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Measurement system for testing the magnetic field uniformity

***Abstract**. The article describes a measurement system for magnetic field scanning using a CNC plotter. Comprehensive studies have been conducted on various materials, confirming the effectiveness and precision of the system in analysing the uniformity distribution of the magnetic field*

***Streszczenie.** W artykule opisano system pomiarowy, który opiera się na skanowaniu pola magnetycznego nad powierzchnią materiału płaskiego z wykorzystaniem plotera CNC. Przeprowadzone zostały kompleksowe badania różnych materiałów, które potwierdzają skuteczność i precyzję systemu w analizie równomierności pola magnetycznego. Zaprezentowane wyniki stanowią podstawę kontynuacji prac technologów nad doskonaleniem właściwość materiałów magnetycznych oraz ich dalszej klasyfikacji. (**System pomiarowy do testowania** **Jednorodności pola magnetycznego**)*

Keywords: CNC scanner, magnetic scanner, magnetic field map, magnetic field uniformity.
Słowa kluczowe: skaner CNC, skaner magnetyczny, mapa pola magnetycznego, jednorodność pola magnetycznego.

Introduction

In today's times, magnetic measurements play a crucial role in various fields such as industry, science, and medicine [1-4]. Precise and accurate measurements of magnetic induction on the surfaces of different objects are essential for understanding their magnetic properties and evaluating the quality and characteristics of materials. To achieve increasing precision and efficiency in magnetic measurements, new technologies and methods are being developed and utilised.

The concept of the presented measurement system is based on the use of computer numerical control (CNC) technology for precise and automated control of the magnetic scanner. This scanner has been specially designed and built to enable an accurate measurement of magnetic induction on the surfaces of various paramagnetic and ferromagnetic materials. For this purpose, we employed a Hall effect probe, which is a sensitive measurement device for detecting changes in the magnetic field. CNC technology, which relies on the control of machine tools using computers and software, has wide-ranging applications in industry and also has significant potential in the field of measurements [5-7].

The scanner can perform a series of measurements at predetermined points on the material's surface with a specified resolution, enabling the acquisition of precise values of magnetic induction. Such a measurement system can contribute to the advancement of the magnetic measurement field by providing accurate and reliable data that can be applied in various scientific, industrial, and engineering domains. This allows the utilization of data obtained from the developed measurement system for material classification for specific applications. By analysing the acquired measurements and calculating statistical indicators from multiple measurements at individual points, the materials can be assigned to specific groups on their different magnetic properties.

With this approach, a measurement system equipped with a magnetic scanner can become not only a tool for precise measurements of magnetic induction but also a tool for the analysis and classification of materials based on their magnetic properties. Introducing a method for material classification based on measurement data opens up new possibilities in the field of materials analysis. It allows for the rapid and efficient determination of material magnetic properties and the selection of appropriate materials for specific applications. As a result, CNC technology combined with a magnetic scanner can contribute to the development of the field of materials engineering, where precise magnetic measurements are crucial for the design and production of modern components and devices.

Surface scanning in the measurement system

CNC scanning is an advanced technique for controlling the motion of a measurement tool using a computerised control system. It is an extremely precise method that allows the execution of complex measurement operations with high accuracy and repeatability.

The diagram of the measurement system is shown in Fig. 1. The measurement system consists of three main components: a CNC plotter with a Hall-effect probe, a field meter, and a master control unit, which includes a computer with proprietary software. The CNC scanner is responsible for controlling the movement of the measuring head, which moves along a defined trajectory in the examined area. The Hall-effect probe is mounted on the movable head of the CNC plotter with a working area of (200x200x100) mm. The device is driven using toothed belts and 8 mm guides for the X and Y axes. A trapezoidal screw is used to transfer the drive to the Z-axis. The head moves along a defined trajectory that covers the area where magnetic field measurements are to be taken. CNC scanning enables magnetic field measurements at various points on the surface, allowing for the generation of a three-dimensional map of the magnetic field distribution around a specific object.

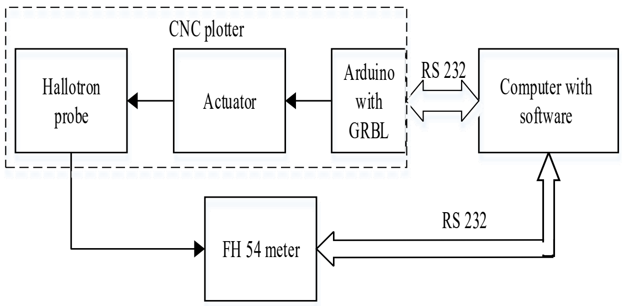

Fig.1. Block diagram of the measurement system

Stepper motors are controlled using a control module built with an ARDUINO UNO board running the GRBL programme to analyse the standardised command format for CNC devices (G-code) and stepper motor drivers. During scanning, the Magnet-Physik FH-54 magnetic field meter records measurement data from the probe, which are then processed by the computer system. As a result of this processing, we obtain information regarding the magnetic field induction in the scanned area. The system also enables the generation of a magnetic field map, which can be visually presented as a three-dimensional graph.

Acquisition and interpretation of measurement data

The acquisition of measurement data involves both the XYZ coordinates of the measurement points and their corresponding magnetic induction values. The CNC scanning system with a Hall-effect probe allows for precise determination of the positions of measurement points in three dimensions (X, Y, Z) and enables serial measurements. A single measurement series involves scanning a specified surface in the XY plane at a defined height from the measurement probe. Communication between the CNC scanner, the field meter, and the computer takes place through an RS232 interface, ensuring fast and reliable data transmission.

To facilitate the acquisition and interpretation of data, a specialised program was developed in C#. The program collects and stores data in an SQLite database, enabling efficient data storage while ensuring scalability and process reliability. The saved data are then utilised to generate an Excel spreadsheet, which includes a detailed map of the magnetic field over the tested object, along with numerical indicators for material selection in specific applications.

Relevant metrological information on the distribution of the measured field is provided by the means and standard deviations calculated for individual points and measurement series. Introducing the appropriate mathematical equations into practical numerical applications often presents a challenge and requires care and precision. However, by adopting an approach focused on the direct implementation of these equations in the application, the process has been greatly simplified. The following is the numerical representation of all equations. The application calculates three means: the mean *a(i)* from measurements of the *i*-th series, performed for all measurement points on the membrane (1), the mean *p(j,t)* at points with coordinates *j* and *t*, calculated from multiple measurements obtained in *the n series,* and the overall mean *m* calculated from all means *p(j,t)*.

Mean of measurements from the *i*-th series:

$$a(i)=\frac{1}{wk}\sum_{j=1,t=1}^{w,k}x(i,j,t) \qquad (1)$$

where: *i* – the current measurement series number, *j* – the current row number of the result table, *t* – the current column number of the result table, *n* – the number of measurement series, *k* – the number of rows in the measurement table, *w* – the number of columns in the measurement.

Mean of the multiple measurements from *n* series:

$$p(j,t)=\frac{1}{n}\sum_{i=1}^{n}x(i,j,t) \qquad (2)$$

A mean of all the means:

$$m=\frac{1}{nwk}\sum_{i=1,j=1,t=1}^{n,w,k}x(i,j,t) \qquad (3)$$

The numerical indicators are updated after each scan of the tested plane. For example, the update of the mean *m* from the *n* series (denoted as m_n) to the mean (denoted as m_{n+1}) after adding another series with the number *n+1* is as follows:

$$m_{n+1}=\frac{1}{n+1}\left[nm_n+\sum_{j=1,t=1}^{w,k}x(n+1,j,t)\right] \qquad (4)$$

The following standard deviations are also calculated in the application:

Estimate of the unbiased standard deviation $s_x(i)$ for a single result in the *i*-th series:

$$s_x(i)=\frac{1}{\sqrt{wk-1}}\sqrt{\sum_{j=1,t=1}^{w,k}\left[x(i,j,t)-a(i)\right]^2} \qquad (5)$$

Estimate of the unbiased standard deviation s_p, for a single mean *p(j, t)*. This estimate is calculated from the measurements *p(j, t)* and characterises the dispersion of the mean values *p(j, t)* across the entire surface of the tested object.

$$s_p=\frac{1}{\sqrt{wk-1}}\sqrt{\sum_{j=1,t=1}^{w,k}\left[p(j,t)-m\right]^2} \qquad (6)$$

The estimate of the unbiased standard deviation s_m, for the mean of means *p(j,t)*, characterises the dispersion when repeating the measurement at the same point on the membrane, and it mainly depends on the nonuniform magnetization of the tested material.

$$s_m=\frac{1}{\sqrt{wk(wk-1)}}\sqrt{\sum_{j=1,t=1}^{w,k}\left[p(j,t)-m\right]^2} \qquad (7)$$

Interpreting the presented formulas for shapes other than *a* square requires adjusting the indices *i* and *k* according to the shape function of the envelope of the tested object, both within the summation limits and under the square root coefficient.

Application Interface

The measurement procedure can be defined by the user interface of the developed application. It can be selected the shape of the scanning surface, accurately determining the measurement step, the surface size, and many other important parameters.

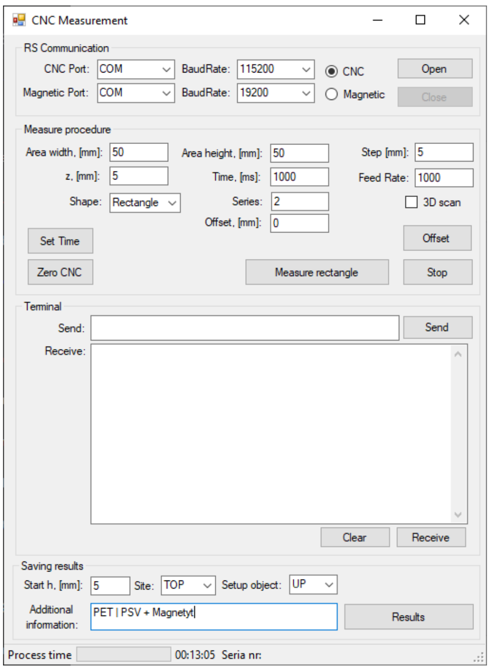

Fig.2. Main application window

One of the main goals of the project was to create a scalable application that can be developed and customised to meet the varying requirements of users. The developed interface can be easily adapted to different measurement specifications and is user-friendly, even for non-technical users (see Figure 2).

The program allows calibrating of the measurement probe position relative to the object being measured (*Zero CNC* and *Offset* options), and it also enables the execution of a spatial scanning procedure in a two-dimensional XY plane with varying Z-axis levels (*3D scan* option).

The measurement data and additional information about the procedure are recorded and stored in a SQLite database (*Results* option), ensuring fast access and effective management.

An undeniable advantage of the developed program is the ability to generate Excel-formatted result files that are appropriately formatted to ensure the readability and clarity of the presented data (see Figure 5). The tables in these files are carefully structured, with borders and highlighted headers in different colors, greatly facilitating the reading and analysis of the gathered information. Under each table, relevant statistical parameters described in the previous chapter are provided.

Algorithm

The algorithmic flow chart is presented in Figure 3. The program operates using threads to perform the measurement procedure, allowing the user interface to remain accessible throughout the measurements. The remaining time for the scanning process is updated, and the measurement results are displayed in real-time (*Receive* window) in the main thread. In the secondary thread, communication with each device is established through the serial port, and the control command is sent to the respective device while receiving data. The standard *SerialPort* class from the .NET Framework library is used to manage the connection and input/output operations. This approach ensures high reliability and precise synchronization of the device's operation time, which positively affects the accurate estimation of the overall procedure duration.

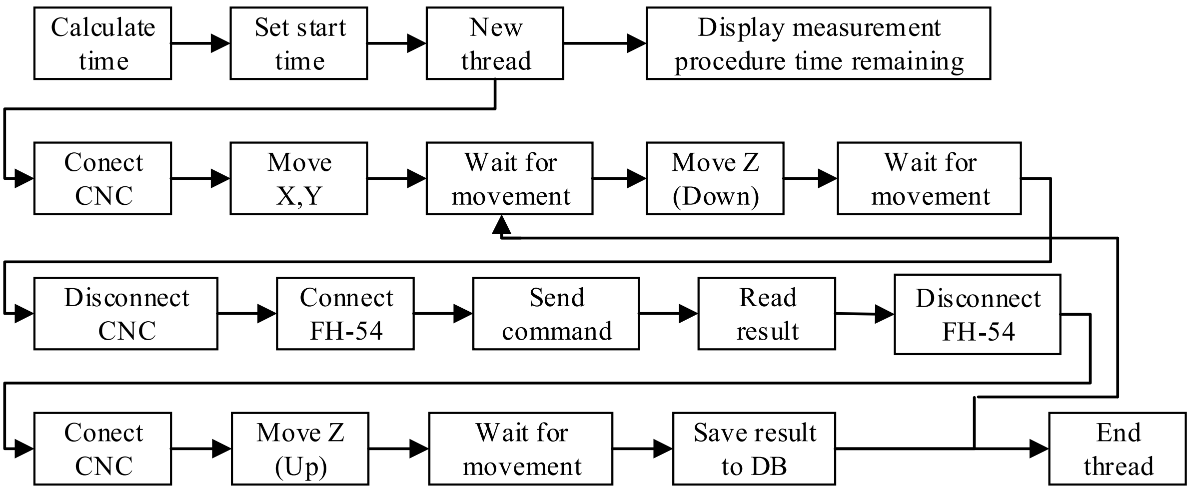

Fig.3. Algorithm flowchart

Table 1ig.5. Saving data in tabular form (Excel)

Averages p(j,t) from multiple measurements at points (j,t) included in n=2 measurement series.											
↓j t→	1	2	3	4	5	6	7	8	9	10	11
1	-0,4105	-0,415	-0,4175	-0,425	-0,4285	-0,427	-0,426	-0,433	-0,4305	-0,426	-0,4295
2	-0,4105	-0,4115	-0,418	-0,4245	-0,411	-0,425	-0,4255	-0,422	-0,424	-0,431	-0,43
3	-0,409	-0,4115	-0,42	-0,419	-0,4245	-0,4235	-0,4245	-0,422	-0,4265	-0,4275	-0,422
4	-0,409	-0,411	-0,4165	-0,42	-0,4245	-0,422	-0,426	-0,4265	-0,4225	-0,424	-0,4285
5	-0,406	-0,416	-0,421	-0,4195	-0,4255	-0,4225	-0,422	-0,424	-0,4265	-0,4245	-0,4255
6	-0,41	-0,415	-0,422	-0,419	-0,425	-0,4235	-0,4265	-0,422	-0,4285	-0,4265	-0,4275
7	-0,4055	-0,4115	-0,4165	-0,42	-0,419	-0,42	-0,422	-0,4235	-0,424	-0,4225	-0,4195
8	-0,413	-0,4145	-0,419	-0,417	-0,417	-0,424	-0,425	-0,42	-0,421	-0,418	-0,4215
9	-0,409	-0,4185	-0,416	-0,4175	-0,421	-0,423	-0,4215	-0,4215	-0,4225	-0,4225	-0,4195
10	-0,408	-0,408	-0,418	-0,421	-0,4195	-0,4185	-0,42	-0,423	-0,421	-0,422	-0,425
11	-0,415	-0,414	-0,4155	-0,415	-0,4195	-0,415	-0,4165	-0,4205	-0,415	-0,4225	-0,4205
m (3)	-0,42033	mean of measurements from all points									
sp (7)	0,005727	standard deviation of a single mean									
sm (8)	0,000521	standard deviation of the mean of means									

Visualisation and analysis of research results

The tested materials constitute a diverse collection of magnetic and paramagnetic substances, which also vary in shape, hardness, and texture (Fig. 4).

To ensure comprehensive analysis, each sample was carefully mounted with respect to the central point of the scanner's working surface and subjected to a two-sided assessment (*Site: Top/Bottom* option).

The obtained results are recorded in a database, allowing the user to select a specific procedure and save the results in the form of tables in an Excel file (Fig. 4). This flexible functionality enables full utilization of the collected data, allowing the user to analyse and present the results in a clear and practical format. As a result, further processing and sharing of measurement results can be done in a convenient manner, tailored to the individual needs and preferences of the user.

The data collected in this system enable the creation of 3 charts, which greatly facilitate the analysis of material properties and their classification in the context of specific applications. Through these charts, we can visually perceive patterns, relationships, and trends in magnetic field induction in a more transparent manner, allowing us to better understand and evaluate the potential uses of different materials.

Fig.4. Material samples under investigation

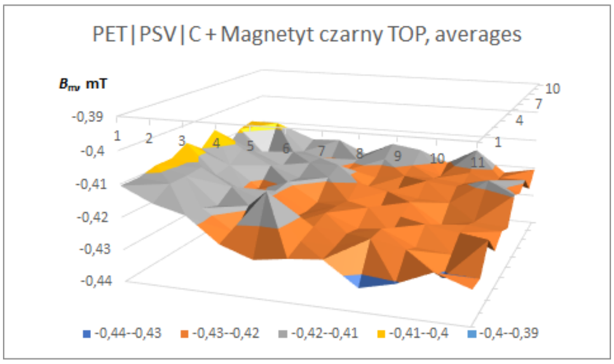

Fig.5. Spatial chart of the magnetic field map

Conclusions

One of the main advantages of the CNC scanning measurement system is the possibility of automating the measurement process. The results of such measurements exhibit high repeatability, which increases the efficiency and precision of the measurements while reducing the time required for conducting comprehensive magnetic field analyses.

The developed measurement system allows for the examination of diverse materials with varying shapes and textures in multiple measurement series. As a result, the results from different series can be compared, allowing for the identification of potential trends, temporal variations in the field, or other characteristic material properties. The data presented in tabular form are easy to interpret, and their analysis can be further visualised using spatial charts.

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