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## Original Article

# Hysteresis analysis of Thornton (IP6, IP12E and TH5V) magnetic materials through the use of Arduino microcontroller

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## ABSTRACT

Electromagnetic devices have become increasingly important within the manufacturing industries and their applications ranges from memory devices, semiconductors to medical and bio-mechatronics (i.e. in the testing of medicines and observation of human internal organs). However, due to high cost and availability, the equipment capable of measuring the magnetic field of humane treatment and observations are difficult to acquire. This work is carried out to develop resources that can be widely adopted for the purpose of presenting science based medical results involved in bio-mechatronics analysis and present science based instrumentation strategy. Effect sensors were incorporated with an Arduino UNO microcontroller to serve as the interface between the sensors and the material. The basic parameters of an electric, magnetic and electromagnetic field were established for Histeresimetro development. This would reduce the problem of measuring magnetic fields and sort different materials according to their behavior when subjected to electromagnetic fields. The proposed strategy could also be adopted to measure the degree of hysteresis of materials at a lower cost.

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## 1. Introduction

Technological revolution involves the adoption of new materials that are developed to meet the frequent demands of modern consumer products at minimum cost, greater durability, and better product performance criterion. The selection

of these new materials for specific applications requires the basic understanding of their parametric and magnetic characteristics, physical, mechanical, electrical and chemical properties, in relation to their electromagnetism properties [1–4]. This is important in order to meet up with the pace of innovative development of magnetic materials and to develop devices that could be widely used for the purpose of enhancing the scientific knowledge base in the area of magnetic fields measurement and equipment development. The magnetic materials play an important role in modern technology hence they are found in a large number of applications in

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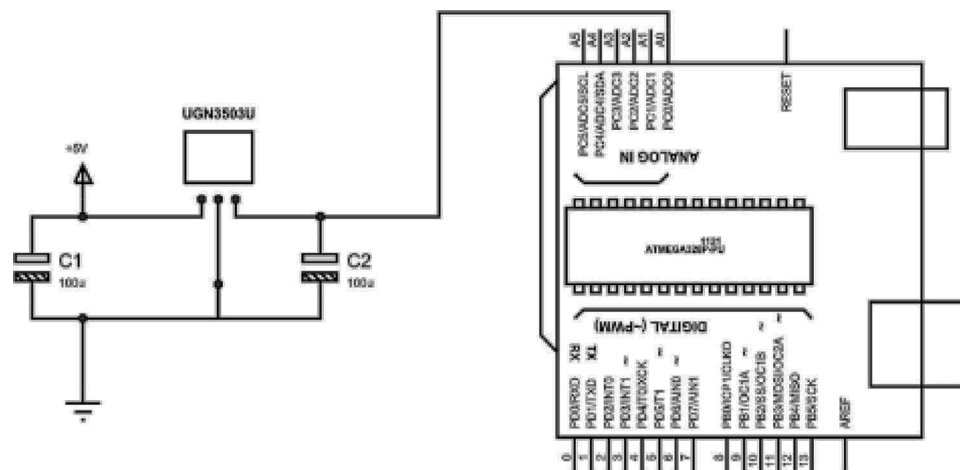


Fig. 1 – The schematic diagram of the Arduino microcontroller with the sensor.

the industrial processes and in different consumer's product. The applications of magnetic materials include devices with simple functions such as small magnets, door locks, furniture and numerous sophisticated components within the electronics industries (medical, industrial laboratories and research centers). For example, from a simple compass (used for navigation) to telephone and telegraph (based on Oersted principle) [5], for data storage on magnetic tapes and devices, etc. Furthermore, magnetic materials were adopted for the development of devices in medical applications that are used for hyperthermia (to eliminate tumor malignantly) and for the application of drugs in the human body [6–9]. They are also used for the development of electrical equipment, electromechanical devices and electronic component. Ferromagnetic materials are commonly used for these devices due to their functional parameters, higher operational efficiency and lower energy usage [10]. The evaluating equipment consists of an electromagnet, an electric current source, a magnetic field sensor and a positioning system sample. The variations in the sensitivity (i.e., field detection capability) of the magnetic-field sensors enable it to be adopted for various applications in system measurement [7–9]. It has been reported that the magnetic field affects the function ability of sensors when electrical current flows through them <http://www.meccanismocomplesso.org/en/arduino-magnetic-magnetism> and hence the magnetic force (in Gauss) exerted on each sensor can be deduced. Also, some authors [10–12] suggested that the use of Arduino platform could be adopted in designing and developing components that encompass the concepts of electromagnetism. Hence, few researchers proposed the use of experimental techniques such as neutron diffraction, resonance magnetic and optical spectroscopy [13–15] to evaluate the microscopic properties of the said materials. Some materials are directly associated with magnetism by presenting high spontaneous magnetization below the Curie temperature [16]. This is possible because there is an interaction between the atomic magnetic moments and its direction [17–19]. Examples of such elements are ferromagnetic iron, which has atomic number 26, cobalt (27), nickel (28), gadolinium (64), terbium

(65), dysprosium (66), holmium (67), erbium (68) and thulium (69). The magnetization of all these materials is higher when compared to the paramagnetic and diamagnetic materials, which have no linear relationship to the 'H' field (where H is in amperes per meter A/m) [14,15,17,20].

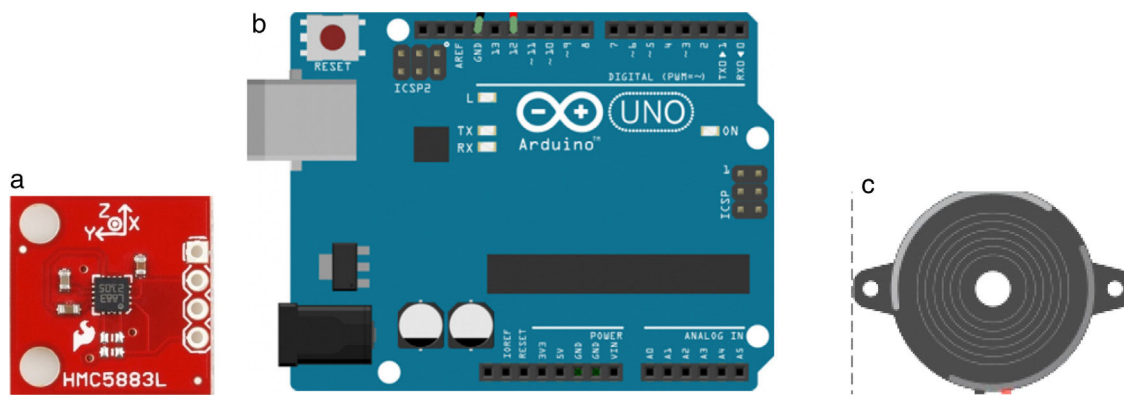
This work considers the Hall effect characteristics of IP6, IP12E and TH5V Thornton magnetic material with the intention to design and establish a magnetic-field measuring device using Arduino under the Curie temperature without generation of heat by the device to disorient the magnetic particles of the materials. The methods and results previously proposed by researchers [15,17,18] were extended for more advanced and further analytical techniques using a 12V generated by a computer system connected to the Arduino UNO to generate the necessary voltage needed for the device to actuate. This help to reduce the heat generated by the device, thereby keeping the arrangement of the particles intact without being disorganized.

Proteus and MATLAB were used for the analytical simulation of the device to determine the necessary improvement, accuracy and reliability of the result obtained. In this work, the construction of a Histeresimetro using the Arduino platform, micro controller and sensor is proposed. The proposed set up of the model is as shown in Fig. 1. Therefore the aim of this work is to build a low cost equipment, capable of measuring the magnetic field and variations of the magnetic field due to external interference, with commercially available Hall effect A1301 sensor.

## 2. Research methods

### 2.1. Materials and methods

The Hall effect sensors were adopted for this application. The Hall effect sensors can perform data acquisition and are cheaper compared with other sensors that are readily available. Among the features that stand out are the durability characteristics, easy control interface, operational stationary inlet, and high operational speed of the sensing device. The



**Fig. 2 – (a) Magnetometer HMC5883L; (b) Arduino A4 HMC5883L SDA; (c) Arduino GND (HMC5883L).**

solid-state magnet can be operated over a wide range of temperature between  $-40$  and  $125$  °C [17–19]. The A1301 Hall effect sensor manufactured by [20,21] is selected for this work. This is due to the fact that they are optimized to provide accurately a voltage output proportional to the applied magnetic field. The A1301 devices have a state or period of inactivity or dormancy output voltage that is equivalent to 50% of the supply voltage. These features make the A1301 to be ideal for the position sensing systems sensor, for both linear and rotational target motion. They are also well-suited for industrial applications over temperature ranges, from  $-40$  to  $125$  °C [1,2]. The size of the commercially available A1301 Hall effect sensors ensures a digital output signal that could be easily read. However, digital signals are not easily interpreted when reading the data. Therefore, for the chosen sensor to provide the output signals that is proportional to the magnetic field in an analog format, the sensitivity of the sensor has to be  $2.5$  mV/G [2,3]. Hence, in designing the experiment, the magnetometer (HMC5883L) that represents the Hall effect sensing element, Arduino A4 (HMC5883L SDA) that stands for the linear amplifier and Arduino GND (HMC5883L) that represented the CMOS transistor at the output are considered as shown in Fig. 2.

Integrating the amplifier and the sensing element (HMC5883L) to the Hall effect sensor (A1301) eliminates the low voltage analog output signal that could have being created without the integration. The coil built around the Hall effect sensor support has been made with copper wire covered with insulating varnish with a thickness of 24 American Wire Gauge equivalents to  $0.51054$  mm. The dimensions of the coil were calculated in such a way as to provide a uniform magnetic field within the central region of the coil, and to have sufficient intensity to promote a proper orientation in samples used and thus promote the correct reading by the sensors [17–19,22]. The winding of the turns was done manually with three layers and proper insulating varnish being set for the application. The varnish played the role of fixing the coils and keeping compact the winding. A sealed battery is utilized in order to keep the power in the coil stable, while the coil drive was used as rheostat because of the need to vary the potential difference supplied. A stepper motor was used to place the samples within the support. A micro

controller, Atmega328P-PU was selected to perform the control of the stepper motor.

The Arduino is a platform design which seeks to facilitate the use of hardware and software. In this work, an open-source software and hardware that comprises of the Arduino UNO boards, Arduino Mega 2560, Arduino Micro, Arduino Nano, Arduino Wireless and Arduino Pro Mini were used to control the different directions, the amount of steps and the speed of the stepper motor. A circuit driver ULN2003 is required in addition to Arduino, which provides the correct drive to the motor coil setup. The ULN2003 is an array of Darlington transistor high voltage and current; it contains seven pairs of collector's Darlington with common entries [13,23,24]. Each channel supports a peak current of about 500 mA and 600 mA. This component is very versatile and useful in targeting a wide range of solenoids, DC motors, LED displays, heads printers and high-power buffers. The combination of these components and connections for magnetic field detection makes this research novel in the field of hyperthermia. This could be adopted to diagnose tumors malignantly and for the application of drug's treatment and production in the medical research area. The desired result is achieved by varying the use of the micro controller, varying the inputs, outputs, memory, oscillators, voltage regulators on the software platform. Due to the high level of complexity of this project, the Arduino UNO model is selected and a simplified model is proposed that presents sufficient resources for the implementation of this equipment. In addition to the integrated development environment (IDE) card interface, the Arduino program software is also available in Arduino IDE software and Proteus software as shown in Fig. 3.

Different complex programming codes have been proposed in literature [13–15,17,23,24], however, for this work the code in Fig. 3 is adopted for its simplicity and understanding. To read the values of the Hall effect, the same Atmega 328 micro controller implemented in Arduino UNO platform sensors was selected, as well as the module stepper motor control. The Arduino card interface allows easy sensing of the devices, thus enabling the reading of values on the computer output display unit. The positioning of the sample and the acquisition of the magnitudes values of the experiment occurs automatically.

```

void loop() {
  if (!(avgDone)) {
    for (int i = 0; i < 100; i++) {
      for (int j = 0; j < 3; j++) {
        b[j] += B(i);
      }
    }
    for (int j = 0; j < 3; j++) {
      b[j] /= 100.;
    }
    double Bx[3];
    for (int i = 0; i < 3; i++) {
      Bx[i] = B(i) - b[i];
    }
    for (int j = 0; j < 3; j++) {
      Serial.print("B");
      Serial.print(j);
      Serial.print(" =");
      Serial.println(Bx[j]);
    }
    delay(5000);
  }
}

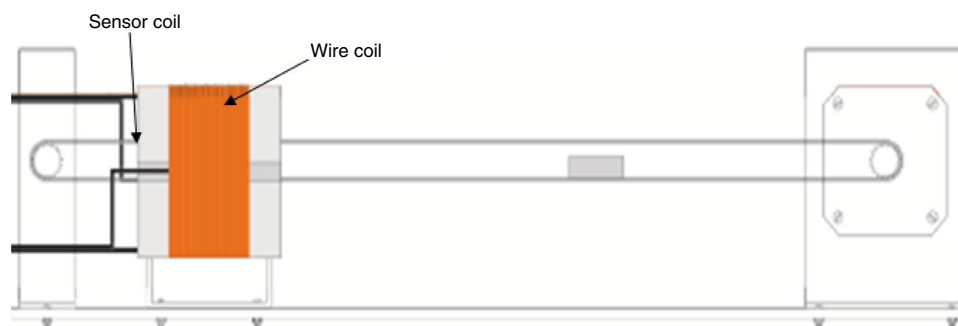
```

**Fig. 3 – An Arduino short programming code [22].**

### 3. Development of the Histeresimetro

For the construction of the equipment, an initial project was set up as shown in Fig. 4. The coil has the sensors mounted on the stepper motor and the strap with the sample port of machining and uses the dowel cylindrical TECHNYL support for winding the coils. The sensor is located on a stepper gear motor and a ribbon (belt) gear, which showed very adaptive effect to the application, so that when moving the stepper motor belt, that carries the door sample, to the center point of the coil it allows the proper conduct of the measurement.

With the Hall effect sensor, magnetic field strength is created by varying the voltage. This voltage is converted into binary coded decimal BCD coded numbers (displayed on the LCD) through the use of the Analog Digital Converter ADC feature. This BCD numbers represents the field strength. Arduino has six ADC channels that could be used as inputs for analog voltage. The UNO ADC is of 10 bit resolution (so the integer varies from 0-(210) (1023)). This means that it will map out the input voltages between 0 and 5V to integer values of between 0 and 1023. This implies that for every input voltage of 5V gives integer value of 4.9 mV (i.e.  $5/1024 = 4.9$  mV) per unit. The sensors were positioned and secured with glue inside the TECHNYL recesses of the support as shown in



**Fig. 4 – Positioned sensors below coil of Histeresimetro.**

Fig. 5. Once positioned, the sensors were rolled with coil in the recessed area of the TECHNYL support. The support was turned to having the recess that allowed these sensors to have a coil wound with less difficulty. A 'push-button' was also mounted on the plate where the connectors of the sensors were fixed. This is to 'START' the stepper motor and ensure the travel positioning of the sample in order to automatically begin the sensor readings when specimens were appropriately positioned in the center sensor. The sensors were connected via wires attached to a plug-in pin. This reduces the soldering time considerably. Once the connectors were mounted in placed under a heat shrink that cover each of the sensor terminals, it is being isolated from each other. The position sensor is used to locate the lines field produced by the inductor that fall perpendicularly to the sensor element. This position made the acquisition of the magnetic-field measurements more reliable. The Arduino IDE program 1.0.1 was activated. This program waited until the button was depressed. The button once triggered, actuate the stepper motor to position the sample TECHNYL inside the support. The outputs from the sensors were read while the engine was not in the positioning step. Then the data acquisition module is initiated at the center position and data were made available to the serial port of the Arduino. The data were collected from an application that is linked to the serial port to a data file in Excel format. When the button was depressed again, the motor returns the sample to the starting position. The Hall effect sensors were connected to analog ports 0-4 on the platform Arduino. The button was connected to the digital port 1, and the stepper motor drive was timed resulting from several calibration measurements. The equipment assembled in Fig. 5 is used to carry out several tests with samples varied from different commercially available ferrites materials. Four samples were selected that consists of ferromagnetic materials in the form of ferrites that are used for the manufacture of core inductors and electric transformers. The magnesium ferrite (MnZn) presents a high permeability and low resistivity material is used as a core to generate frequencies up to 50 MHz [11,12]. The IP6, IP12E and TH5V are Thornton ([http://www.thornton.com.br/pdf/CATALOG%20THORNTON\\_ing.pdf](http://www.thornton.com.br/pdf/CATALOG%20THORNTON_ing.pdf)) ferrite cores, produced in Brazil. These ferrite cores have variable material properties [10]. Magnetic materials are characterized by their permeability. Permeability is the degree of magnetization of a material in response to a magnetic field. The permeability standards of used samples are as enumerated in Table 1.



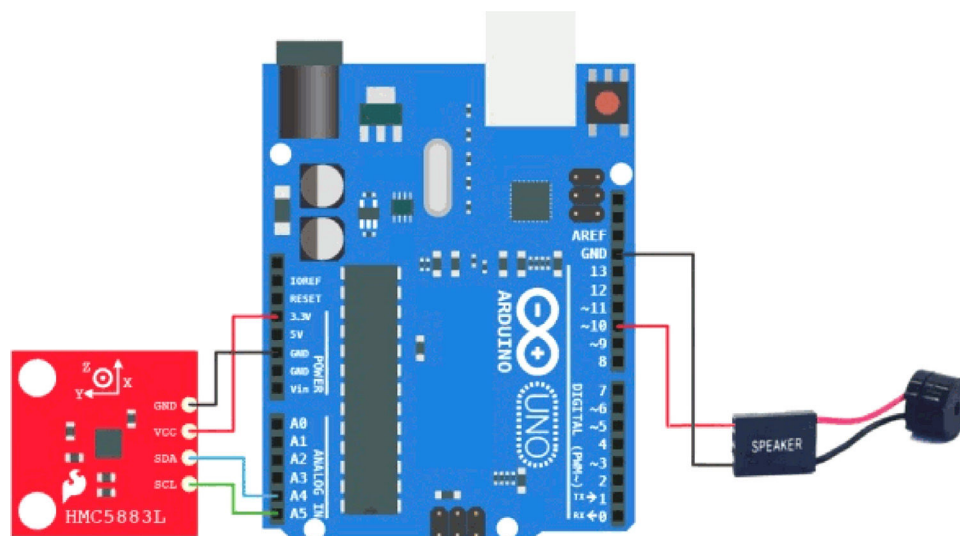


Fig. 5 – Connection of magnetic field measurement with an Arduino and A Hmc5883L.

Table 1 – Permeability standard of used samples [11,12].

Material	IP6	IP12E	TH5V
Initial permeability	2000 ± 25%	2300 ± 25%	5000 ± 25%
Temperature (°C)	≥165	≥209	≥129
Flux density of 10 Oe, 24 °C [10 <sup>-3</sup> T]	-	-	391
Flux density of 15 Oe, 24 °C [10 <sup>-3</sup> T]	479.70	509.5	-
Constant hysteresis [10 <sup>-3</sup> /T]	≤8.0	-	≤1.3
Factor disaccommodation (D <sub>F</sub> ) [ppm]	10	-	-
Density [kg/m <sup>3</sup> ]	4799	4799.5	4901

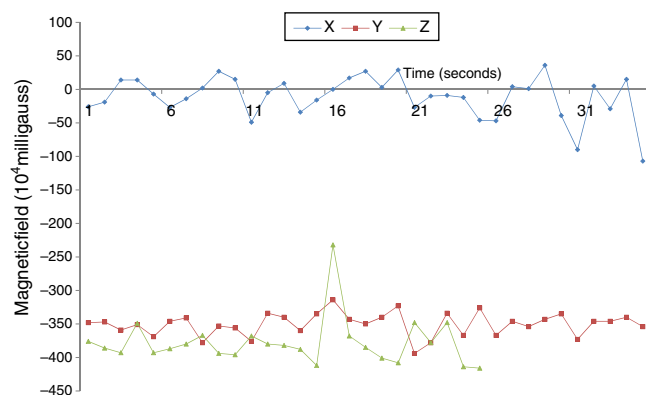


Fig. 6 – The X, Y, and Z coordinate of measurement with the device.

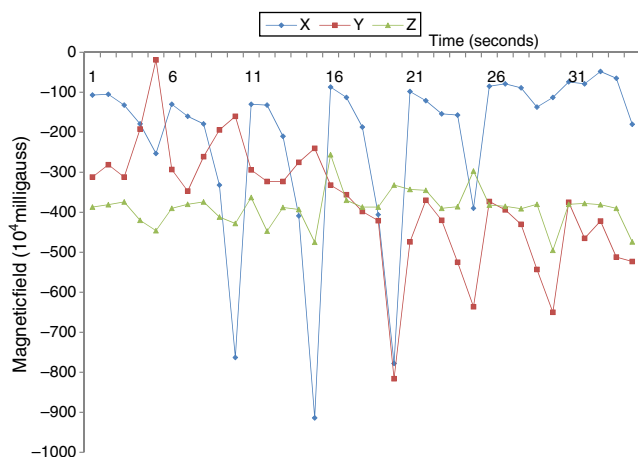
#### 4. Results and discussions

Fig. 6 presents the value of the magnetic reading along the X, Y, and Z coordinate measured with the device. It was ensured that the value of the magnetic field displayed at the output screen of the PC was stable with time before recording of the readings serially. From Fig. 6, the X-axis is the time in seconds that affect the series of the magnetic field for the magnetometer, and the Y-axis is the magnetic field in the milligauss output from the system for each series of the experiment. Since the purpose of this research is to measure the magnetic field around the earth in the beginning of the run while keeping the magnets far from the sensor, it is important to move the magnetic field to be mapped closer to the sensor and record the values obtained for each position in respect to the sensor. From each value, the corresponding value when the magnet is far from the device is subtracted to give the accurate

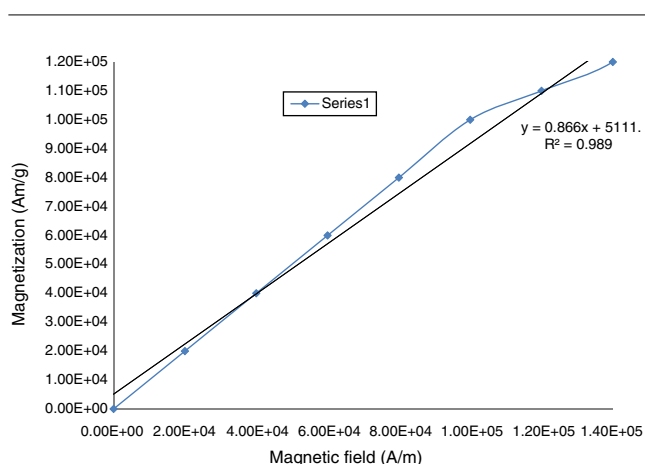
magnetic field value. This is done in order to eliminate the contribution of the earth's magnetic field and influence on the measured magnetic field of the sample. The values are represented in Figs. 6 and 7. After all the values have been obtained, a session was open in MATLAB software to define a matrix SX and SY containing the measured values respectively for X and Y from the measured value. This makes the spatial distribution of the measurement to be reliable. This was carried out repeatedly, and the value is as represented in Fig. 7.

Fig. 8 represents the hysteresis curve of the observed values for the magnetic field on TH5V sample material in line with the values of magnetization and the loop component in the first quadrant. The measurements reflected in Fig. 8 were obtained from the TH5V sample after being thermally treated to relieve the stress within the material.

It was observed that the measurement obtained from the proposed equipment is found to be relatively comparable with the commercially available devices with a high level of accuracy after due calibration.



**Fig. 7 – The X, Y, and Z coordinate of measurement with simulation software.**



**Fig. 8 – Hysteresis curve for sample in the first quadrant.**

## 5. Conclusion

This work presents the results from the data acquired from the measurement of the magnetic field using Arduino and simulations of the average values of the magnetic material. The result obtained shows the possibility and verification of the consistency of the device, which showed satisfactory results. The following conclusion can be deduced from the study thus:

1. The basic parameters of an electric, magnetic and electromagnetic field were proposed and established for Histeresimetro development.
2. This work proposes the incorporation of Arduino UNO within the measurement system as a series of embedded magnetic sensors along with the magnetic field. It establishes the types of materials and their magnetic classification and solves the problem of measuring magnetic fields and sort materials according to their behavior when subjected to electromagnetic fields.
3. The optimization of a density magnetic field to enhance the sensitivity of the device was also proposed in order to measure the degree of hysteresis of particular materials at

a lower cost that satisfy the economic objectives for commercialization since the interface between the sensors and the user is made through an Arduino UNO.

4. The proposed measurement strategy and equipment requires minimum operational energy hence the cost of expensive energy and heat generation during magnetic-field measurement is saved.

## Conflicts of interest

The authors declare no conflicts of interest.

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