An integrated Nine-dimensional Hall-Gradient-Sensor

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Abstract

Magnetic sensors for position detection are used in many products and apparatuses. In most cases the sensor, which is used to solve the problem, can only detect one single mechanical dimension (1D) of the magnetic field or flux-denisity. But generally, mechanical movements consist of 3 degrees of translatory and 3 degrees of rotary freedom. Temperature and external fields are further quantities, which may influence the measurements. So, at least 8 independent measures have to be taken, to detect mechanical movements correctly.

In this paper, we present a new integrated multi-dimensional Hall-sensor-system, which is able to take measures of all three components B_x, B_y and B_z of the magnetic flux density and their spacial gradients with respect to the x- and y-direction, which are parallel to the surface of the device. This means, that 9 measures can be taken, whereas 8 are needed to cover all degrees of freedom in the system. This allows to develop sensor-systems for universal detection of position and orientation of permanent magnets.

As such systems and their sensor-signals are very complex, the microsystems technology group at the Fraunhofer Institute IIS has developed a tool, which is able to simulate magnetic fields of permanent magnets and electrical currents and calculates the induced sensor signals as a function of any user defined movement. This allows a very effective system design for contactless position measurements.

Problems with 1D-Sensor Systems

Systems for position measurement using magnetic field sensors for one single sensitive direction (1D-sensors) suffer from several problems. They are sensitive to external magnetic fields, that cannot be avoided in most applications. One can use magnetic shields, but this increases costs and size.

In most applications the temperature of the system cannot be kept constant. This leads to two parasitic effects on the system: the sensors' sensitivities show drifts over temperature. This is also the case for the magnitude of the magnetisation of permanent magnets, which show non linear characteristics over temperature. The drifts of sensitivities could be corrected using onchip-coils for calibration. But for a correction of magnetisation drifts, it would be nessecary to measure the magnet's temperature. This means far too much effort.

Solutions for Robust Position Measurement

A good solution, to cope with temperature effects in mangetic measurements, is to measure angles instead of magnitudes. While the magnitudes change with temperature, the geometry of magnetic fields does not. Also a change of sensitivity of the sensors means, that the magnitude of the measured vector changes, but not its direction. Only noise will increase with rising temperature. There is still a small -but important- restriction: all sensors must have the same temperature, so that their sensitivities' drifts are well coupled. This is indeed the case for sensors, which are integrated into one and the same silicon cristal. If several discrete devices are used, their temperature will never be identical and the measurement of the angles will again show temperature drifts.

A method, to suppress the sensitivity to external field, is the use of gradients instead of absolute values. For homogeneous magnetic fields, this is simple to understand. If the magnetic field doesn't change from one point to another, then the spatial gradient of this field is zero and thus doesn't have any influence on the result of the measurement.

In contrast, inhomogeneous magnetic fields will have influence on the measurement, because their spatial gradients are finite. But the situation is one order of magnitude more relaxed than with magnitudes. To proof this, we take a look at the equation for an ideal infinitely small magnetic dipole, as it is described in literature [1]. The dipole has a magnetisation in z-direction m_z and is placed in the origin of a spherical system of cordinates, where ϑ is the zenit angle from the z-axis to the point $\vec{r}$.

The dipole's magnetic flux vector is a function of position:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \cdot \frac{m_z}{r^3} \cdot \left(2\cos(\vartheta) + \sin(\vartheta)\right) \qquad \textbf{Eq. 1}$$

As one can see, the magnitude of the magnetic flux density vector decreases with the third power of the distance r ($r = |\vec{r}|$).

$$\frac{\partial \vec{B}(\vec{r})}{\partial r} = -3 \cdot \frac{\mu_0}{4\pi} \cdot \frac{m_z}{r^4} \cdot \left(2\cos(\vartheta) + \sin(\vartheta)\right) \qquad \textbf{Eq. 2}$$

Looking at the gradient with respect to the distance (**Eq. 2**), one recognises, that it decreases even with the fourth power to the distance. This means, that a measurement, based on gradients instead of magnitudes, is one order of magnitude less sensitive to inhomogeneous external fields. Or, in other words, an external magnet can come closer to a gradient system to cause the same error as in a system using normal magnetic field values.

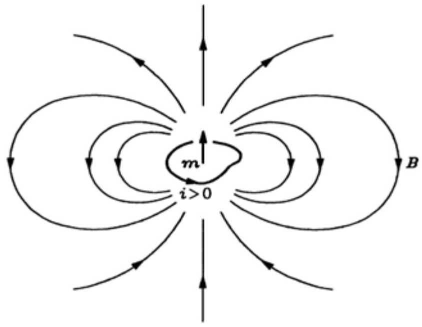

Figure 1: flux lines of an ideal dipole

We have seen, that problems with temperature drifts can be eliminated using angular measurements and the influence of external fields can be eliminated or at least significantly reduced using gradient measurement.

There are already products in the market, that use these methods in part. Here are some examples: Devices from Melexis [2] and Sensitec [3] use the measurement of two components to measure the angle. Another product from Senis [8] is able to measure a complete magnetic field vector and thus offers more flexibility in the mechanical arrangement of sensor and permanent magnet. All of them suppress temperature effects, but are still sensitive to external fields.
Austriamicrosystems delivers interesting goniometer products (the AS50XX-series e.g. [4]). These combine both methods, by using gradients with respect to the x- and y-direction as x- and y-component of a vector and calculate the phase of this vector, which cancels out the temperature drifts.

Mechanical Degrees of Freedom

Generally, bodies have 3 translatory and 3 rotary degrees of freedom. Indeed, as Eq. 1 shows, a magnetic dipole has a field, that is identical if it is rotated around ist magnetisation axis, which is the z-axis in this case. If no special arrangements are made, a magnetic system for contactless position measurement can thus only detect 5 degrees of freedom. But this no matter of principal, because the system could be extended by further permanent magnets. So, in general it is useful to take into account all 6 degrees of freedom and additionally an external field and the temperature. This means, that at least 8 quantities have to be measured to come to a robust system for contactless magnetic position detection.

An integrated Nine-dimensional Hall-Gradient-Sensor

A first sensor, which allows to take all necessary measurements of a complete vector of magnetic flux density on one single die, was published in 2008 ([5], [6]). In this paper we present a new device, developed on a 0,8µm CMOS-technology. This device includes 9 3D-sensors, which consist of one lateral sensor for the z-direction and two vertical sensors for x- and y-direction each (see **Figure 2**). According to the red-green-blue (RGB)-pixels in optical arrays, these 3D-sensors are called pixel-cells, where B_x, B_y and B_z represent the “R-, G- and B-parts of the magnetic field”. The pixel-cells are arranged in an array of 3 rows and 3 collomns with equal pitch. This allows to measure 27 different quantities, especially the following

- the magnetic flux vector B_x, B_y and B_z (3 quantities),
- their spacial gradients of 1st order with respect to either the x- or the y-direction (6 quantities)

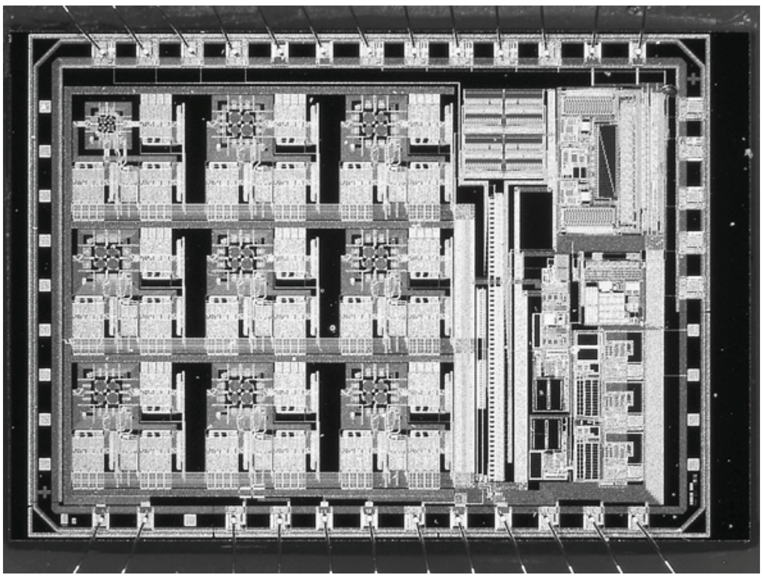
Figure 2: Photograph of the sensor-device

- their spacial gradients of 2nd order with respect to either the x- or the y-direction (6 quantities) and
- mixed gradients with respect to x- and y-direction for experimental puposes. (6 quantities).

This means, that there are 21 different quantities, which could make sense for position detection. But in practice the gradients of 2nd and mixed orders have lower importance. Generally it is not very useful to measure them. But the remaining 9 quantities can be used very effectively to develop robust systems.
Together with these sensors, the integrated sensor device includes a low noise programmable gain amplifier, which has a block for adjustment of offset for offset-centering puposes [7]. A 1st order delta sigma modulator with 4 bit feedback and 2 MHz maximum clock frequency was integrated in order to quantise the sensor signals. Its decimation filter is not included but has to be implemented in a FPGA or microcontroller. These external digital circuits are needed to control the device by means of a digital shift register, which was implemented for communication. All reference voltages and bias currents are generated on chip and an integrated current source allows to make a magnetic test of the sensors and to calibrate their sensitivities.

This multi-dimensional Hall-gradient-sensor is intended to be used in demonstrators for new concepts of robust magnetic position sensor systems using angles between gradients of magnetic fields. The Fraunhofer Institute IIS will lend evaluation kits to developers, who are interested in the investigation of these new concepts.

1st Order Gradients with Respect to Z-Direction

All sensor systems, which are integrated in CMOS-devices, have only a 2D-surface. This means that only gradients with respect to the x- and y-directions can be directly measured. But by means of analysing of Maxwell's equations it turns out, that magnetic field have certain characteristics, that can be used for completion of the set of gradients.
There are two Maxwell equations (Eq. 3 and Eq. 4), which are relevant for magnetic fields [1].

$$div(\vec{B}) = 0 \qquad \textbf{Eq. 3}$$

$$curl(\vec{B}) = \mu_0 \left(\vec{J} + \varepsilon_0 \frac{\partial}{\partial t} \vec{E} \right) \qquad \textbf{Eq. 4}$$

In these equations $\vec{B}$ means the vector of magnetic flux density consisting of the three components B_x, B_y and B_z, which are depending on position and time. $\vec{J}$ is the current distribution and $\vec{E}$ is the field of electrical flux, which are both three-dimensional vectors in space, too. μ_0 and ε_0 represent the electric and magnetic constants and $\frac{\partial}{\partial t}\vec{E}$ represents the derivation of the electrical flux with respect to time.
Eq. 3 describes, that magnetic fields have no source. Whereas Eq. 4 describes, that the magnetic flux density has only rotative parts, if there is either a current through this point or there is an electrical field in this point, which is changing over time.
In a more detailed vector notation in cartesian coordinates div and curl can be described as operations on the components of the vectors. Furthermore, in practice the electrical field is constant or zero and the sensors are well designed, so that the magnetic fields of the currents in the chip cancel each other. This means, that also the current desity in Eq. 4 can be set to zero for applications in practice. So, the following rules for the calculation of 1st order gradients with respect to the z-direction can be formulated:

$$div(\vec{B}) = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0 \qquad \textbf{Eq. 5}$$

$$\frac{\partial B_z}{\partial z} = -\left(\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} \right) \qquad \textbf{Eq. 6}$$

$$curl(\vec{B}) = \begin{pmatrix} \frac{\partial B_z}{\partial y} - \frac{\partial B_y}{\partial z} \\ \frac{\partial B_x}{\partial z} - \frac{\partial B_z}{\partial x} \\ \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \qquad \textbf{Eq. 7}$$

$$\frac{\partial B_y}{\partial z} = \frac{\partial B_z}{\partial y} \qquad \textbf{Eq. 8}$$

$$\frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial x} \qquad \textbf{Eq. 9}$$

$$\frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} \qquad \textbf{Eq. 10}$$

These equations (Eq. 6 and Eq. 8 to Eq. 10) are very important for the design of magnetic systems in general. Eq. 6, Eq. 8 and Eq. 9 show, that the derivations of the magnetic flux density with respect to the z-direction can be calculated from derivations with respect to the x- and y-directions. Additionally Eq. 10 means, that there are two derivations, which are always identical, so they are redundant and if one is known the second one doesn't deliver any new information.

2nd Order Gradients with Respect to Z-Direction

The Laplacian operator ∇^2 can be applied to vectors, which is defined by Eq. 11.

Due to Eq. 5 and Eq. 7, the right side of the equation must be zero. Together with an explicit notation of the Laplacian operator this equation can be modified to Eq. 12, and then be simplified to come to Eq. 13, Eq. 14 and Eq. 15.

$$\nabla^2 \vec{B} = grad(div(\vec{B})) - curl(curl(\vec{B})) . \qquad \textbf{Eq. 11}$$

$$\nabla^2 \vec{B} = \begin{pmatrix} \frac{\partial^2 B_x}{\partial x^2} + \frac{\partial^2 B_x}{\partial y^2} + \frac{\partial^2 B_x}{\partial z^2} \\ \frac{\partial^2 B_y}{\partial x^2} + \frac{\partial^2 B_y}{\partial y^2} + \frac{\partial^2 B_y}{\partial z^2} \\ \frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial y^2} + \frac{\partial^2 B_z}{\partial z^2} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \qquad \textbf{Eq. 12}$$

$$\frac{\partial^2 B_x}{\partial z^2} = -\left(\frac{\partial^2 B_x}{\partial x^2} + \frac{\partial^2 B_x}{\partial y^2} \right) \qquad \textbf{Eq. 13}$$

$$\frac{\partial^2 B_y}{\partial z^2} = -\left(\frac{\partial^2 B_y}{\partial x^2} + \frac{\partial^2 B_y}{\partial y^2} \right) \qquad \textbf{Eq. 14}$$

$$\frac{\partial^2 B_z}{\partial z^2} = -\left(\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial y^2} \right) \qquad \textbf{Eq. 15}$$

These calculations proof, that the presented integrated Hall-gradient-sensor is able to deliver a complete set of the magnetic flux density vector an its 1st and 2nd order gradients. Nevertheless for many applications the 2nd order gradients are rather noisy, so that only the 1st order gradients are really useful.

Systematic Design of Magnetic Position Sensor Systems

Even in simple systems it is hard to understand, how the magntic field looks like in three dimensions and how it will change during movements. It is nearly impossible to get a detailed idea of the scenes, if distortions from external magnets or electrical currents affect the system additionally. So, it is necessary to find a systematic approach for the design of complex magnetic position sensor systems.

From a mathematical point of view, a very systematic procedure for the design of a position sensor is to build the system of equations of the magnetic flux density of a permanent magnet as a function of its position and orientation with respect to the sensor. This system of equations can be solved to get the position and orientation of the permanent magnet as a function of the magnetic field, which can be measured with this sensor. This seems to be a good idea, but everybody, who ever tried to do so, has noticed, that this is very hard to do this analytically. It is possible to solve these equations with numerical solvers, but this much too complex for simple position sensors with a small microcontroller or onchip-DSP (= digital signal processor).

Another approach would be the construction of a mechanical experiment to emulate the movements of the permanent magnet for each design idea and measure the magnetic values for many positions and orientations. But this is a method, which needs very precise construction to be able to separate different distortions and their causes. Therefore it is an expensive way and it costs time, too.

There are also many simulators, which are able to simulate complex magnetic arrangements. A moving magnetic application, which is very often simulated are electric drives, for example. But the simulators, which are used for this purpose, are FEM-simulators (FEM = finite element method). They build a mesh, which represents the magnets, yokes and air gaps, and use some kind of relaxation algorithm, which calculates the state of every node depending on the state of their neighbours several times for one single step of a movement. For the next step, a new mesh must be built, because due to the movement of the experiment, the nodes don't fit to the new positions of the magnets, yokes and air gaps anymore. In many cases the designer even has to help the computer to find a mesh, which allows to find a precise solution. Then the relaxation algorithm has again to run through several iterations until the solution for the second position is found. This procedure must be repeated until every step of the movement has been calculated and the solutions for all positions are found. This method needs very high computing power and long time. Furthermore the effort to define the magnetic arrangement and movement of all parts is complex and means high effort for the designer.

These are the reasons, why the microsystems technology group at the Fraunhofer Institute IIS has desided to develop an own simulator, which uses analytic electrodynamic models of permanent magnets, which assume a homogeneous magnetisation of the magnets. In this case their magnetic field can be calculated from surface currents using the Biot-Savart equation [1]. In most cases, the models consist of integrals which do not have an explicit analytic solution and thus have to be solved with numerical algorithms, but nevertheless, they have to be solved only once for each sensor position. This means, that

these electrodynamic models need less computational effort than FEM-models. The modelling procedure in contrast is a challenge. But once the design of such a model is finished, the simulation itself is very efficient.
At the moment, there are models for an ideal magnetic dipole, spherical, cuboid and cylinder magnets. The most complex model up to now is a rotational solid, whose transverse section is a polygon, which can be freely defined by points in the xy-plane. Furthermore there are models for electrical currents and planes with ideal magnetic permittivity, which are needed to simulate magnetic shields. These models are scaleable in geometric dimensions and can be freely combined. Above all, movements of any body can be defined independent of each other.
If it is intended to use a special permanent magnet, which cannot be modelled using the available models, it is possible to take 3D-measurements of its magnetic field with a spatial resolution of 10µm, and to include these measurements in the simulations.
All of these features allow very precise simulations of rather complex magnetic position sensor systems within a short time. The additional capability to consider further effects like noise in the sensors and amplifiers and quantisation-effects in analog to digital converters or digital signal processors like a cordic algorithm or digital linearisation is a unique capability of the simulation tool.
For plausibility checks, it is possible to make three-dimensional images of all movements of the arrangement which is simulated. In these images the magnetic flux lines, which pass through all sensors, are displayed with the direction of the flux-vector. This helps to get a better idea of the magnetic circumstances in the modelled system. This helps the designer to improve and optimise the system. When all definitions of the arrangement of models and movements are finished, it is possible to combine the images of every step of the movement to a small movie for presentation purposes. Some examples of simulations are shown in the following images.

The first example (**Figure 3**) shows the results of a simulation of a linear position-sensor using a cuboid permanent magnet. From left to right, the figure shows the mechanical arrangement with a gradient-sensor with 5 pixel-cells, the sensor signals as a function of position of the magnet with respect to the sensor, a root locus diagram with 4 different root locuses using different sensor signals and the residual error of the position sensor if a linearisation with a table of 16 supporting points.

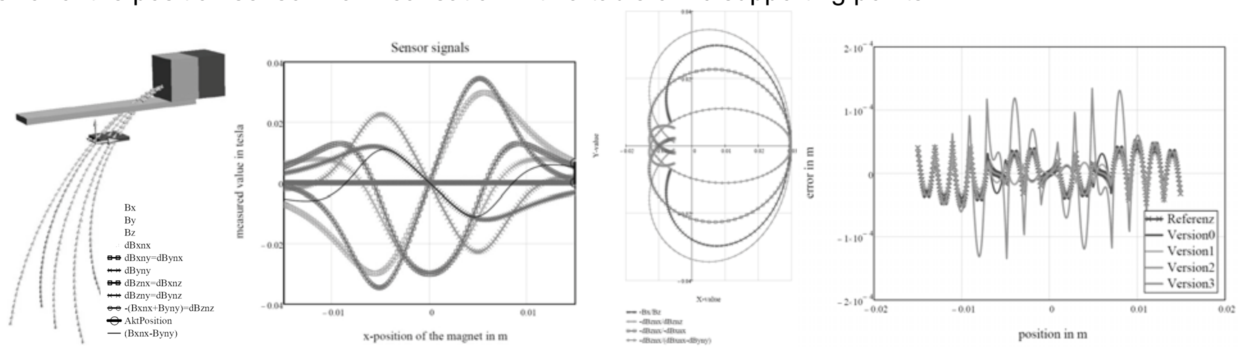

Figure 3: Mechanical arrangement, sensor signals, root locuses, error of linearised position measurement

The second example (**Figure 4**) is a variation of the system for linear position measurement with a ring-magnet.

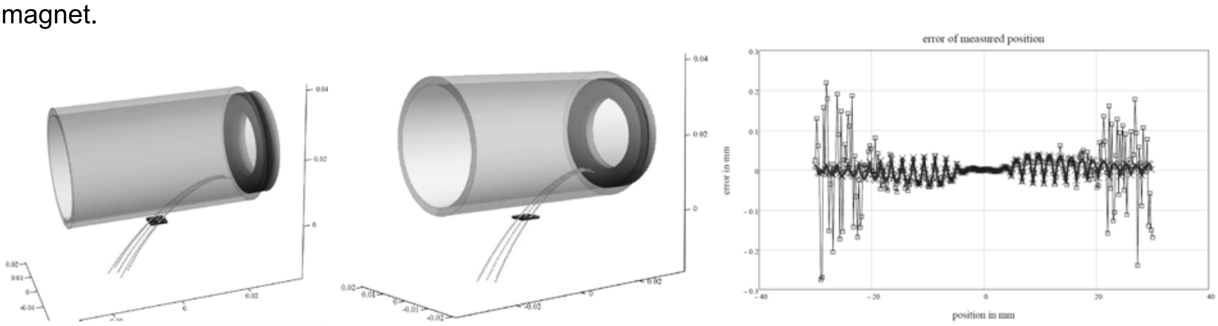

Figure 4: Mechanical arrangement with axial magnetized ring magnet and residual error of the position signal

The new simulation tool allows within a short time to deside, whether a magnetic position sensor system works as intended, and whether it is able to achieve the specifications for resolution and linearity.

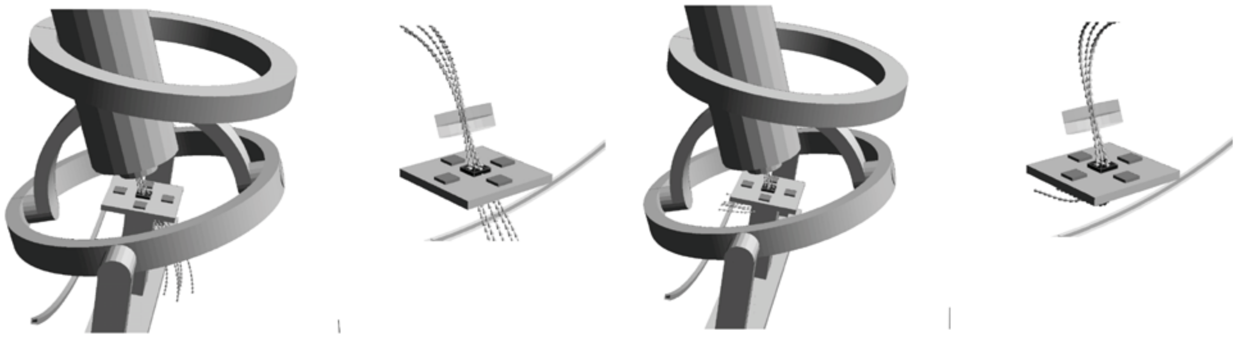

Figure 5: Example for a joystick application with -250A (left) and +250A (right) current in a wire

Conclusion

In the past the requirements for magnetic position detectors have not been very high. In most applications simple switching functions were sufficient. But as systems become more and more complex, the requirements for magnetic position sensor are rising, and in many cases, it is necessary to use more than one sensor to fulfill the requirements. Offerers of magnetic sensor respond to the new challenges by creating more complex sensors, which measure all three components B_x, B_y and B_z or gradients of B_z of the magnetic field. The Fraunhofer Institute for Integrated Circuits was the first institution to present an integrated sensor system, which is able to take measures of a complete set of spacial components of the magnetic field and their gradients in space of 1st and 2nd order. This opens new possibilities to enhance the robustness of position sensors and detect more complex movements.

But with rising capabilities of the sensors, the design of magnetic position sensor systems becomes a complex challenge for designers. It is necessary to use suitable tools which help the designer to find the best solution. Therfore, a new tool for simulation of magnetic position sensor systems has been developed by the microsystems technology group at the Fraunhofer IIS. This tool allows to evaluate the accuracy and the sensitivity to external distortions of a system with reasonable effort for modelling and for computational power. Now it is possible to design very robust and capable magnetic position sensor systems by using integrated multi-dimensional Hall-gradient-sensors and the suitable tools for simulation and optimisation of the magneto-mechanical arrangements.

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