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Large Area Magnetic Field Camera for Inline Magnet Inspection

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Abstract:
We report on further advancements in the field of magnetic field camera technology for magnet inspection, based on high resolution high speed two-dimensional magnetic field mapping of the magnetic field distribution of permanent magnets. The advancements presented here extend the applications of the technology to inspection of large magnets and magnets with non-planar geometries, such as rotary symmetric magnets (e.g. permanent magnet rotors or radially or diametrically magnetized cylinder or ring magnets for sensor applications.

The innovation consists of combining multiple redesigned magnetic field camera sensor modules into a single large area magnetic field camera, that can record the magnetic field distribution in a virtually unlimited area, at about the same speed as one single sensor module, due to parallel read-out. The technology is suitable for both manual and automated magnet inspection tasks, as well as development and quality control applications.

Key words: magnet inspection, magnetic field camera, Hall sensor 2D array, magnetic field mapping, sensor magnet.

Introduction

Fast and accurate quality inspection of permanent magnets is increasingly important in development and production of sensor systems, electric drives, medical devices, consumer electronics and other products containing high-end magnets [1,2]. Previously we presented the magnetic field camera (MagCam) technology as the most advanced state-of-the-art magnet inspection platform for all kinds of permanent magnets [3], including uniaxial and multipole magnets in various applications. The MagCam technology is based on high resolution, high speed two-dimensional (2D) mapping of the magnetic field distribution of a magnet, using a patented chip with an integrated 2D array of more than 16000 microscopic Hall sensors. A complete magnetic field map of 13mm x 13mm with 0.1mm resolution is captured in less than 1 second, without moving parts.

Measuring larger areas than the abovementioned 13mm x 13mm requires mechanical scanning of the sensor using e.g. a robot or a scan stage. Thereby, measurement speed can be increased by combining several camera modules into a larger system. It is the practical realization of this large area solution that is the innovation of the present work.

The measurement data are analyzed by the powerful MagScope data analysis software which uses advanced algorithms to extract unprecedented magnet information from the MagCam measurements, including magnetic asymmetries and inhomogeneities, the full magnetization vector, deviations from a ‘perfect’ magnet, local material defects, angle failures, pole uniformity, distance and angle measurements, the exact magnet position and more. All these quantitatively measured magnet properties can be used for immediate and automated pass/fail or classification analyses, all in real time.

The MagCam technology was recently awarded with the first place in the election of the “Produkte des Jahres 2012” (Products of the Year 2012) in the ‘Sensors’ category by the readers of the leading German industrial electronics magazine Elektronik [4]. This award underlines the innovative character, as well as the industrial relevance of the magnetic field camera technology.

Magnetic Field Camera Technology

The magnetic field camera platform consists of sensor hardware and measurement and analysis software. The core of the hardware is the magnetic field camera sensor module, a

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compact cube with size 24x24x24mm³. A single USB-cable connects the camera module to a computer. The system is operated through the MagScope measurement & analysis software. In its simplest mode of operation, the measurement sample (a permanent magnet or magnetic assembly) is placed on the sensitive sensor surface of the magnetic field camera, as shown in Fig. 1 (top). The magnetic field camera sensor measures a high resolution 'image' of the magnetic field distribution of the magnet at high speed. A typical MagCam image is shown in Fig. 1 (bottom). The measurement of one full resolution frame takes less than one second. Higher speeds are possible at lower resolutions. This speed allows real time measurement and analysis of magnetic images.

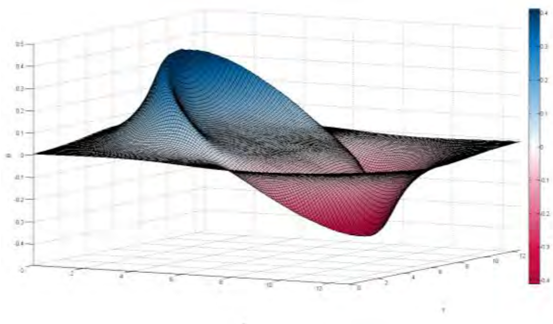

Fig. 1. Top: magnetic field camera module measuring a cylindrical magnet (8mm diameter) with diametrical magnetization. Bottom: measured quantitative magnetic field distribution (Bz component) of the magnet shown above.

The measurement principle of the magnetic field camera is based on a high resolution and high speed quantitative 2D mapping of the magnetic field distribution of the magnet, using a patented sensor chip with an integrated 2D array of 128 x 128 (= 16384) microscopic Hall sensors. The sensors have a pitch (spatial resolution) of 0.1mm in both X and Y directions. Each Hall sensor has an active area of $40\mu m \times 40\mu m$ and locally measures the perpendicular component (Bz) of the magnetic field. All sensors are electronically scanned at high speed, resulting in a quantitative high resolution magnetic field map over an area of 12.8mm x 12.8mm, as shown in Fig. 1, bottom. The sensor chip is located at 0.2mm below the surface of the camera module, allowing a very small measurement distance to the magnet.

The magnetic field camera chip has a built-in flexibility for recording any submatrix of the 128x128 sensor matrix. Both in X and Y directions, the start pixel, stop pixel and step size can be specified. This allows not only to operate the sensor in lower resolutions (measuring e.g. every second pixel), but also allows to operate the camera in line scan mode.

It is important to mention that the pixels on one magnetic field camera module are read out in sequential order, whereby each pixel needs about 50 microseconds measurement time. This means that one can calculate the total needed time for recording one frame by simply multiplying the total number of pixels in the frame by the time per pixel of 50 microseconds. The measurement times for some special cases are listed in Tab. 1.

Tab. 1. Measurement times for various submatrices of the sensor matrix in one camera module

Measured pixel matrix	time
Full range, full resolution	800ms
Full range, half resolution	200ms
Single line, full resolution	6.4ms
Single line, half resolution	3.2ms

Data analysis

The MagScope measurement and analysis software records and analyzes in real time the magnetic field maps measured from the magnetic field camera, as shown in Fig. 2. The measured MagCam map is represented as a high resolution interpolated quantitative color scale graph. This graph can be analyzed using both Cartesian and cylindrical coordinates, depending on the magnet geometry. In Cartesian coordinates, cross-section analyses can be performed across horizontal and vertical lines. In cylindrical coordinates, cross-sections can be analyzed across radial and circumferential lines. Along the cross-section lines, accurate distance and angle measurements can be made between points of interest in the magnetic field map, such as magnetic field zero-crossings, pole segments, pole extrema, localization of specific magnetic field values and anomalies. These analyses can be performed with absolute magnet position indication. The software can also perform image processing algorithms and statistical image analysis, all in real time.

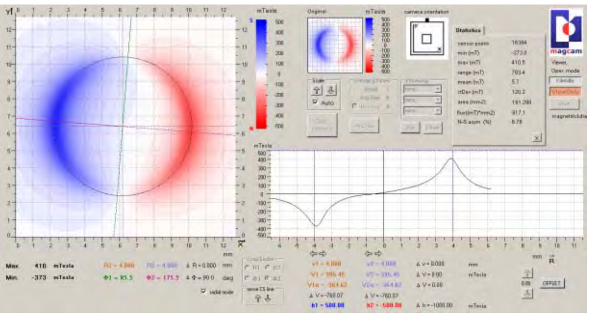

Fig. 2. Screenshot of the MagScope measurement and analysis software. The data shown is measured from the magnet shown in Fig. 2.

These features allow to directly characterize a large number of quantitative magnet properties such as: multipole magnet angle failure, north-south pole asymmetry, magnet homogeneity, material/magnetization defects etc.

Automation

The complete functionality of the MagCam system can be automated. This includes hardware programming, performing measurements, complete data analysis etc. The MagCam system can thus be implemented in automated production lines. The inherent speed of both measurement and analysis opens the opportunity for e.g. a 100% inline magnet inspection.

Miniaturization of the camera

As a first step in creating a platform for large area magnetic field camera solutions, the existing MagCam sensor module was thoroughly redesigned. Several improvements were implemented during this redesign process. The most important are:

- Strongly reduced size of 24x24x24mm
- Industrial locking connector
- Optimized mechanical properties
- Improved manufacturability

The most obvious change of the miniaturized MagCam with respect to the previous MagCam sensor module is its size, which was reduced from 91x71x23mm^3 to 24x24x24mm^3, which corresponds to a volume reduction of a factor 11. The redesigned MagCam module was named 'MiniCube'. The MiniCube is shown in Fig. 3, next to its predecessor for comparison.

Although the camera electronics and housing are completely renewed, the core component, i.e. the magnetic field camera sensor chip, is the same as in the previous model. The lateral sizes of the MagCam MiniCube (24mm x 24mm) were chosen such that it would allow placing multiple modules next to each other, while the dead measurement zone in between the modules (24mm - 12.8mm = 11.2mm) is smaller than the active measurement size of the camera itself (i.e. 12.8mm). This principle allows filling up this dead zone by moving the set of modules with one single step of 12mm in each direction. As shown in the following sections, this principle makes possible a number of different module configurations that are suited to perform fast large area magnetic field mapping measurements.

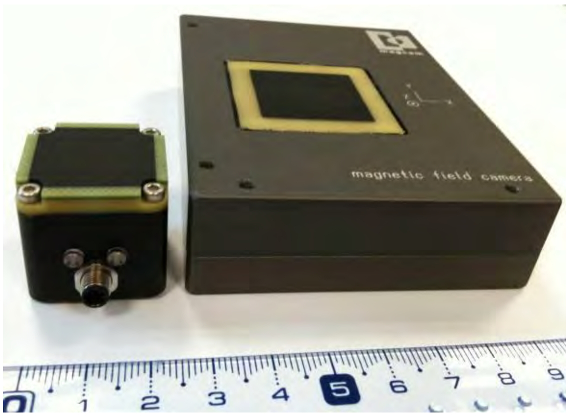

Fig. 3. Redesigned MagCam MiniCube (left), next to the previous version of the magnetic field camera (right).

Large Area Magnetic Field Camera Configurations

The redesign of the magnetic field camera into the MiniCube allows a modular approach towards large area magnet inspection. Using the MiniCube as a building block, many different configurations can be used, depending on the application. Possible configurations are:
A. Mechanical XY(Z) scanning of a single magnetic field camera module
B. 2D array of n x m camera modules
C. Line scan setup of n camera modules in a '1.5D' configuration
D. Rotor inspection

Only the first two configurations (A. and B.) are treated in this paper. For more details on the other arrangements, we refer to [5].

A. Mechanical XY(Z) scanning of a single MiniCube camera

The most straightforward way of covering a large area using a magnetic field camera is to mount it onto a XY(Z) scan stage (or on a robot) and to sequentially measure multiple small-scale magnetic field maps which are subsequently stitched together to obtain a large area image. The advantage of this method is

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that only a single magnetic field camera module is needed. In this approach there is furthermore the possibility to use the camera in 2D mode (where a 2D image is measured with the camera standing still) or in line scan mode, where a single sensor line is continuously measured and the camera is moving at a constant speed relative to the magnet to be measured. While the length of a line scan image is in principle unlimited, the width of the image is limited to 12.8mm, i.e. the size of the sensor array on the camera chip. Therefore, magnets with a width of less than 12.8mm can be measured in one go using line scanning, even if they are longer than 12.8mm. However, if the magnet is also wider than 12.8mm, multiple parallel line scans needs to be recorded and stitched together in order to cover the full magnet area.

In order to accurately stitch the different measured images into a larger image, several approaches can be taken. Either the scan step (in X and Y directions) can be taken to be exactly equal to the corresponding size of the measurement area (i.e. 12.8mm). In this case there is no overlap between consecutive images. The quality of the resulting stitched image depends then on the accuracy of the scan stage and the alignment of the sensor X and Y axes to those of the scan stage.

Another technique, which is also found in optical image stitching, is to take the scan step somewhat smaller than the sensor size, as to assure an overlap region between neighboring images. This way, image stitching algorithms can be applied to the images, where the optimal overlap position is automatically detected. This method can correct for the lack of accuracy of the scan stage or of the alignment of the sensor to the scan stage axes.

Since the measurement speed of a magnetic field camera is relatively high (i.e. 12.8 x 12.8mm² / 0.8seconds in full resolution) large areas can quickly be measured using this technique. However, for some applications, such as fast inline inspection, the speed may not be sufficient, especially for larger areas. The speed in this configuration is limited by mainly two factors:

- The MagCam measurements are performed sequentially, i.e. not in parallel
- The number of mechanical steps scales with the measurement area

Roughly, the total measurement time for an area A is equal to

$$T_{total} = (T_{\sin gle} + T_{scanstep}) * A / A_{sensor} \qquad (1)$$

where

T_{total} is the total measurement time,

$T_{\sin gle}$ is the time needed to measure a single 12.8mmx12.8mm image,

A is the area to be measured,

A_{sensor} is the area of the sensor, i.e. 12.8mmx12.8mm.

In what follows we will take A_{sensor} to be 12mm x 12mm instead of 12.8mm x 12.8mm for the reason that we will allow for some overlap between the different images to make it possible to use automatic stitching algorithms. In practice, we will therefore use a scan step of 12.0mm.

Expression (1) shows that the total measurement time increases proportionally to the area to be measured. Based on this formula we can calculate quantitative measurement times for a few realistic cases.

Concerning the time per single measurement, we take the following approach. In practice, magnetic field camera measurements are often performed with half spatial resolution (i.e. 0.2mm) instead of full resolution (i.e. 0.1mm), especially for larger magnets. This means that only each second pixel is measured in X- and Y-directions, resulting in only ¼ of all pixels being effectively read-out. This also means that the measurement time per frame is four times smaller, i.e. about 0.2s/frame. On the other hand, multiple frames are usually recorded and averaged in order to reduce measurement noise. A realistic number of averages would be 5, resulting in a total measurement time per frame of 1 second, which is comparable with the time for a single frame at full resolution.

The second parameter in the expression above is the time needed for a mechanical scan step, which is 12mm in either the X or Y direction. Depending on the type of scan stage used, this time can vary. We will take 0.5s, corresponding to a speed of 24mm/s, totaling the time for a single measurement + scan step to 1.5s. The total measurement time for a few realistic areas is calculated in Tab. 2.

Tab. 2. Total measurement times for different areas when mechanically scanning a single magnetic field camera on an XY-stage

Meas. area	#steps	Time/step	Total time
12x24 mm²	2	1.5s	3s
24x24 mm²	4	1.5s	6s
24x48 mm²	8	1.5s	12s

48x48 mm²	16	1.5s	24s

For large areas the measurement time becomes relatively long, as is clear from Tab. 2. This measurement time can be considerably shortened by using a configuration of multiple camera modules, as shown in the next paragraph.

B. Two-dimensional array of magnetic field camera modules

The second configuration for large area magnet inspection consists of arranging a number of miniaturized magnetic field camera modules into a 2D array of arbitrary size (n x m modules), as shown in Fig. 4. This configuration makes it possible to perform a much faster measurement of a large area than in the previous configuration, without losing spatial resolution.

The main advantages of this configuration are:

- All camera modules in the 2D array are measured in parallel, decreasing the total measurement time.
- The 'dead measurement zone' between the modules can be filled up with only 3 mechanical scan steps of the complete configuration of 12mm (one in X, one in Y and one in X+Y directions), independent of the number of camera modules used and thus of the actual measurement area. To this end, the camera array can again be mounted onto an XY(Z) scan stage.

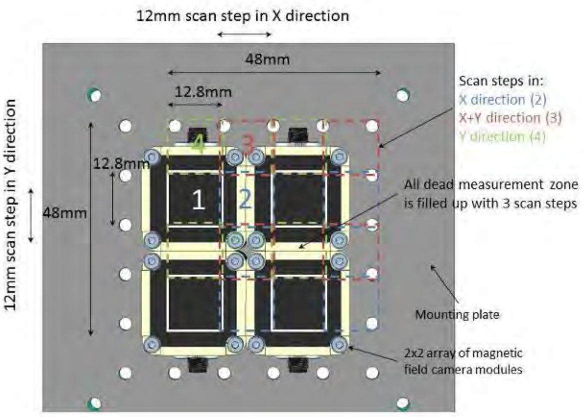

Fig. 4. 2D array configuration of 2x2 magnetic field camera modules providing a total measurement area of 48mm x 48mm

The total measurement time in this configuration is

$$T_{total} = 4 * (T_{single} + T_{scanstep}) . \quad (2)$$

Note that expression (2) is independent of the measurement area. Although only three mechanical scan steps are required, we included the returning (fourth) step to the initial position, thereby covering the full measurement period, i.e. after T_{total} a new measurement can immediately be performed.

To show that this configuration allows considerably faster measurement cycles in comparison to the arrangement with only one camera, Tab. 3 gives measurement times for the same measurement areas as in Tab. 2.

Tab. 3. Total measurement times for different areas using an array of camera modules

#camera modules	Meas. area	#steps	Time /step	Total time
1x1	12 x 24 mm²	2	1.5s	3s
1x1	24 x 24 mm²	4	1.5s	6s
1x2	24 x 48 mm²	4	1.5s	6s
2x2	48 x 48 mm²	4	1.5s	6s

From Tab. 3 we make following observations:

- For areas up to 24mm x 24mm only one camera module is needed. This is because each camera is scanned once in X, Y and X+Y directions, thereby covering an area of 24 x 24mm².
- For areas larger than 24 x 24mm² (i.e. starting from 24 x 48mm²) the measurement time is always 6 seconds, independent of the area.
- Adding an additional camera increases the measurement area with 24 x 24mm².

By comparing the measurement times in Tab. 2 and Tab. 3 it is clear that for larger areas, significant speed gains are realized by using a camera array configuration, in comparison to scanning a single camera over the area. For example, an area of 48x48mm² is scanned 4x faster using a 2x2 camera array (6 seconds) than using one single camera (24 seconds). Moreover, the measurement speed can be further enhanced by:

- Recording less averaging frames
- Reducing the spatial resolution
- Increasing the mechanical scan speed

For example, a NdFeB magnet with a lateral size of 40mm x 20mm can be measured using a 2x1 array of camera modules (measurement area of 48x24mm²). For a fast inline measurement cycle, a spatial resolution of 0.2mm is in most cases sufficient. Usually also no averaging is required, given the strong magnetic field produced by the magnet (i.e. large signal/noise ratio). One camera shot hence only takes 0.2s. When the mechanical scan speed is then also increased to the order of 120mm/s, the 12mm step is performed in 0.1s, bringing the time for one measurement phase down to 0.3s. The complete area is thus scanned in 4*0.3s = 1.2 seconds. This time, in the order of 1 second, is compatible with typical measurement times required in inline inspection stations. It becomes therefore a realistic option to perform such things as a 100% inline quality control of large magnets and magnetic assemblies.

Note that the resulting time of 1.2 seconds above is independent of the measurement size. I.e. a larger area is measured in exactly the same time by simply adding extra camera modules.

Conclusion

Driven by an industrial need for advanced inspection equipment for high-end permanent magnets as used in sensors, drives, medical applications, consumer electronics and other products, we have presented the magnetic field camera as a powerful and unique measurement platform for fast and accurate inspection of all kinds of permanent magnets. Previously we already showed the capabilities of the system to perform a full characterization of permanent magnets, including their quality-defining characteristics, which up to now were often not measurable using existing magnetic measurement technology, at least not in an economic way which is suited for automated environments. For uniaxial magnets the measured properties include the absolute magnetic field distribution, the magnetization vector size and skewness, magnetic field homogeneity, material/magnetization defects etc. For multipole magnets the measured properties include pole segment angle (deviations), north-south pole symmetry and pole height homogeneity.

In this paper we reported on further advancements in developing the magnetic field camera for inspection of relatively large magnets, as they are commonly found in e.g. sensor and drive applications. We followed a modular strategy by first redesigning the core magnetic field camera sensor module, thereby strongly reducing it in size. This effort opens the door to a range of different configurations of these camera modules, allowing large area magnetic field mapping with record speed and high spatial resolution. We have shown that a solution with one mechanically scanned camera can be speeded up considerably when the measurement area becomes large. We then proposed a solution where a 2D array of cameras is recording in parallel, thereby allowing the measurement of large areas with a total measurement time of down to 1.2 seconds, independent of the measurement area.

These results show that the magnetic field camera technology is scalable to larger areas and other geometries, whereby its inherent speed and spatial resolution are not compromised. These characteristics make the magnetic field camera technology by far the most advanced magnetic inspection technology available today, applicable for a wide range of applications and suitable for automated inline inspection in production lines, quality control and R&D.

References

[1] K. Vervaeke, Inline magnet inspection using fast high resolution MagCam magnetic field mapping and analysis, *Proceedings of 1st International Electric Drives Production Conference (EDPC)*, 172–180 (2011)

[2] J. Tremel, J. Franke, Hall Sensor Line Array for Magnetic Field Inline Measurements of PM-Excited Rotors, *Proceedings of 2nd International Electric Drives Production Conference (EDPC)*, 182-185 (2012); IEEE Catalog Number: CFP1285P-PRT, ISBN: 978-1-4673-3006-0

[3] K. Vervaeke, Magnetic field camera for fast - high resolution inline magnet inspection, *Proceedings of 16. GMA/ITG-Fachtagung 'Sensoren und Messsysteme 2012'*, 2.3.1 (2012)

[4] www.elektroniknet.de/bauelemente/news/article/86768/1/Die_Produkte_des_Jahres_2012/

[5] K. Vervaeke, Large Area Magnetic Field Camera for Inline Motor Magnet Inspection, *Proceedings of 2nd International Electric Drives Production Conference (EDPC)*, 186-194 (2012); IEEE Catalog Number: CFP1285P-PRT, ISBN: 978-1-4673-3006-0