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Simulation of Hall sensor based localization in a production process

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***Abstract*— Localization of products and tools during production is of great significance in automated systems, as it gives valuable information that enables production optimization. Hall sensors provide contactless detection of magnetic field strength, and are often applied for detection of proximity, position and speed, as well as for current measurements in conductors. This paper presents an idea for Hall sensor based product localization with the application of small strong permanent neodymium magnets N5211. Simulation results are presented for monitoring the product position during linear and semicircular movements in the production process.**

Keywords—component; formatting; style; styling; insert (key words)

I. INTRODUCTION

Product transport during the production process is inevitable when the production takes place in several different automated machines in several steps. In some cases the transport is short and the product moves to smaller distances (transport of products between tools or between machines), and in some cases, the transport of products happens over long distances within the production process (e.g. between two distant points of the plant). Transport of workpieces through the production process is performed by various rotating tables and conveyor belts, robots and manipulators.

Modern customer-dependent production when the customer directly or indirectly influences the end product [1] (e.g. various trim levels in automotive industry), requires working with many subproducts that are later assembled to the complete product. In order to enable production process optimization it is necessary to monitor the operation cycle of machines, current machine occupancy and the workpiece path in the process (transport time and current position). The machine control unit can use the information about the current position of the workpiece and the time required for getting to the next position when deciding upon which product should be chosen for processing if the machine serves multiple product lines.

Automated workpiece monitoring throughout the production process is a complex problem and requires a combination of multiple technologies, depending on the monitoring goal. For identification of workpieces and tracking the corresponding information, control systems can use RFID(*Radio-Frequency IDentification*) technology, identification based on an optical system such as machine vision, as well as barcode and 2D code identification [2], [3]. When determining the current position the control system can use machine vision, indoor positioning techniques based on sensor networks, presence detection in specific pre-known positions [4], etc. Each of these possibilities has its own advantages and disadvantages. Machine vision is good as the system is detached from the workpiece and determines its characteristics only based on its image, i.e. there is no need for additional tagging of workpieces or transport platforms for this purpose. Disadvantage of such systems is in the specific controlled lighting conditions that are required for their normal operation. Application of RFID systems, barcodes or distance and presence sensors requires additional tags (e.g. an RFID tag or a barcode must be attached to the workpiece), but on the other hand these systems are more robust to external interference caused by lighting conditions, but not to the presence of metal that can greatly influence operation of an RFID system or a sensor network.

Hall sensors (Hall effect based sensors [5]) enable contactless position detection based on magnetic field strength measurements, and are applicable for detecting position, speed, proximity as well as for current measurements in conductors [6]. If a permanent magnet is attached onto/into the pallet, Hall sensors can detect its magnetic field strength and thus enable the calculation of workpiece distance from the sensor [7].

This paper presents an idea for workpiece localization based on Hall sensors, with the application of small strong permanent neodymium magnets N5211 along the product movement path, as well as the simulation results for

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monitoring the product position during linear and semicircular movements in the production process.

II. HALL SENSORS AND MAGNETIC FIELD MEASUREMENTS

If a current-carrying conductive strip or semiconductor plate is kept in a magnetic field perpendicular to its surface, its side-edges experience a potential difference called the Hall voltage. This phenomenon is named after the American scientist Edwin Herbert Hall who was the first to describe it in 1879 [5], [8].

TABLE I. MAGNETIC FIELD STRENGTH FOR VARIOUS PERMANENT MAGNETS

Magnet	B [T]	H [kA/m]	BHmax [kJ/m3]
$Nd_2Fe_{14}B$ [a]	1.0–1.4	750–2000	200–440
$Nd_2Fe_{14}B$ [b]	0.6–0.7	600–1200	60–100
$SmCo_5$ [a]	0.8–1.1	600–2000	120–200
$Sm(Co, Fe, Cu, Zr)_7$ [a]	0.9–1.15	450–1300	150–240
Alnico [a]	0.6–1.4	275	10–88
Sr-ferrite [a]	0.2–0.78	100–300	10–40

a. produced by synthesizing

b. produced by casting

Hall voltage is proportional to the magnetic flux density and the current. Hall voltage amplitude V_H depends on the conductor current and the magnetic field strength and can be expressed as (1) [8], [9]:

$$V_H = \frac{K_H * B * I}{d} \tag{1}$$

where:

V_H – Hall voltage,

K_H – Hall constant,

B – magnetic flux density,

I – current flowing through the conductor,

d – thickness of the conductor.

The magnetic flux density can be expressed through the magnetic field strength H and the magnetic permeability μ (2):

$$B = \mu * H \tag{2}$$

where H is given in amperes per meter. Based on this the dependence of Hall voltage V_H and the distance x between the magnetic field generator (e.g. permanent magnet) and the Hall sensor (Fig. 1) can be acquired. As the magnet approaches and moves away from the sensor cell, the sensor outputs a variable analog voltage signal, based on which the distance between the magnet and the sensor can be determined. If the fact that the monitored movement depends only on one monitored signal coordinate is taken into account, it is easy to determine the current magnet position, and thus the position of the object to which it is attached.

Generally Hall sensors are designed for very limited displacements, thus the measurement resolution for a greater distance depends on the number of sensors used and their density distribution along the movement path of the monitored object [9].

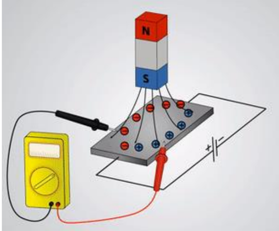

Figure 1. Dependance of Hall voltage V_H on the distance x between the sensor and the permanent magnet (*Source: Fraunhofer IIS*)

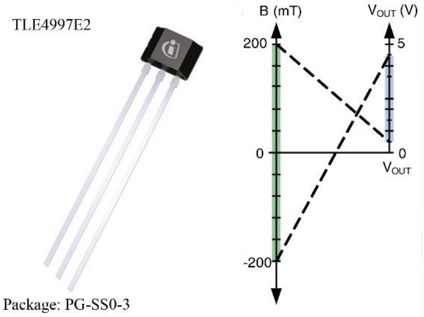

Figure 2. Hall sensor TLE4997 with bipolar inverted output [10]

A. Sensor unit

Hall sensors are produced in two basic categories:

- *binary sensors* – when detecting the presence of magnetic field (e.g. when detecting the position of the piston rod in pneumatic cylinders with embedded permanent magnet), and
- *analogue sensors* – when the sensor output is proportional to the detected magnetic field strength. In this case, the sensor output can be an analogue value (voltage or current signal) or a digital number transferred either by a communication protocol or by a PWM signal (*Pulse Width Modulation*).

For continual monitoring of the magnetic field strength, such as in the case of position monitoring, the analogue type is more suitable.

A great number of various relatively cheap Hall sensors (sometimes also called magnetic sensors) can be found on the market. The chosen sensor for analysis in this paper is from the *TLE499x* family produced by *Infineon Technologies AG*. These are analogue sensors with various outputs: voltage, current, PWM or communication (SPC[1] or SENT[2]). Specifically, the sensor *TLE4997* [10] is designed for monitoring linear or angular position in fine automation applications. Measurement resolution of this sensor is 12 bits: for the full range of the magnetic field of ±200 mT (0.097656 mT/bit), middle range of ±100 mT (0.048828125 mT/bit), or low range ±50 mT (0.024414063 mT/bit). The range can be chosen when calibrating the sensor. The sensor has embedded digital temperature compensation, as well as a 20-bit DSP (*Digital Signal Processing*) for signal processing and sensor calibration. The sensor supply voltage ranges from 4.5 to 5.5 V (4-7 V in the extended range). The temperature range is from -40 to 150°C. Fig. 2 shows the sensor as well as the method for creating the analogue output signal depending on

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[1] SPC - short PWM codes

[2] SENT - single edge nibble transmission

the magnetic field strength. Since it is a bipolar inverted output, the magnetic field strength of 200 mT (or more) generates the output voltage of 0 V, and the magnetic field strength of -200 mT (or less) the output voltage of 5 V. The sensor's measurement range is limited to -200 to 200 mT, but the magnetic field strength that can act on the sensor is not limited [10], which is important in the specific application. Considering that the measurement resolution is 12 bits, the sensor output sensitivity is 0.12207 mV per 0.097656 mT of the magnetic field.

B. Permanent magnets

In order to detect the magnetic field with a Hall sensor from a greater distance, the application of a strong permanent magnet is necessary, which would provide a magnetic field strong enough to be detectable from a greater distance. Neodymium ($Nd_2Fe_{14}B$) with iron and boron are currently the strongest permanent magnets, with greatest magnetic field per area unit (Table I). For example, the magnet N5211 with residual induction *Br = 1450 mT*, with dimensions of 20x15x10 mm (Fig. 3: *L*-length x *W*-width x *H*-height), on its surface (toward the *Z* axis in Fig. 3.) has the catalog value for the magnetic field *B* = 498 mT, and 3 mm from its surface toward the *Z* axis (in Fig. 3) *B* = 345.6 mT [11]. The magnetic field data at the distance of 3 mm on the Z axis is important as the simulations use the sensor in zero position on *X* axis (in Fig. 3) 3 mm away from the magnet in the direction of the *Z* axis.

III. MAGNETIC FIELD SIMULATION RESULTS

A. Magnetic field change

Simulation of the magnetic field change is based on the data [11] for neodymium magnet type N5211 with dimensions 20x15x10 mm (Fig. 3: *L* x *W* x *H*). The measurements were performed in points Z = 3 mm, X = -200 to 200 mm, and the magnetic field ranges from 345,611 mT (for X=0, Y=0, Z=3 mm) to 0,041 mT (for X={-200, 200}, Y=0, Z=3 mm). The diagram of magnetic field change *B[mT]* for the parameter range *X*={ -200 to 200 mm} is shown in Fig. 4, where it can be noticed that the magnetic field is symmetrical about the *y* axis (*B[mT]*). In order to determine the 2D magnetic field in X-Y plane, the magnetic field was also measured for points X={-60, 60}, Y={-60, 60}, Z=3 mm, and the diagram of 2D magnetic field change is shown in Fig. 5.

B. Hall sensor integration

Taking into account the sensitivity of the chosen Hall sensor (*TLE4997*) in the full range (±200 mT), then:

$$\Delta V_{out} = \frac{0.12207\ mV}{0.097656\ mT}$$

Based on the data shown in Fig. 4 and 5 and depending on the sensor's output voltage and the change in magnetic field strength (3) it can be concluded that the combination of the chosen sensor and neodymium magnet type 5211 with dimensions 20x15x10 mm can be used for unique determination of the workpiece position, when it is tracked during linear movement along the *X* axis, in the range of ±58 mm. It must be noted that for positions within ±10 mm the sensor will give the same output signal, since in this case the magnetic field is greater than 200 mT.

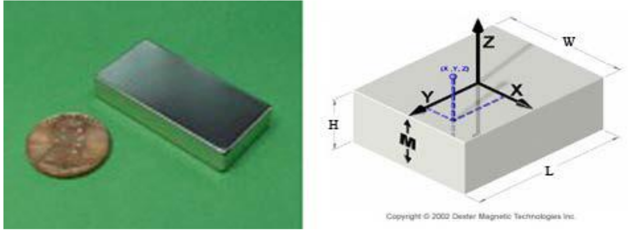

Figure 3. Size of the neodymium magnet (left, *source:K&J Magnetics*), dimensions and axis for movement from the magnet (right, *source: dextermag.com*)

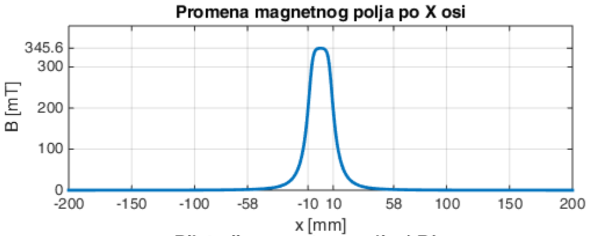

Figure 4. Magnetic field change along the *X* axis for the magnet type N5211 with dimensions 20x15x10 mm

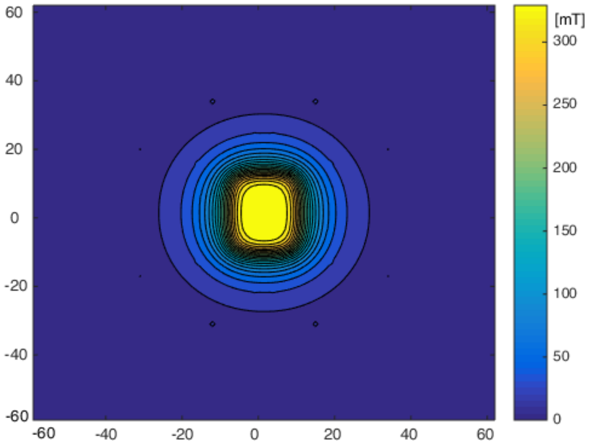

Figure 5. 2D magnetic field change in *X-Y* plane for the magnet type N5211 with dimensions 20x15x10 mm

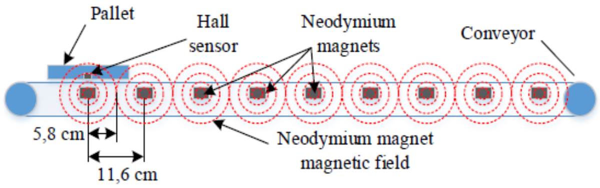

Figure 6. System for position monitoring with a single sensor and multiple permanent magnets

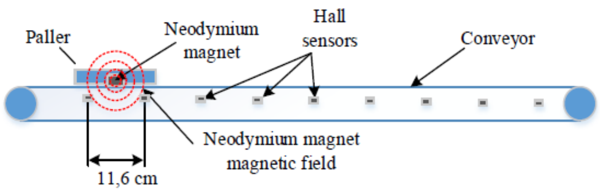

Figure 7. System for position monitoring with multiple sensors and a single permanent magnet

C. System for position tracking

Based on the simulation of the magnetic field change (Fig. 4 and Fig. 5) and the operation mode of the chosen Hall sensor (*TLE4997*) there are two ways for tracking the current position of the workpiece during linear movements in the production:

1. *Using a single sensor and multiple magnets* (Fig. 6.) – if multiple fixed-position permanent magnets are placed along the movement path, such that their magnetic fields overlap, which provides constant presence of a strong enough magnetic field and the possibility of monitoring the magnetic field change, and a single Hall sensor is attached to the pallet. The current position can be acquired by analysing the magnetic field change.
2. *Using multiple sensors and a single magnet* (Fig. 7.) – in this case the permanent magnet is attached to the pallet, and the sensors are placed along the movement path in order to detect the change of the magnetic field while the pallet is moving.

In both cases the distance between the fixed-position permanent magnets (in the first case) or sensors (in the second case) must be such that it provides different magnetic field measurements for each movement range of interest. E.g. if the distance should be measured with 1 mm resolution, the distance of 116 mm should be chosen in both configurations (two times 58 mm), as for 58 mm each magnet gives the field sufficient for unique detection, and each sensor can detect the field from that distance [7].

Since the aim of this research is determining the position during linear movement of products in the production process, the magnetic field strength has been modelled for the conveyor part that is 400 mm wide, and consists of a 1000 mm linear part and a semicircular part with a radius of R=1000mm. The magnets are placed in the middle of the conveyor at each 116 mm, at a total length of 2572 mm, where the first 1000 mm is along the linear path, and the rest is along the semicircular path. Fig. 8 (upper panel) shows the map of magnetic field strength along the movement path of the conveyor, as well as the value of the magnetic field detected with the sensor with the measurement range of ±200 mT (Fig. 8 lower panel). The graph in Fig. 8 (lower panel) clearly shows that for all values greater than ±200 mT the sensor gives the same output, as in that range the sensor is in saturation.

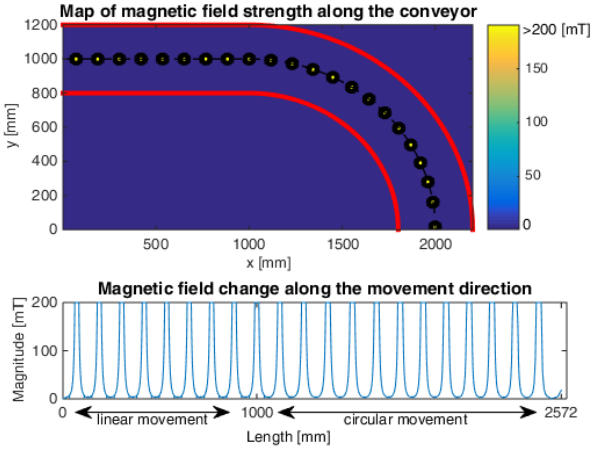
Map of magnetic field strength along the conveyor
Magnetic field change along the movement direction

Figure 8. Magnetic field change along the movement path on the conveyor

IV. CONCLUSION

This paper discussed the possibilities for application of Hall sensors in the combination with neodymium permanent magnets for contactless tracking of workpiece position during linear movement through the production process. A simulation was carried out for magnetic field change for neodymium magnets type N5211 with the dimensions 20x15x10 mm (Fig. 3: L x W x H) based on the data given in [11]. Based on the acquired data and the analysis of the operation mode of the given Hall sensor, a strategy was adopted for placing the neodymium magnets along the movement path. Furthermore, a simulation was carried out for the magnetic field change along the chosen conveyor part, consisting of linear and semicircular paths, as well as a simulation of the magnetic field detection with the given Hall sensor along the movement path on this conveyor. The processing of the measured magnetic field value would give the position of the workpiece.

Based on the acquired results it can be concluded that sensors with greater measurement range should be used (minimally ±350 mT), as the used sensor goes in saturation within the ± 10 mm radius around the magnet.

Furter research would include development of an experimental system that would provide the possibility for confirmation of the simulation results in practice, both in laboratory and industrial conditions. Furthermore, development of an acquisition unit is planned, that would enable sensor data processing and the calculation of the current position of the workpiece.

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