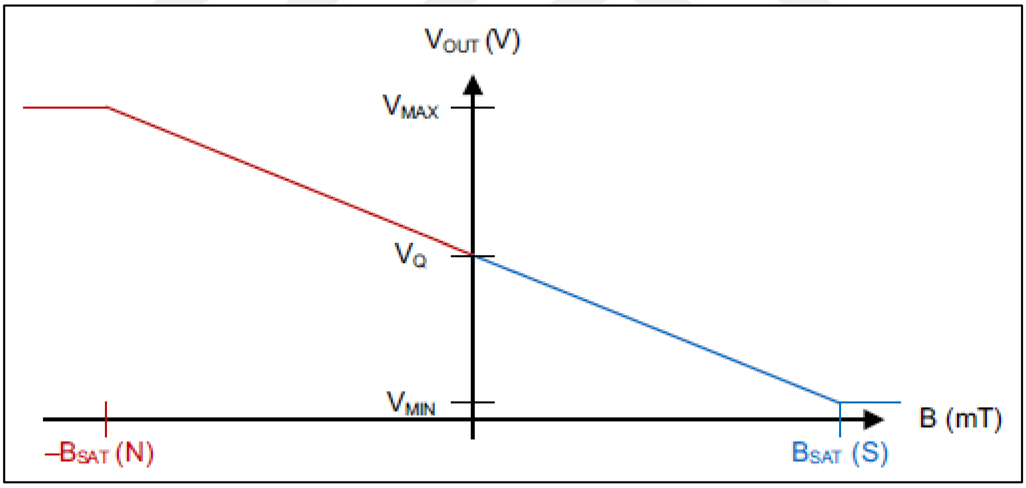


Figure 4.8. DRV5053 – Negative Sensitivity

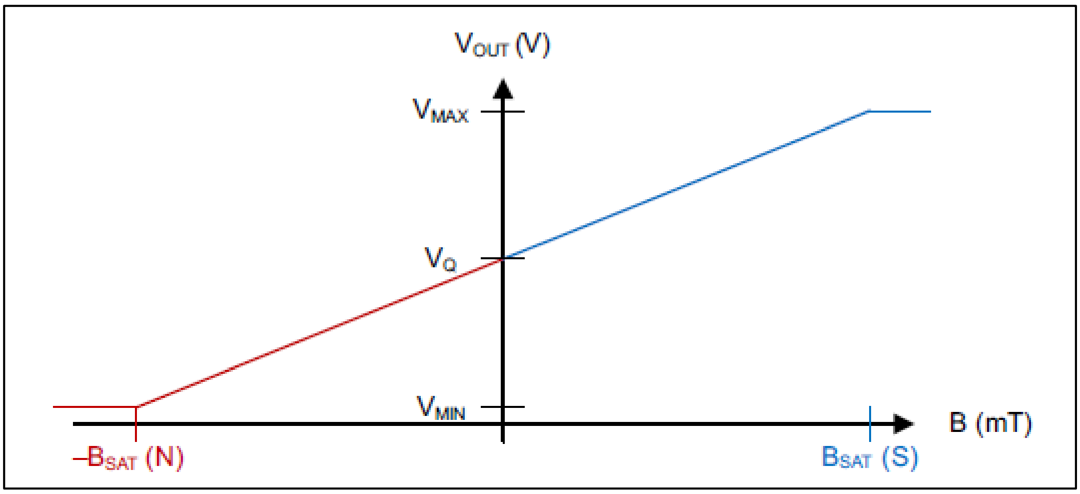


Figure 4.9. DRV5053 – Positive Sensitivity

4.6. AD7680 ADC

The AD7680 is a 16-bit successive approximation ADC that is quick and low power. The item is powered by a single 2.5 V to 5.5 V supply and has throughput speeds of up to 100 kSPS. A low-noise, wide-bandwidth track-and-hold amplifier is included in the part, which can handle input frequencies of up to 7 MHz.

CS and the serial clock are used to regulate the conversion process and data gathering, allowing the devices to communicate with microprocessors or DSPs. On the falling edge of CS, the input signal is sampled, and the conversion is also started. There are no delays in the pipeline because of this section.

The AD7680 employs cutting-edge design strategies to produce extremely low power dissipation while maintaining high throughput rates. The part's reference is taken internally from VDD, allowing the ADC to handle the broadest dynamic input range possible. As a result, this part's analog input range is 0 V to VDD. The SCLK frequency determines the conversion rate; this process is depicted in Figure 4.10.

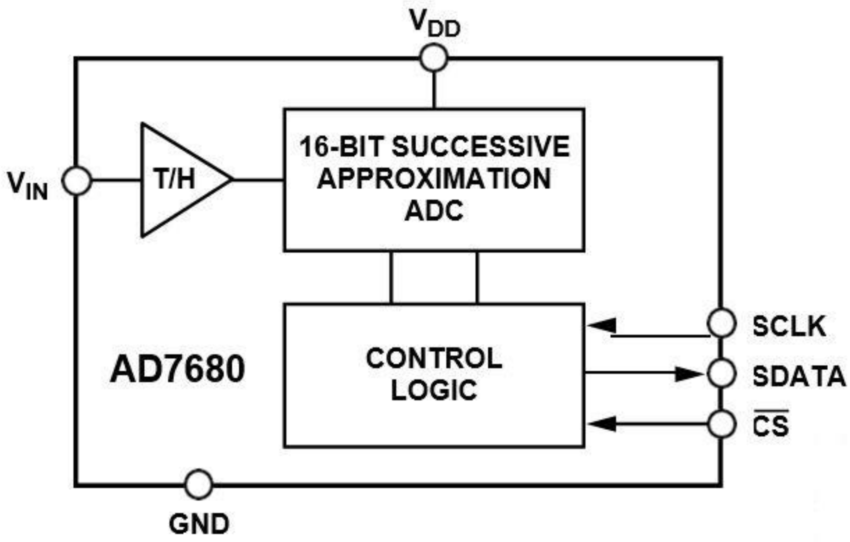


Figure 4.10. Functional block diagram of the ADC.

MATLAB has been used as a software for transferring data and showing the results on an application designer in MATLAB (GUI) as shown in Figure 4.11:

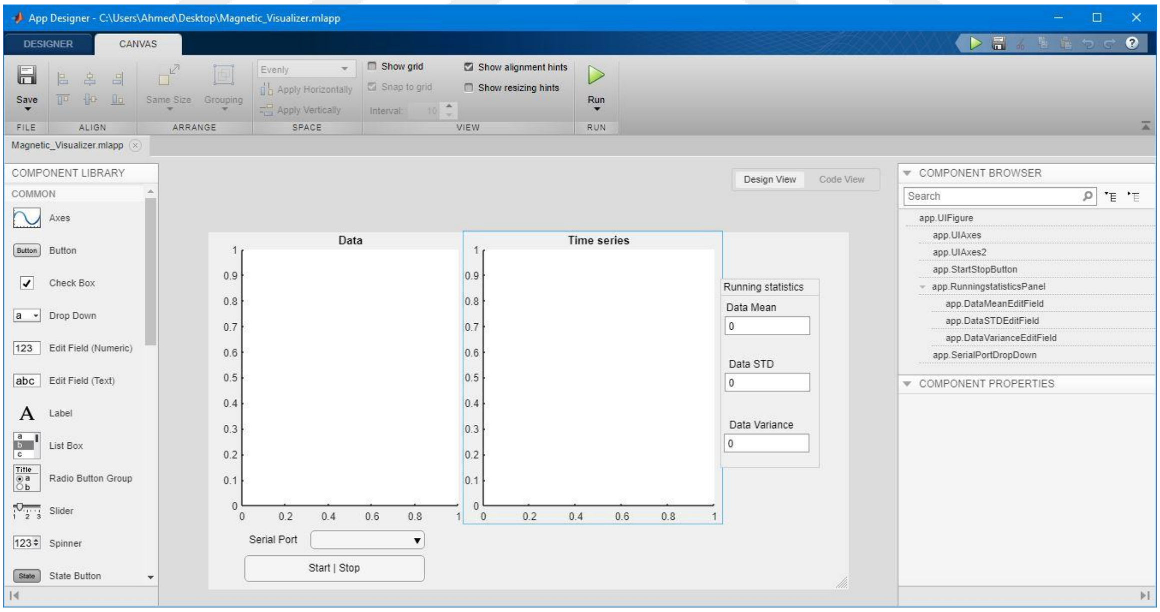


Figure 4.11. Application Interface using MATLAB.

And Figure 4.12 illustrates a piece of the code that has been programmed:

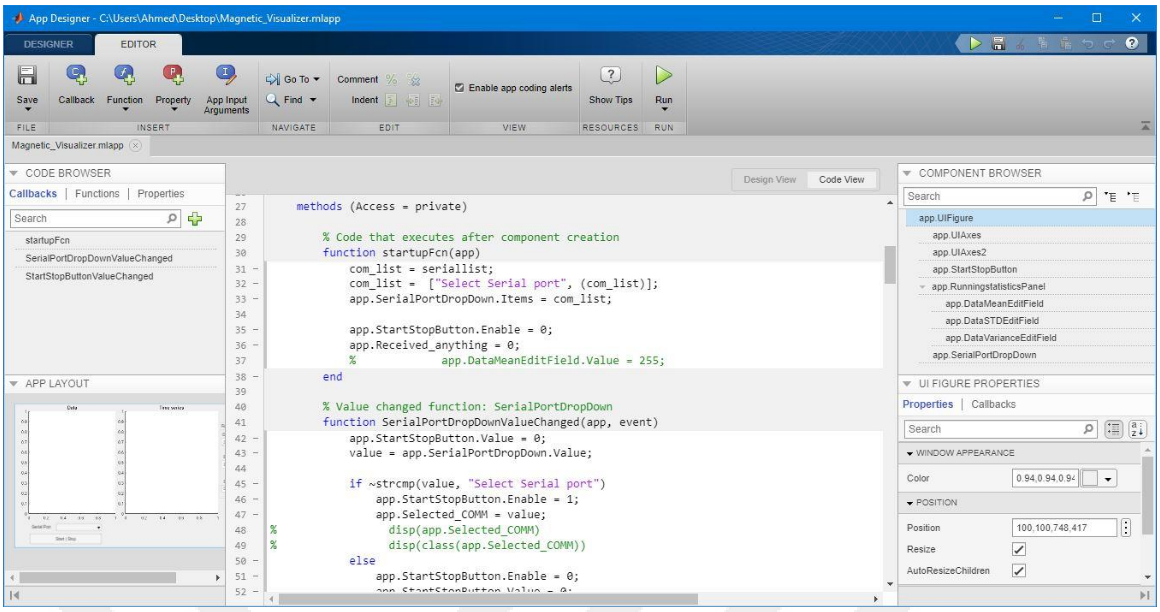


Figure 4.12. Code Interface using MATLAB.

5. THEORY AND MODELING

Linear or analogue sensors produce a continuous voltage output that may be raised or reduced in response to a strong magnetic field. In linear output Hall effect sensors, as the magnetic field strength rises, the amplifier's output signal grows proportionately, until it saturates owing to the power supply's limitations. Any further increase in the magnetic field has little impact on the output and simply serves to drive it further towards saturation [55].

Bipolar and Unipolar Hall effect sensors are the two primary kinds. Bipolar sensors need a positive magnetic field (the south pole) to function and a negative magnetic field (the north pole) to discharge, while unipolar sensors require just a single magnetic south pole to operate and discharge as they move in and out of the magnetic field [56].

5.1. Theory of the Hall Effect

When a current-carrying conductor is put in a magnetic field, a voltage perpendicular to both the field and the current is produced. This is known as the Hall effect. The Hall effect's fundamental theory is shown in Figure 5.1. It depicts a current flowing across a thin semiconducting sheet (Hall element). The output connectors are parallel to the current direction. In the absence of a magnetic field (Figure 5.1), the current distribution is uniform, and the output has no potential difference.

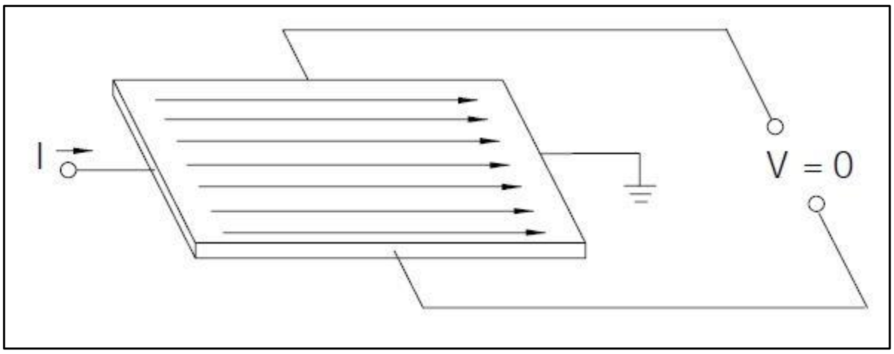


Figure 5.1. Hall effect principle, no magnetic field [57].

A Lorentz force is exerted on the current when a perpendicular magnetic field is present, as shown in Figure 5.2. This force creates a potential difference (voltage) across the output by disrupting the current distribution. That voltage is called Hall voltage. The following equation represents the interaction of the magnetic field and the current:

$$V_H \propto I \times B \tag{5.1}$$

Hall effect sensors can be used in a verity number of sensing applications and devices. The Hall sensor can perform the task if the quantity (parameter) to be sensed contains or may contain a magnetic field.

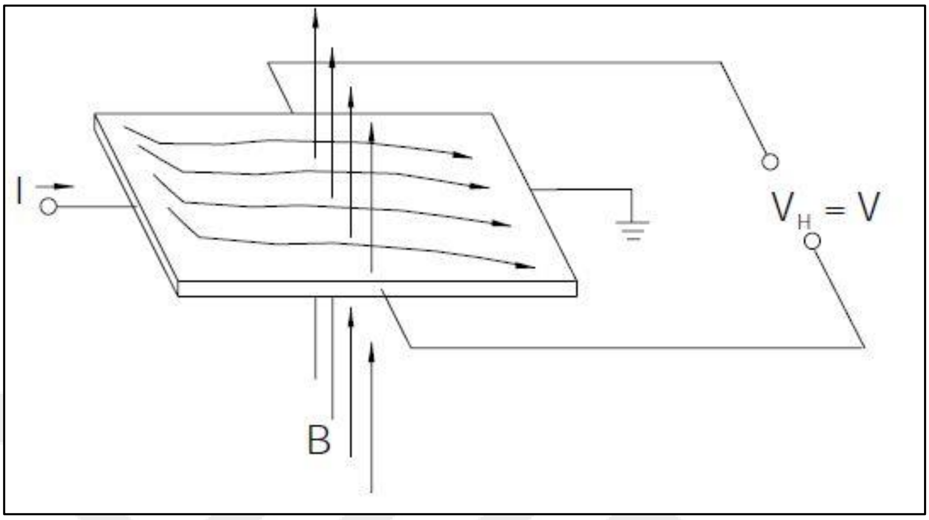


Figure 5.2. Hall effect principle, magnetic field present [57].

5.2. Transfer Function

A device's transfer function quantifies its output in terms of its input. The transfer function may be represented mathematically or graphically. The transfer function describes the connection between a magnetic field input (gauss) and a voltage output for analog output Hall effect sensors. Figure 5.3 illustrates the transfer function for a common analog output sensor.

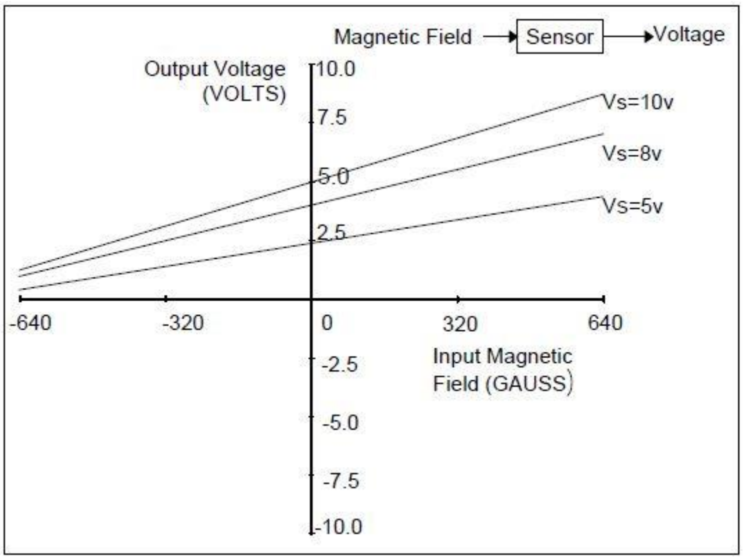


Figure 5.3. Transfer function (Analog output sensor) [57]

The following equation is an analog approximation to the sensor's transfer function:

$$V_{out}(Volts) = (6.25\ x\ 10 - 4\ x\ Vs)B\ +\ (0.5\ x\ Vs) \quad (5.2)$$

-640 < B (Gauss) < +640

The transfer function of an analog output sensor is defined by its sensitivity, null offset, and span. Sensitivity is defined as the change in output that occurs as a consequence of a change in the input. The slope of the transfer function shown in Figure 5.3 is proportional to the sensor's sensitivity. The factor B (6.25 x 10-4 x Vs) in the above equation denotes the sensor's sensitivity. Null offset is the output of a sensor that is not excited by a magnetic field. Null offset is the output voltage at zero gauss and a certain source voltage in the case of the transfer function shown in Figure 5.3. Second term Equation 2-2, (0.5 x Vs), expresses the null offset.

B- Field is calculated in two ways at the hall sensor: line integral and point technique. The magnetic field surrounding a current-carrying conductor is measured to determine current. The flux collector concentrates the magnetic field at the detecting element as the conductor passes through it. The current flowing through the conductor is precisely proportional to the magnetic field. As a result, the output voltage of the current sensor and the level of input current have a direct relationship. This output voltage's waveform will match the waveform of the measured current [58].

5.3. Hall Effect Sensor Modeling in MATLAB

Those sensors that are implemented in the system, are built in Matlab / Simulink based on theory and knowledge about those sensors that are implemented in the device. Figure 5.4 illustrates the hall sensor blocks. The model contains Low Pass filters to remove unwanted high frequencies and demodulating the system as well.

Since the model is based on theory, it is perfect and without limitations. The model consists of three (increasable) analog Hall-effect sensor components (as a sample) with filtered output signals. To create a digital output, the relays act as Schmitt triggers.

The model consists of three (increasable) analog Hall-effect sensor elements with filtered output signals. To create a digital output, the relays operate as Schmitt triggers.

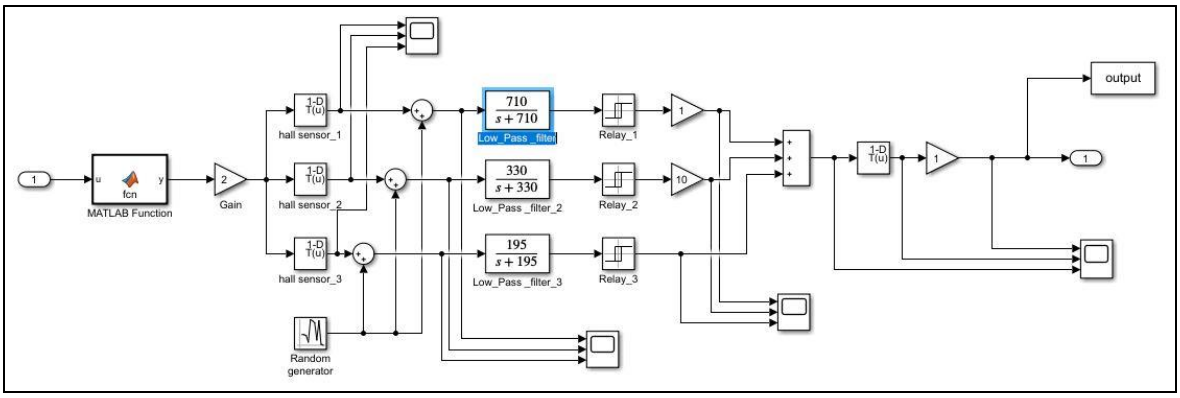


Figure 5.4. Hall-effect sensor model (3 sensors as a sample)

An input constant used to input value, then MATLAB function contains the main function of calculating the field for just one state and one value. The gain maximizing the input signal, we used three hall sensors as a sample of 64 sensors. Then using SUMs blocks for summation with randomly generated numbers and then the signals has been filtered using LOW PASS FILTER to keep low frequencies that we need and remove unwanted high frequencies.

After that, RELAYs are used to switch between signals and every switched signal has been gained with different value. Then adding them together using ADD block and put them to last accumulated hall sensor and gain it again to show the output in work space and scope.

As we have a matrix of 64 sensors, we can model all sensors with some sample values just like those got from the sensors like the array data shown in Table 5.1:

Table 5.1. Sensor data

342	339	351	375	378	382	377	369
325	325	357	426	461	411	397	376
299	259	237	647	649	484	403	399
278	164	58	667	665	561	432	391
287	166	57	117	663	563	433	390
287	214	69	110	520	479	415	375
320	295	249	278	364	393	385	373
337	323	326	319	345	357	361	373

And they are converted according to the equations 4 and 5 into values in Table 5.2:

Table 5.2. Sensor data in mT.

-12.2581	-12.1505	-12.5806	-13.4409	-13.5484	-13.6918	-13.5125	-13.2258
-11.6487	-11.6487	-12.7957	-15.2688	-16.5233	-14.7312	-14.2294	-13.4767
-10.7168	-9.28315	-8.49462	-23.19	-23.2616	-17.3477	-14.4444	-14.3011
-9.96416	-5.87814	-2.07885	-23.9068	-23.8351	-20.1075	-15.4839	-14.0143
-10.2867	-5.94982	-2.04301	-4.19355	-23.7634	-20.1792	-15.5197	-13.9785
-10.2867	-7.67025	-2.47312	-3.94265	-18.638	-17.1685	-14.8746	-13.4409
-11.4695	-10.5735	-8.92473	-9.96416	-13.0466	-14.086	-13.7993	-13.3692
-12.0789	-11.5771	-11.6846	-11.4337	-12.3656	-12.7957	-12.9391	-13.3692

And the combining sensors will be look like Figures 5.5 – 5.9:

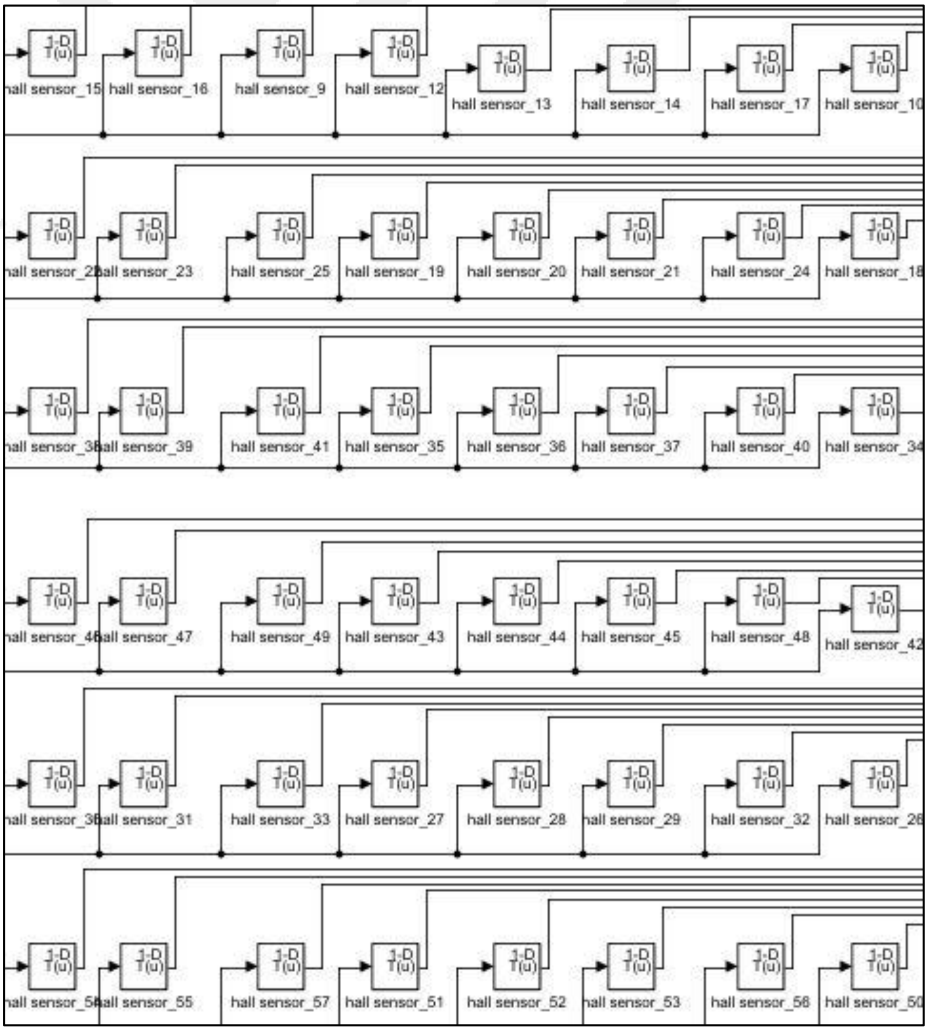


Figure 5.5. 64 matrix of hall sensors

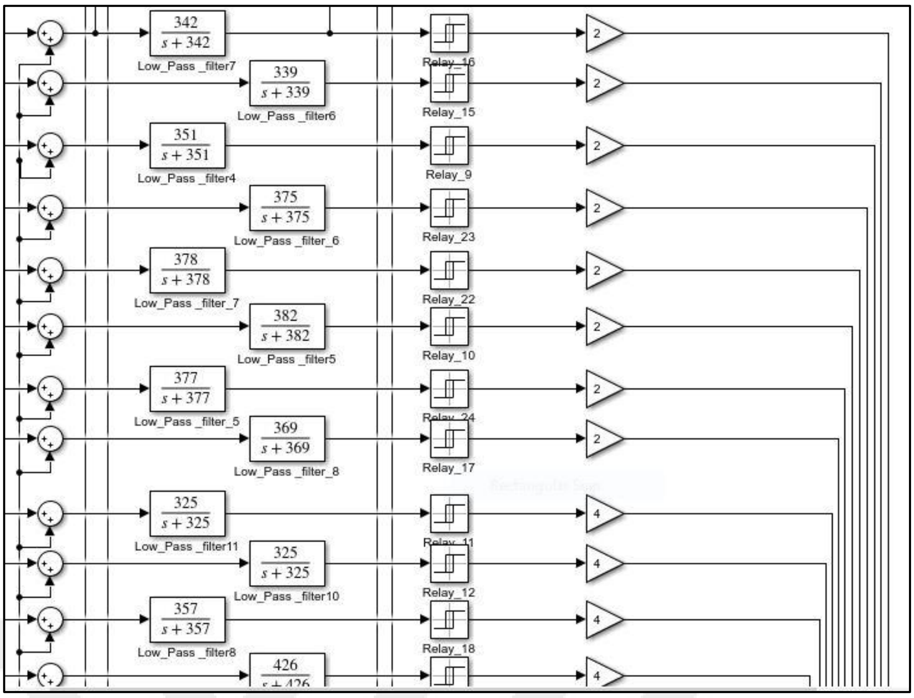


Figure 5.6. Giving the values samples using low pass filters and relay them.

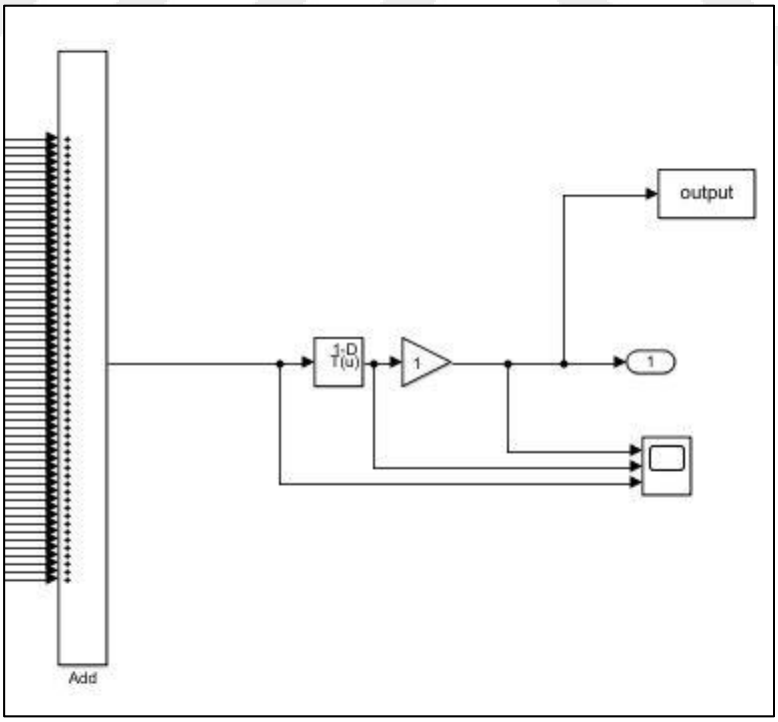


Figure 5.7. Combining the results and find the output.

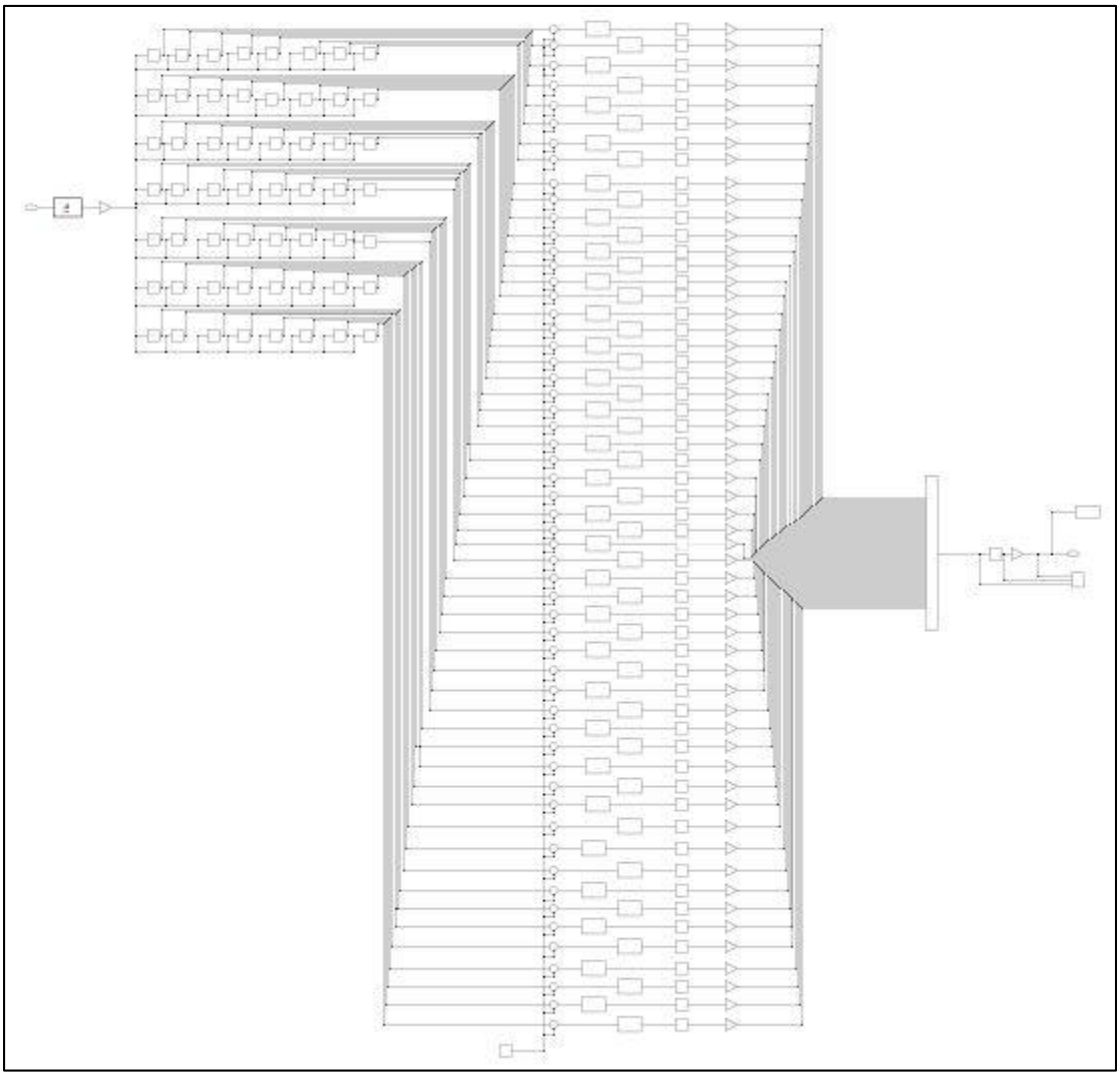


Figure 5.8. Modeling the hall system

And we can combine the repeated sensors and gains together by making subsystems like the Figure 5.9:

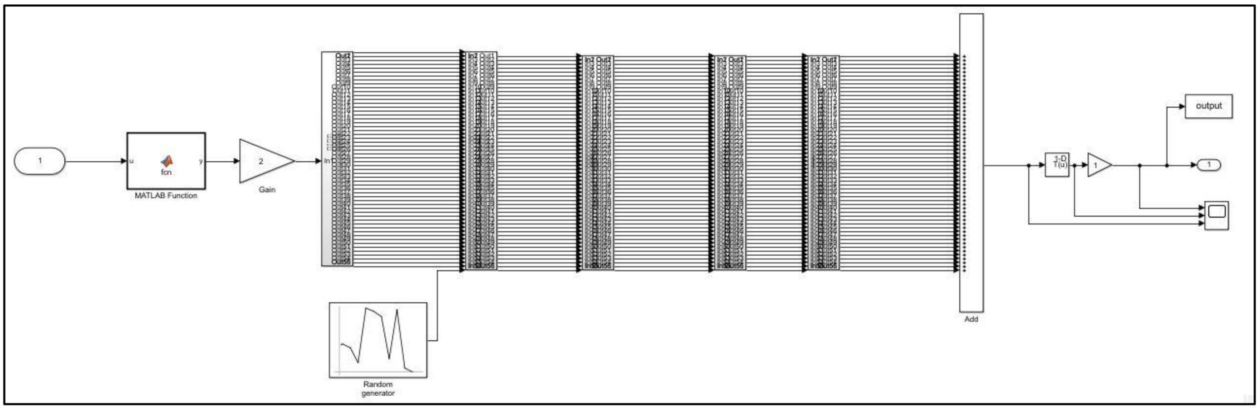


Figure 5.9. Modeling the hall system using subsystems

6. MATERIAL AND METHOD

This study is based on the principle of Hall Effect and signal converter. The board is small but it gives good results in addition to ease of use, low cost and power.

The magnetic field emitted from the material to be checked is converted to visual spectrum. Which means that magnetic fields can now be seen in real time, the magnetic sensors used on the tile are some of the most highly sensitive.

6.1. Used devices

1. The magnetic imaging tile (Hall magnetic sensors and converters).
2. Arduino Microcontroller (Chipkit MAX32).
3. MATLAB MathWorks and application designer (2018a version is recommended).

1. The magnetic imaging tile

This is a board intended to function as a magnetic field camera to visualize magnetic fields. https://www.aliexpress.com/item/32920944413.html

In this project, we use the ARDUINO microcontroller to implement the ADC principle. To test the field strength of a magnet, we'll utilize a Hall Effect sensor and an Arduino Chipkit Max32. The analog Hall Effect sensor that we used here is the DRV5053VA. This is a hall sensor that detects the strength of a magnetic field and outputs a changing voltage proportional to the field intensity.

6.2. DRV5053 Analog-Bipolar Hall Effect Sensor

So, with this sensor we will have field strength as varying voltage. By using ADC feature we will convert this voltage to a number. This number represents the field strength and is shown as a graph plotted on MATLAB as shown in Figure 6.1:

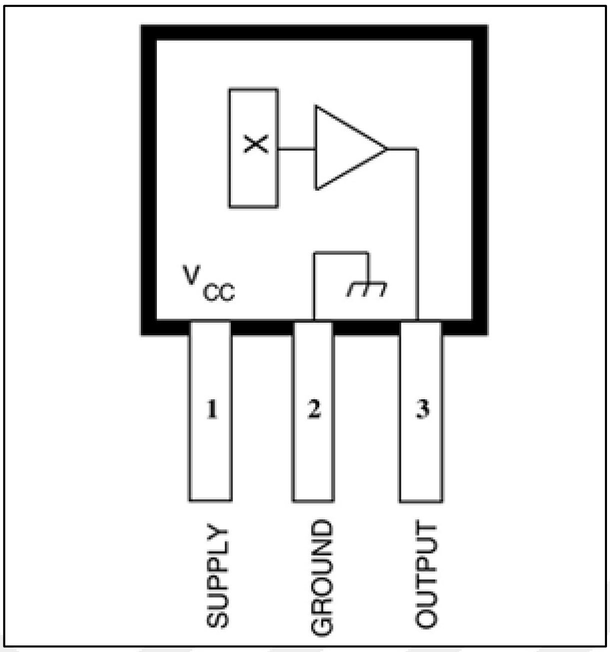


Figure 6.1. Functional Block Diagram.

6.3. Calculation of B-field

B-field at the center of Hall element is calculated by taking line (as shown in Figures 6.2 and 6.3) integral using the following expression:

*B = Scl: * (Integrate (Line (Polyline1), ScalarY (< B_x, B_y, 0>)), 10000)*

B-field at the center of Hall element is calculated at a center point using the following expression:

*B = Scl: * (PointValue (Point (Point1), ScalarY (< B_x, B_y, 0>)), 10000)*

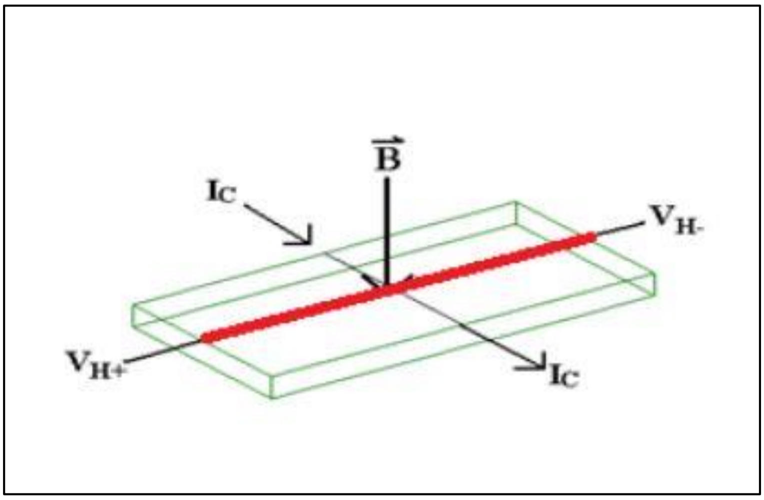


Figure 6.2. Line integral calculation of B Field [49].

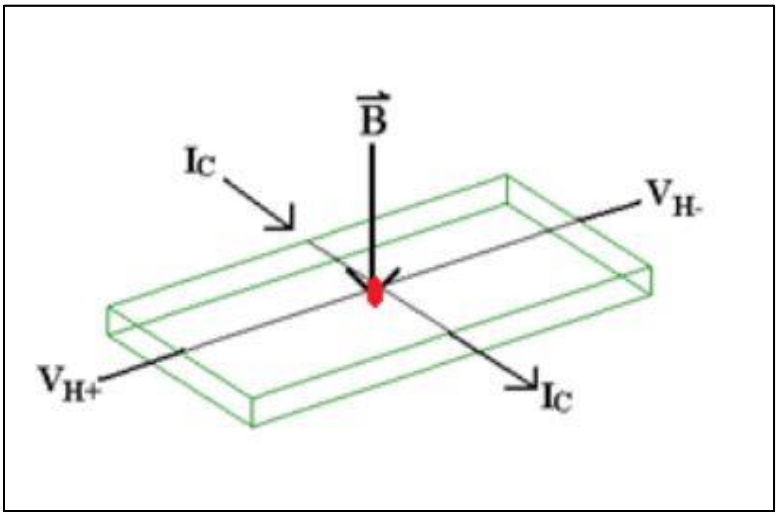


Figure 6.3. Point calculation of B Field [49].

Consider a current-carrying conductor that is surrounded by a perpendicular magnetic field. Current flows in a straight line in the absence of a magnetic field; however, when a perpendicular magnetic field is applied, electrons concentrate on one side of the material and positive charges build on the other, resulting in a potential difference called the Hall voltage. The voltage across the Hall plate is:

$$V_H = \frac{R_H}{d_H} = IBk_H \tag{6.1}$$

Where k_H is the sensitivity of the Hall generator, d_H is thickness of the Hall plate, R_H is the Hall coefficient, I is the current flowing in the conductor, and B is the applied magnetic field.

The transverse part of the flux density passing through the sensing element is linearly proportional to the Hall voltage output signal. Lorentz forces act on charges passing through a magnetic field, creating the Hall effect [59].

$$F_L = q\,.(V \times B) \tag{6.2}$$

$F_{hall} \propto B$

The input, output, and ground pins make a three-pin unit known as a hall sensor. In the presence of 10_4 T, the Hall sensor normally produces an output voltage of around 30 µV. An amplifier is sometimes already built into the chip to amplify it.

According to the datasheet of our used DRV5053VA Analog-Bipolar Hall Effect Sensor, the sensitivity of is –90 mV/mT and specified for Vcc of 3.3 Voltage as shown in Table 6.1, we can calculate Magnetic field in mT from all 64 sensors in real time in addition to the position of the field.

Table 6.1. DRV5053VA Characteristics [60]

DRV5053VA			Unit
S - Sensitivity	V_{CC} = 3.3 V	–90	mV/mT

We have the followings:

V_{out} = V0 – V1 = D (Data got from the sensor)

Sensitivity = -90

We can calculate B from the equation:

$$V_{out} = 3.3 \times \frac{D}{1023} \tag{6.3}$$

$$B = 1000 \times \frac{V_{out}}{S} \tag{6.4}$$

B measured by mT

7. Results and Discussion

Depending on the previous theories and equation, we can obtain an output of colors contains the magnetic field strength measured in mT by using Hall effect sensor. We chose an objects in multi positions and different speed and get the data to compare and analysis. For example, Figure 7.1 illustrates the object put in the middle of the tile (board).

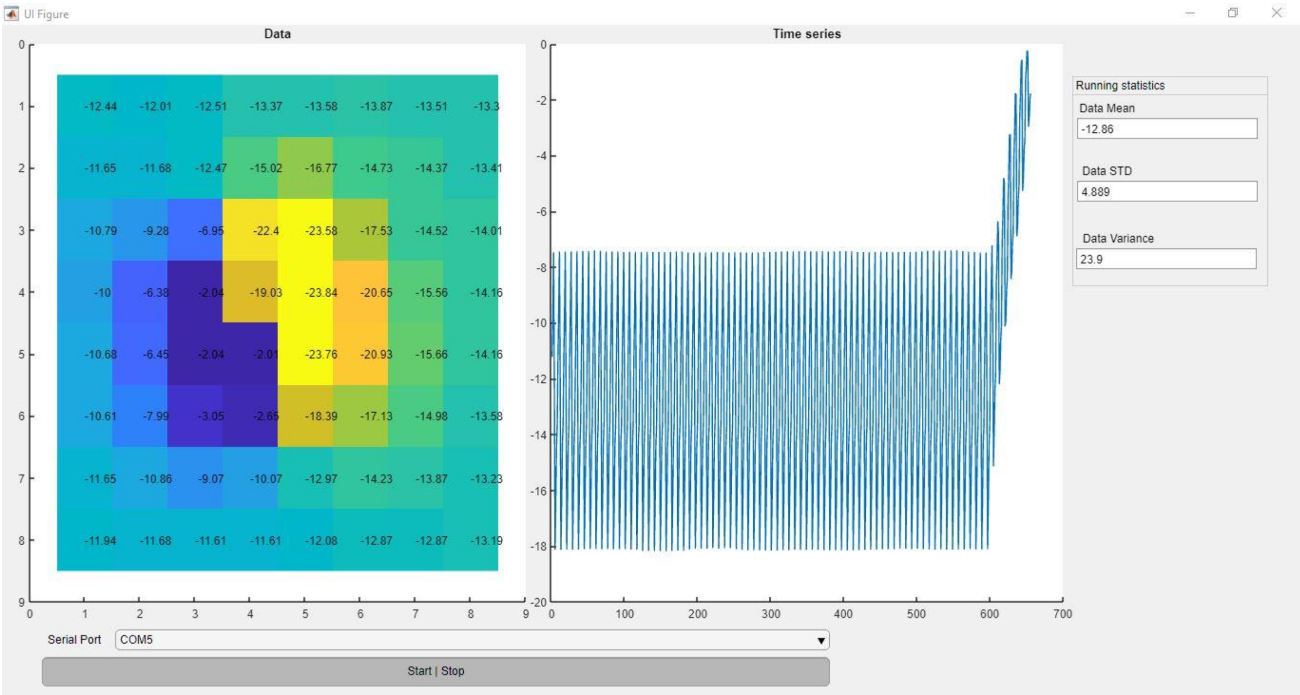


Figure 7.1. The object placed on middle of the board (blue is the North and yellow is the South).

Figure 7.1 shows as well as the data of time sequence and some statistical values such as Mean, Standard Deviation and Data Variance of all data in real time.

And the Figure 7.2 show a smaller object comparing with the previous object, the mean and other statistical information are different:

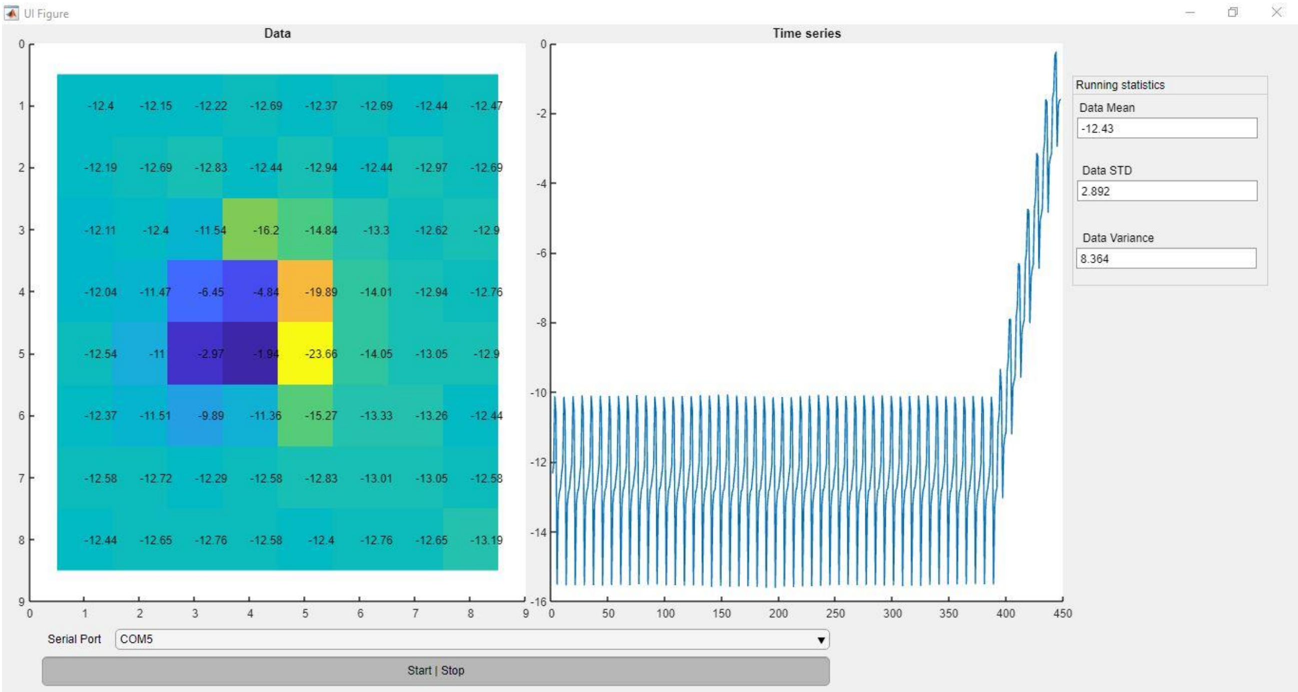


Figure 7.2. Smaller object placed on middle of the board.

Figure 7.3 shows different positions of an object placed on the board, we can put it in any positions.

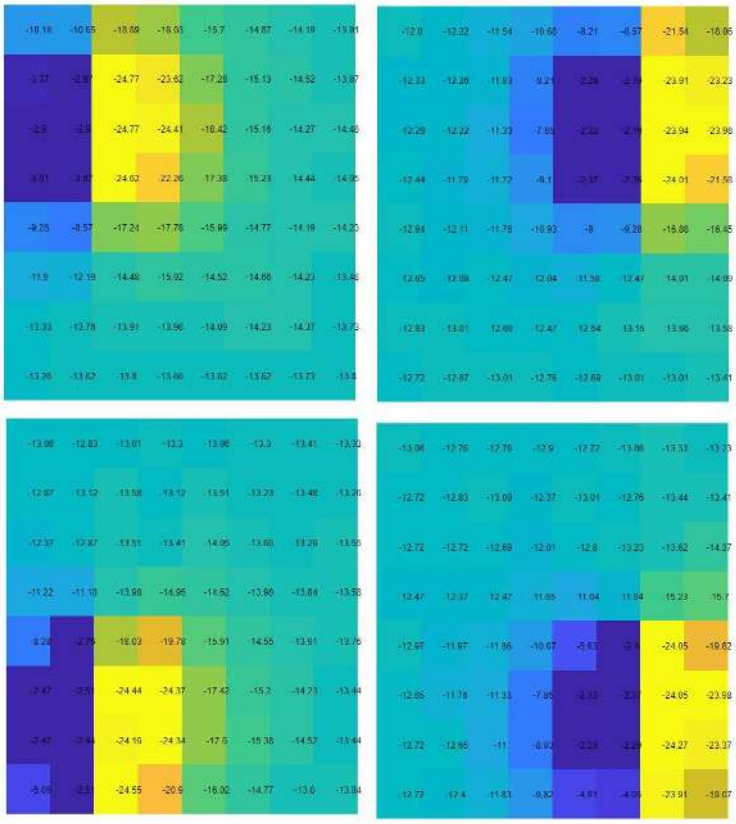


Figure 7.3. Different positions of an object placed on the board.

Proper QC documentation and magnet tests & methods can be created by putting the sample object (used for comparison) on the board (showed in Figure 7.4) and getting the data, then put other objects that we want to test and compare among them. We made three tests, one is the accepted state, and the other two states are not acceptable, as shown on Figures 7.5 -7.8.

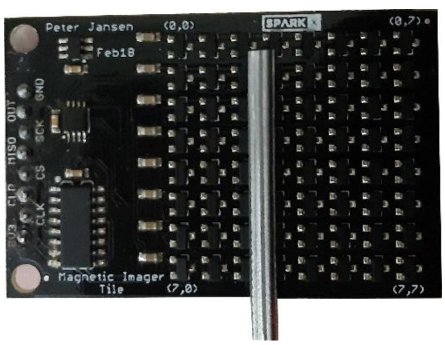


Figure 7.4. Sample test.

Now suppose we have a sample of Figure 7.4 and it's statistics are shown in Table 7.1:

Table 7.1. Statistics of sample test.

Mean	-12.72
Standard Deviation	2.355
Data Variance	5.548

And real time data are shown in the Figure 7.5:

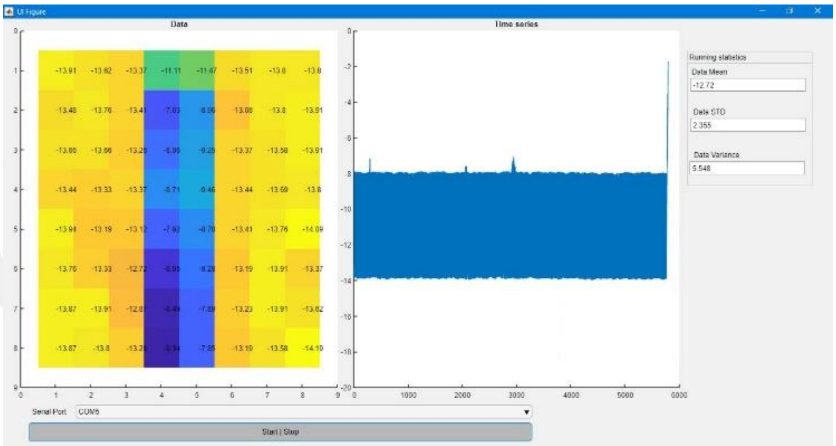


Figure 7.5. Sample of the test.

Now we apply three test states and compare with the first result (shown in Figures 7.6 – 7.9):

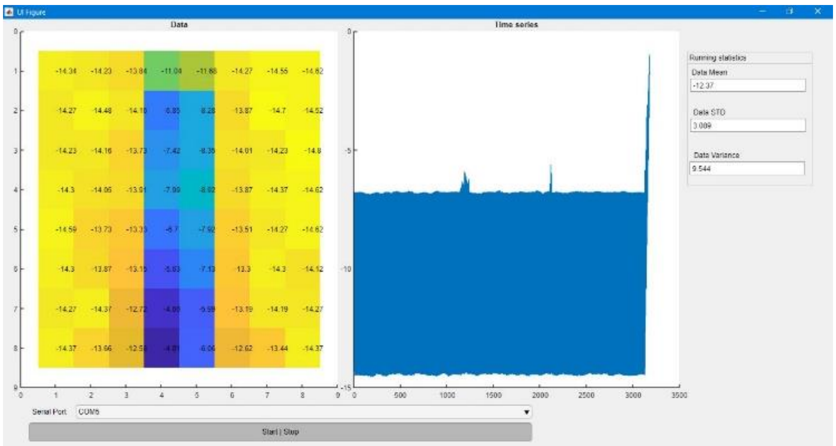


Figure 7.6. First test.

In Figure 7.6, we noticed that the data are shown in Table 7.2:

Table 7.2. Statistics of first test.

Statistics	New values	Sample Values
Mean	-12.37	-12.72
Standard Deviation	3.089	2.355
Data Variance	9.544	5.548

And comparing with the other sensor data, it means that this state is not acceptable.

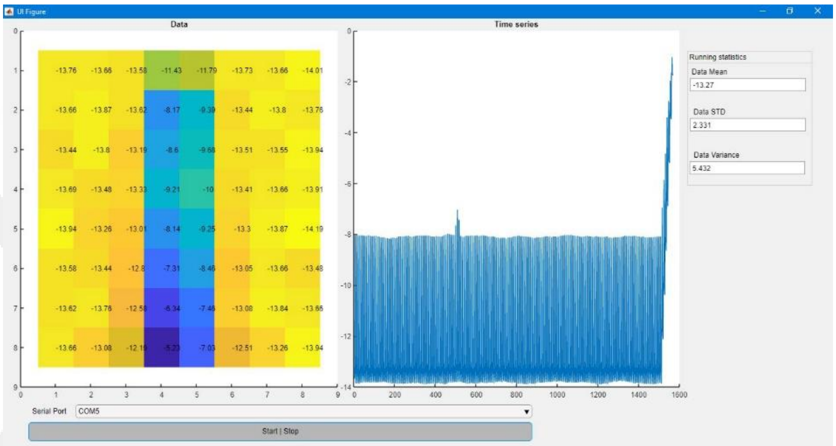


Figure 7.7. Second test.

In Figure 7.7, we noticed that the data are shown in Table 7.3:

Table 7.3. Statistics of second test.

Statistics	New values	Sample Values
Mean	-13.27	-12.72
Standard Deviation	2.331	2.355
Data Variance	5.432	5.548

And comparing with the other sensor data, this state is close to the sample state, so it means that this is acceptable.

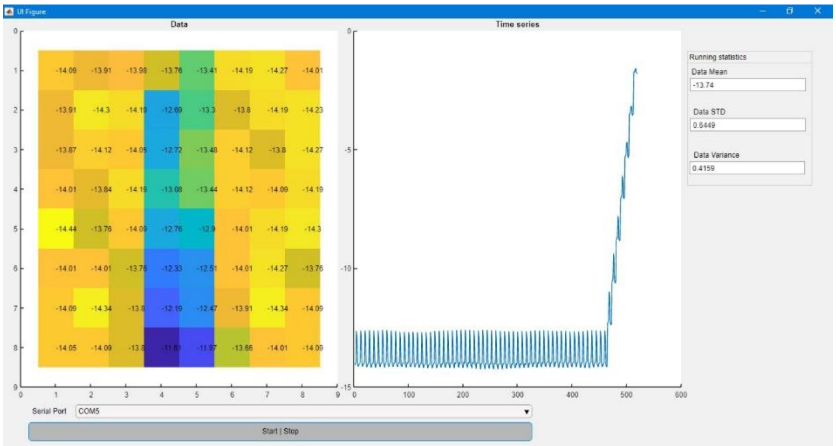


Figure 7.8. Third test.

In Figure 7.8, we noticed that the data are shown in Table 7.4:

Table 7.4. Statistics of Third test.

Statistics	New values	Sample Values
Mean	-13.74	-12.72
Standard Deviation	0.6449	2.355
Data Variance	0.4159	5.548

And comparing with the other sensor data, it means that this state is also not acceptable.

Another example for testing is testing two plates, one has magnetic properties while the other doesn’t contain it, shown in Figure 7.9 and 7.10:

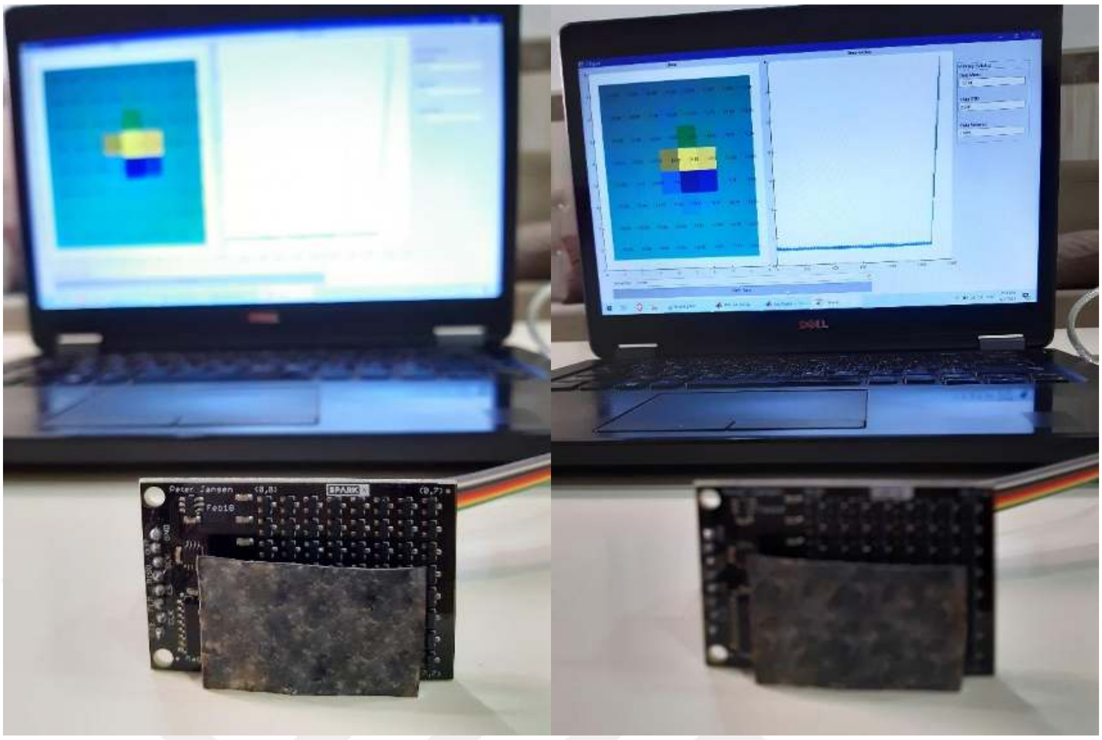


Figure 7.9. Testing a plate while magnetic field present.

Figure 7.10 shows the data of putting the plate on the board:

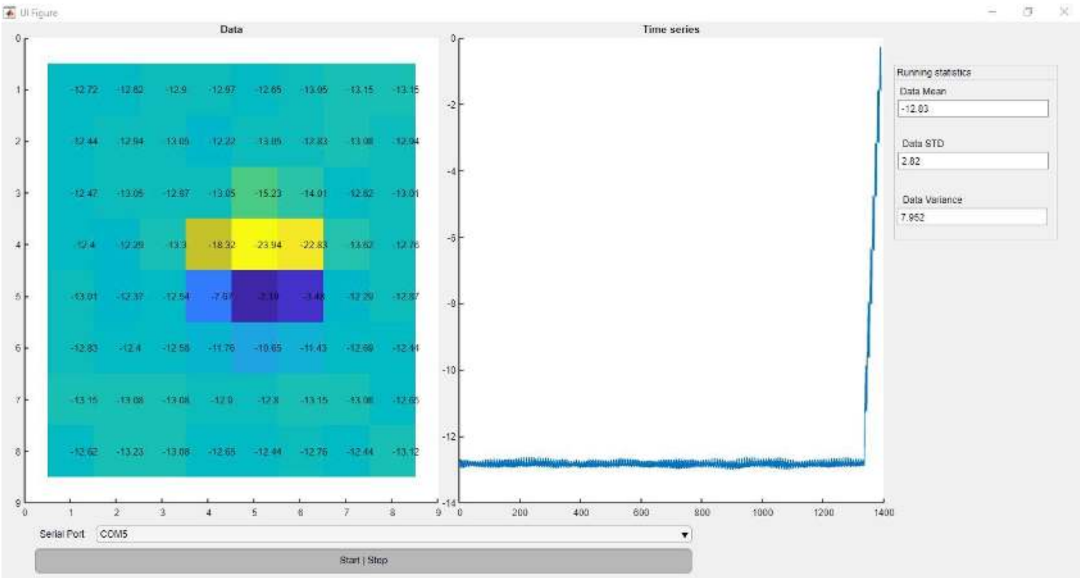


Figure 7.10. Data of testing plate while magnetic field present.

Figure 7.11 shows the testing an object without magnetic properties:

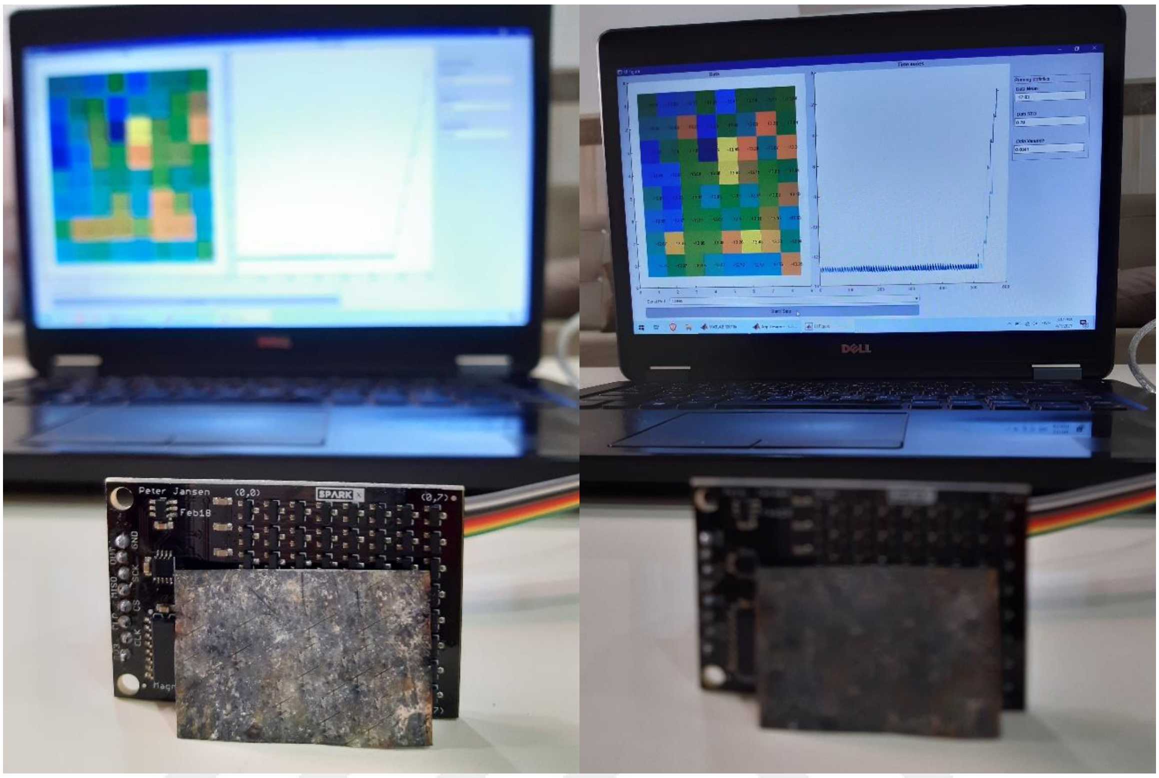


Figure 7.11. Testing a plate while not magnetic field.

Figure 7.12 shows the data of putting the normal plate on the board:

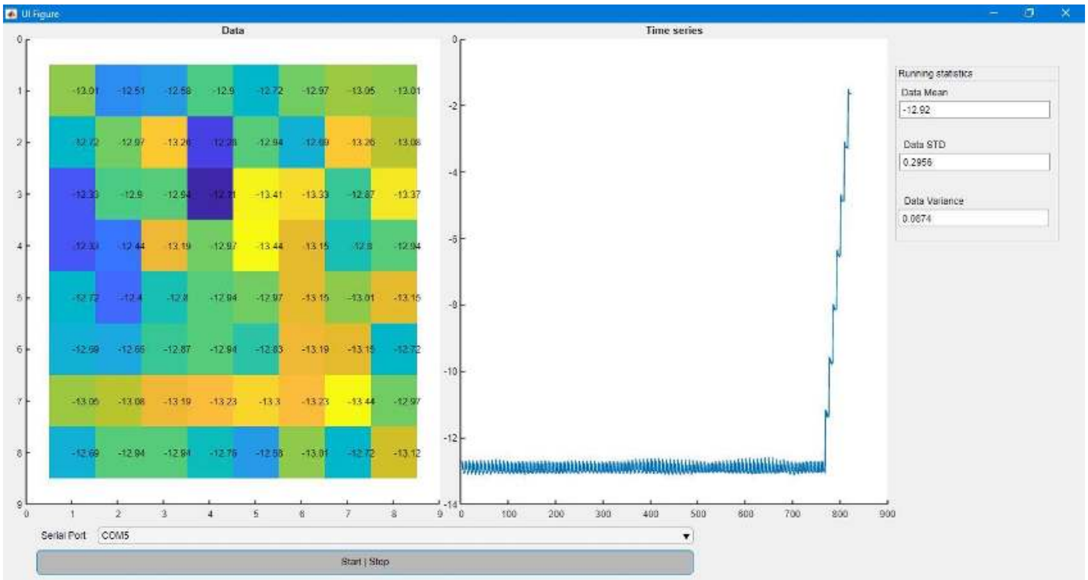


Figure 7.12. Data of testing plate while no - magnetic field.

8. CONCLUSIONS

There are many types of magnetic sensors and they are used in daily in our life because of their safety and relatively easy to use.

Signal processing and digital image processing is one of the main and important areas of the fields such as system engineering, applied mathematics and electronics engineering. In general, analysis on digital and analog signals can be knows as an application to many systems by determining temporal and spatial changes. Applying signal processing of sound signals, electromagnetic waves, visual elements such as pictures, the values perceived by the sensor could be used, and those signals control systems, communication systems, radar can be applied to many areas [61].

It is known that the Hall effect sensor is a device used in magnetic-field sensing applications in wide range, but by combining multiple sensors and using an amplifier and an adapter (Analog to digital converter - ADC), the result will be something different and interesting to work with.

In this research, it has been shown to us that the magnetic field imaging is not limited to high cost and expensive sensors, which also need difficult algorithms to work well as required. We used a normal and cheap sensor as a camera for capturing the magnetic field.

In addition to imaging the magnetic field, we noticed that we can see the strength and the position of the field. Not only single image, but real and live. And this can distinguish magnets and minerals that demonstrate magnetic properties and sort through according to strength and colors, and even just using the human eye. However, the magnetic field appears in colors, the human eye can clearly see and distinguish the field (because it shows the field as colors).

Although the sensor sensitive is relatively not very accurate, it offers an acceptable and reliable result in inaccurate uses and in cases of weak magnetic field as the used sensor (Hall Effect sensor) depends on the voltages principle (Hall voltage).

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APPENDICES

APPENDIX- 1: UNITS AND DEFINITIONS OF MAGNETIC FIELD TERMS

Magnetic field strength is one of two ways that the intensity of a magnetic field can be expressed. Technically, a distinction is made between the magnetic field strength H, measured in Amperes per meter (A/m), and magnetic flux density B, measured in Newton per Ampere-meters (N/Am), also called Tesla (T). In SI units, B is measured in Tesla (symbol: T) and correspondingly the magnetic flux is measured in Weber (symbol: Wb) so that a flux density of 1 Wb/m2 is 1 T. The SI unit of Tesla is equivalent to (Newton·second)/(Coulomb·meter)=Vs/m2. In Gaussian-cgs units, B is measured in Gauss (symbol: G). (The conversion is 1 T = 10000 G. The H-field is measured in Amperes per meter (A/m) in SI units, and in Oersteds (Oe) in cgs units.

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RESEARCH EXPERIENCES

- ✓ Hall Effect Sensor, Arduino Microcontroller (Chipkit MAX32)
- ✓ MATLAB, C
- ✓ Mathematics

ACADEMIC ACTIVITIES

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