Design of multi-dimensional magnetic position sensor systems based on HallinOne® technology

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***Abstract*-Systems for measurement of relative displacements or rotations in a single dimension by means of Hall sensors are state of the art. Fraunhofer HallinOne® Technology delivers 3D Hall sensors which can measure the complete spatial magnetic field vector as well as its change in all spatial directions at once. This allows in principle the design of position sensor systems which can detect all six degrees of freedom (positions and angles) of any device with a single magnet and a single magnetic field sensor. Unfortunately, complexity of the design increases significantly with the number of DOF in question. In this paper, after giving an overview on Fraunhofer IIS' HallinOne® technology, we present a software environment for the design of 3D magnetic position sensor systems, which supports the design process from feasibility studies unto preliminary testing of virtual prototypes. An application in the automotive domain is shown as an example.**

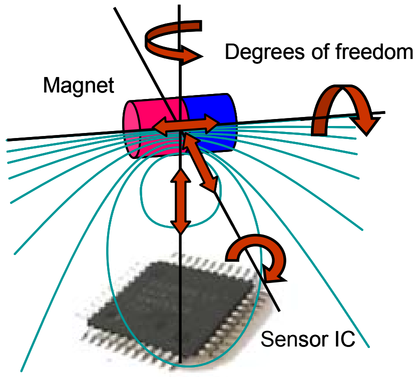

Fig. 1 Magnetic position sensor system

I. INTRODUCTION

Magnetic field sensors based on the Hall effect are useful to measure relative displacements and contortions. The magnetic field generates a Hall voltage U_H in the device, which is proportional to a certain component B_z of magnetic flux. If only a single coordinate (displacement or angle) z is wanted, it is easy in general to find an arrangement of magnet and sensor, where B_z is known as a well-defined function of z, and then to conclude back from measured voltage U_H to z.

Position sensing based on magnetic flux has many practical advantages against alternative principles of measurement, especially because of its minor sensitivity against environmental influences. State of the art are Hall effect based sensor elements integrated on CMOS ICs, which measure a flux component B_z perpendicular to the surface of the IC. For some years, Hall sensors have been developed also for chip-parallel flux components B_{xy} [1][2][4][7]

HallinOne® technology, developed by the Fraunhofer Institute of Integrated Circuits (IIS), enables integrated sensors which can measure all three magnetic flux components as well as all gradients quasi at a single point, avoiding ferromagnetic flux concentrators which cause nonlinear field distortions [5]. Additionally, even second derivatives in chip-parallel directions are measurable. With those sensors, higher dimensional position sensing problems become technically solvable (dimension is used here for the number of coordinates to measure).

With higher dimension and because of high integration density and complexity of the sensor elements on a sensor IC, complexity of the design problem is rising significantly, too. The relation between displacement/distortion of the magnet and magnetic flux density at the position of the Hall elements becomes nonlinear in general. Uniqueness of the multi-dimensional mapping *magnetic flux density* → *Hall voltage* → *position* is not guaranteed everywhere in the domain of freedom. Attainable resolution will not be easy to estimate, as it becomes spatially non-uniform due to different properties (sensitivity, offset) of lateral and vertical Hall elements as well as to the spatial extension itself. Costs of development rise sharply relative to common 1D Hall position sensors, even for prototypes.

In the light of this it does not only make sense to simulate the entire position ¬sensor system just economically. Indeed simulation will be inevitable for the solution of the design problem even in two dimensions. Fraunhofer Institute for Design Automation (EAS) in Dresden, Saxony, which is part of Fraunhofer IIS, has developed a design environment for multi-dimensional magnetic position sensing systems, which can be used to simulate magnetic source, sensor IC and several degrees of freedom of their relative movement at different levels, in order to test for basic assumptions of feasibility in early stages of development as well as to examine gradually refined prototypes.

We present first the Fraunhofer HallinOne® sensor IC HATA-3-1, application of which is shown in section 4 for a headlight swivel module prototype. Section 3 describes a design IDE for magnetic position sensor systems which can be used for feasibility studies and simulations with 3D-HallinOne® and other Hall Sensors.

II. HallinOne® – CMOS Integrated 3D Hall Sensors

At the Fraunhofer Institute for Integrated Circuits (IIS), research on innovative Hall sensors is done since 1997. In 2000, the first prototype of a vertical Hall sensor was patented, which operates without flux concentrators and can be manufactured without dedicated technological steps in standard CMOS technology [6]. Later on, vertical and conventional lateral Hall elements were integrated on a single chip. The technology was branded as HallinOne® and a first serial application (S³TAP out-of-balance sensor for washing machines by Seuffer) came to market in 2006 [11].

Fig. 2 shows a sketch of the design principle of the so called well sensor, a vertical Hall element which can measure surface-parallel magnetic field components [7].

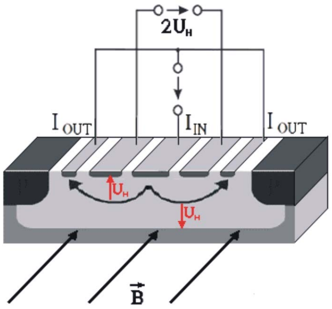

Fig. 2 Principal design of the well sensor – a vertical Hall element

In 2007, the first integrated Hall sensor IC worldwide was developed in a joint project funded by the German Federal Ministry of Education & Research (BMBF), which is able to detect all three spatial flux components as well as their 1st and lateral 2nd derivatives quasi at a single point (Fig. 3).

$$\begin{array}{cccccc}
B_x & \frac{\partial B_X}{\partial x} & \frac{\partial B_X}{\partial y} & \frac{\partial B_X}{\partial z} & \frac{\partial^2 B_X}{\partial^2 x} & \frac{\partial^2 B_X}{\partial^2 y} \\
B_y & \frac{\partial B_Y}{\partial x} & \frac{\partial B_Y}{\partial y} & \frac{\partial B_Y}{\partial z} & \frac{\partial^2 B_Y}{\partial^2 x} & \frac{\partial^2 B_Y}{\partial^2 y} \\
B_z & \frac{\partial B_Z}{\partial x} & \frac{\partial B_Z}{\partial y} & \frac{\partial B_Z}{\partial z} & \frac{\partial^2 B_Z}{\partial^2 x} & \frac{\partial^2 B_Z}{\partial^2 y}
\end{array}$$

Fig. 3 Measurands of the HATA-3-1 Hall sensor IC

The device, manufactured under the label HATA-3-1 by Micronas AG in Freiburg, Germany, delivers 15 independent measurement readings, which allows for the determination of all six spatial degrees of freedom. Moreover this prototype can perform self-monitoring and -calibration as well as external field compensation. This qualifies the HallinOne® technology especially for applications in the automotive domain, where robustness and security aspects are highly significant.

On the HATA-3-1 IC (Fig. 4) there are 5 3D sensors placed in a way that all measurands are determined with reference to the chip center. The central sensor delivers the real field measurement, while the data of the symmetrically arranged outer sensors deliver data for the computation of gradients.

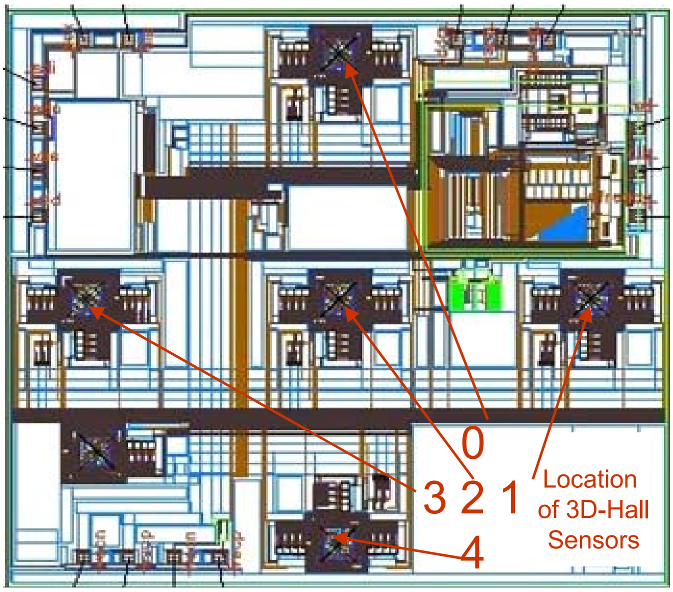

Fig. 4 HATA-3-1 sensor IC layout & arrangement of the 3D Hall sensors

Each 3D sensor consists of 1 lateral and 2 vertical Hall sensors, one per field component, which in turn consist of four point-symmetrically arranged Hall elements each, which are operated in “spinning current“ mode for offset reduction, composing their Hall voltages to an analogue Hall signal, which is digitized by a ΣΔ modulator of 1st order with 4-Bit feedback and can be read from a shift register by a PC or FPGA (Fig. 5). The analogue Hall signal amplitudes differ significantly due to different sensitivity and offset of lateral and vertical Hall elements; hence they must be aligned to the ADC input limits by a 4-step pre-amplifier.

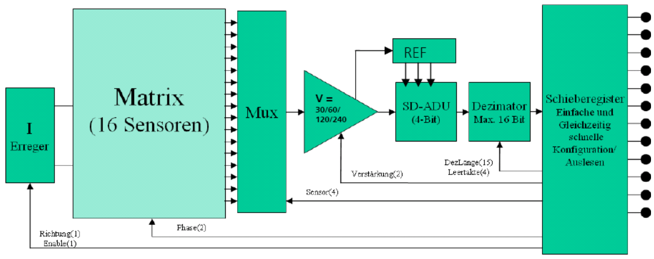

Fig. 5 Block diagram of the HATA-3-1 HallinOne® IC, with Hall sensors, multiplexer, preamplifier & AD converter

The HATA-3-1 sensor IC is running with supply voltage between 3.5V and 5V, its 20 lateral and 60 vertical sensor elements reach sensitivity values of 120mV/T and 50 mV/T, and offsets <50μT and <2.5mT, respectively, at 3.5V. Attainable resolution of the magnetic field is 1μT (B_z) and 5μT (B_{xy}). At 5V these values increase proportionally, at measuring frequencies between 110 Hz und 80 kHz, depending on the application.

III. Design Support for Multi-dimensional Position Sensor Systems

When designing magnetic position sensor systems, essentially four domains of the system are in the focus of interest, namely magnetic source(s) & sensor with their degrees of freedom (DOF) of relative movement, as outlined in Fig. 1, and an algorithm which would decode the magnetic field measurement back into a position and/or angle(s). On part of the hardware, the magnetic source and – in certain leeway – the sensor IC offer some freedom of design. There may be more strict design specifications regarding the relative trajectory of sensor IC and magnet, which form a kind of hyperspace in 3D. Furthermore, the decoder module for the actual determination of the position from the Hall signals may introduce constraints in complexity and accuracy.

In development of such systems, the basic aspects of uniqueness of the mapping *position* → *magnetic field* and the required resolution are important first. Additionally, attention must be paid to constraints of installation space and capabilities of the decoder hardware. In further design stages, estimates of the influence of a manifold of tolerances (magnetization, IC manufacturing, assembly, sensor parameters) and disturbances come to the fore.

Requirements in the design process of position sensing applications rise sharply with dimension. Even for two DOF, support by simulation of the system modules will improve and accelerate the design process significantly.

The modular design environment developed in the project focuses on support for the early stages of design, on basic feasibility studies for 3D magnetic position sensing applications [5]. It is roughly divided into three functional domains – configuration, simulation and visualization – which are operated via a graphical user interface and are related to the design tasks of defining, simulating and validating the sensor system (Fig. 6).

The design flow is supported in separate steps for each system domain. The designer starts by defining number and kind of mechanical DOF and simulates the trajectory of the relative movement. After verifying the correct traverse path, a magnetic field source is configured (Fig. 7) and the spatial magnetic field around as well as at the trajectory itself can be simulated (Fig. 8). After these simulations have been evaluated according to principal demands, and necessary corrections to the setup have been made, the Hall sensor IC is configured, its measurands upon the trajectory are simulated and then visualized with appropriate indicators for relevant design criteria, e.g. overdriving of the ADC (Fig. 10)

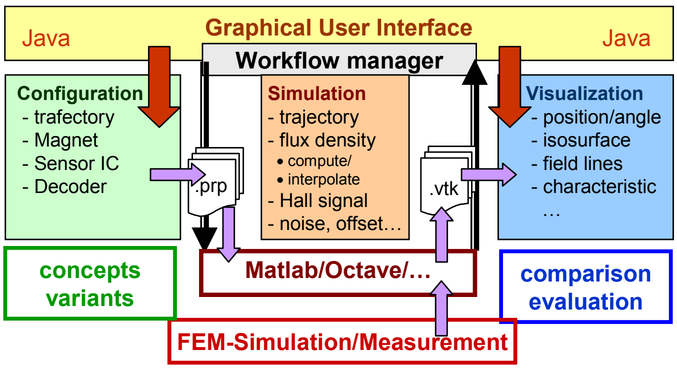

Fig. 6 Functional layout of the design environment, design flow and data exchange concepts

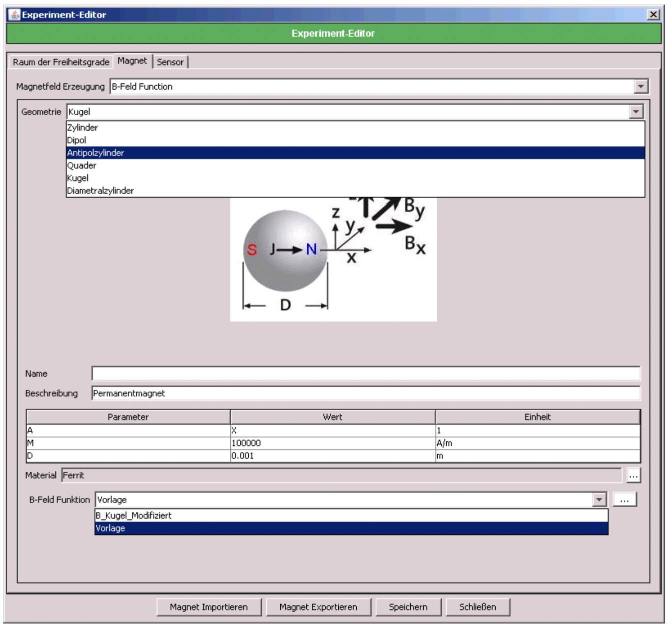

Fig. 7 Configuration panel for the magnetic source

The design environment is implemented in a platform-independent way in Java, while the simulation core is running alternatively in Matlab™ or GNU Octave. Visualization is built on the Visualization Toolkit (VTK) [9]. For each system module, model templates in Java property format are available, which can be modified, exported and imported.

Besides direct simulations for standard forms of permanent magnets, it is possible to import magnetic field data stemming from FEM simulations, e.g. in ANSYS®, COMSOL® or Maxwell3D®, or from measurement records. Several HallinOne® sensor models including the HATA-3-1 device are available, virtual sensor ICs with fictitious arrangement of 3D sensors and parameters can be generated. Sensor models for industrial Hall ICs as well as models for available magnets are developed as those arrive on the market.

For each quantity to evaluate and every sensor on the IC, there are well-suited visualisations available to observe, symmetric domains of the magnetic field or spatial domains, where resolution demands are not met or sensors overdrive the ADC because magnetic flux is to strong, (Fig 9 below) or the signal is dominated by noise. Simulation data are saved in the common VTK 2.0 legacy ASCII data format, providing seamless import into several external software tools for field analysis and visualisation, e.g. MayaVi [10]. The GUI is well-documented and available in both German and English.

Due to its modular structure, the design environment is extensible to multi-body systems (several magnets/sensors, disturbing bodies) as well as different principles of measurement (e.g. based on magneto-resistive effects) and corresponding sensors. Application specific modules for position decoding can be integrated.

Our design environment will allow engineers to explore the chances of robust 3D magnetic position sensing in a wide area of industrial applications and to significantly spare time for development & testing of their innovations.

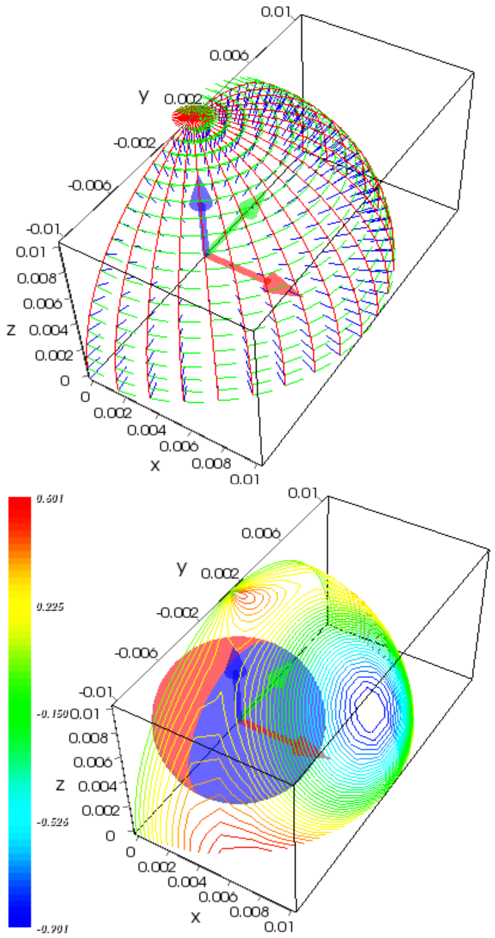

Fig. 8 Semi-spherical trajectory of a sensor (positions) with global (magnet) and local (sensor) axes (above); spherical magnet & isolines of flux density as seen by a single Hall sensor (below)

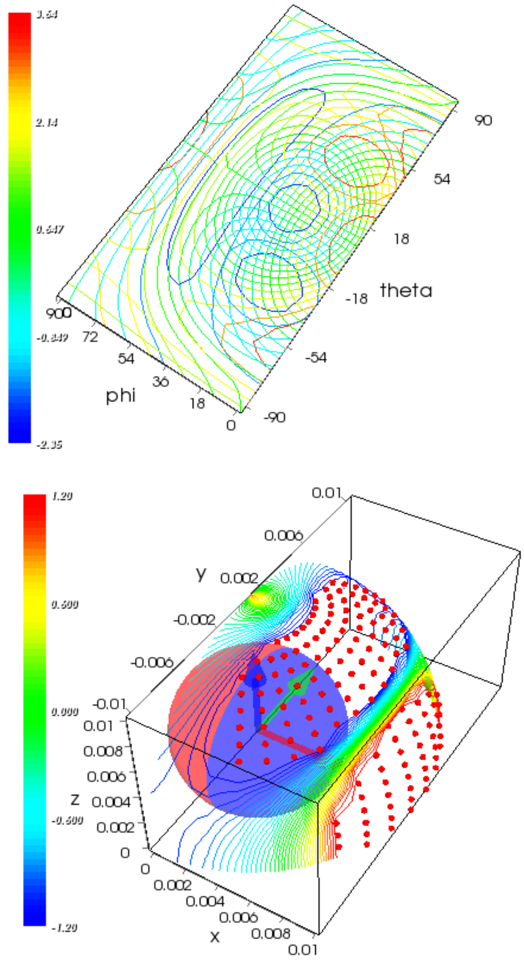

Fig. 10 Isolines of pre-amplified Hall voltage for all three Sensors in the 2D degree of freedom space (above); digital Hall signal (below), points instead of isolines indicate ADC overdrive

IV. APPLICATION: HEAD LAMP SWIVEL MODULE

In the framework of our research project, application of and design support for HallinOne® sensor ICs have been evaluated by means of four demonstrator applications for driver assistance systems outlined in Fig. 9. For Hella KG, this application was a new sensor for the detection of the orientation of a head lamp swivel module. Such swivel modules are driven by stepper motors and allow both a tracing of the headlight range – which changes e.g. during accelerating and braking or with load – and a lateral swiveling, in order to optimally illuminate the roadway also in sharp curves.

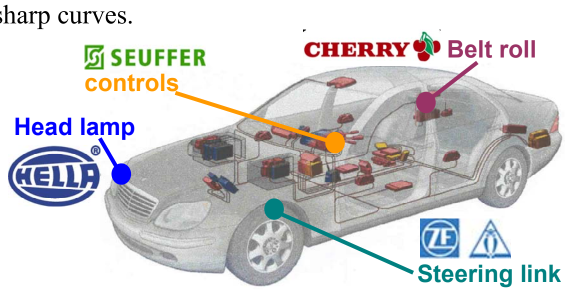

Fig. 9 HallinOne® demonstrator applications for the automotive domain

Fig. 11 shows the two degrees of freedom of the system, pivoting angle SA and tilt angle EA, while in Fig. 8, one can see the corresponding DOF space and a magnetic field simulation upon it. The HATA 3 1 Sensor is mounted on a fixed frame, while a permanent magnet is mounted on the tilting and swiveling head lamp module.

The conventional solution is based on determination of the zero position by a reference drive and the subsequent incremental counting of steps. This allows a feed-forward control of the light distribution, but feedback control was preferable.

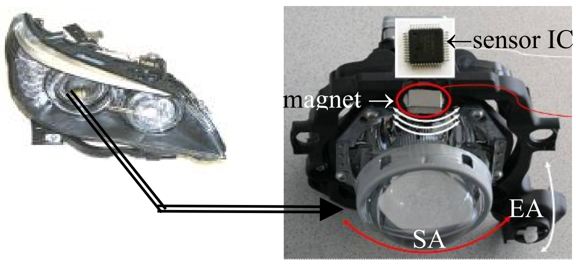

Fig. 11 Head lamp and swivel module with 2 degrees of freedom EA,SA; mounting position magnet/sensor indicated by arrows

The three-dimensional HallinOne® technology will now enable us to go forward from discrete, incremental position sensing, which is restricted to a single axis, to the simultaneous measurement of movement in two axes – a vertical tilt in order to adapt headlight range and a horizontal rotation for lateral swiveling. Additionally, this sensor IC enables analogue position sensing, i.e., giving up reference drives (realizing so called „true power on“ functionality).

Development of a tangible solution for this problem – detection of two rotatory angles – incorporates several steps and knowledge domains. The same holds for the subsequent validation process. Starting with the definition of possible constellations of the magnet and the sensor upon the frame and the swivel module of the headlamp, these concepts are evaluated first according to more qualitative criteria and constraints, e.g. the advantages of a fixed sensor mounting against possible negative influence of ferromagnetic materials in the frame or of disturbing magnetic devices. Later on, the concepts are evaluated according to signal to noise ratio and other, more quantitative criteria [8]. In the project, the classical, expensive design flow with its laborious experimental setup was executed first in order to gain actual measurements.

Fig. 12 exemplifies the result of such a measurement, variation of two components of magnetic flux density B_x and B_z in form of predominantly horizontal and vertical isolines as a function of the actual control variables pivot (SA) and tilt (EA). One can see that both signals can be separated easily, and that resolution is nearly uniform over the domain of interest, which covers ±10° for both DOF. Both results are advantageous for implementing decoder algorithms later on. The observed deviations of the signal B_x for EA outside ±10° are artifacts resulting from measurement setup.

In diverse design states, different measuring concepts were examined, which reached from an assembly with three rotatory and three translatory degrees of freedom, which allowed for any kind of 3D relative movement (Fig. 13, left), to an actual swivel module from a production series in its headlight casing, whose design space was restricted to certain concepts due to installation space constraints (Fig. 13, right).

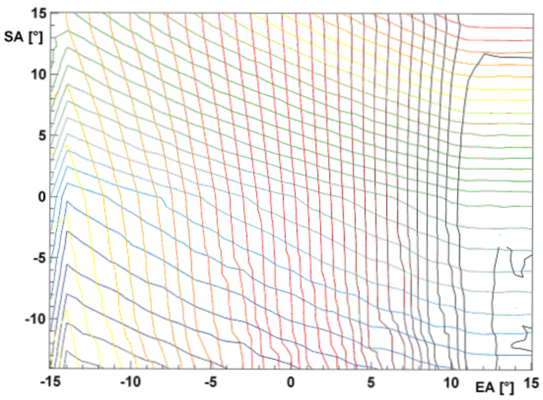

Fig. 12 Flux density components as a function of headlight range EA and pivot angle SA from measurements at the swivel frame mounted in the headlight casing seen in Fig. 13, right

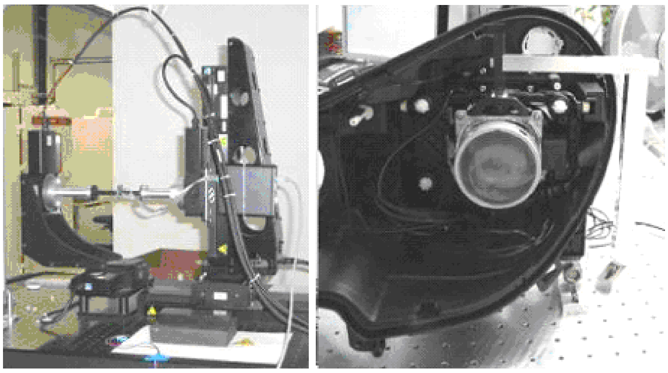

Fig. 13 Measuring assembly for evaluation of the 3D HallinOne® ICs: traversing unit with 6 DOF (3 positions, 3 angles, left side); swivel module in headlamp assembly (right)

While the first assembly exhibited more leeway regarding possible movements, this required also more complex algorithms und posed higher demands in programming both the traverse path and the decoding algorithms. In contrast, the built-in swivel module was more useful in fine tuning, e.g. in examination of possible cross-sensibilities in practice caused by disturbing fields, or the influence of the broad temperature range cars are used in.

With the design environment, it was possible to cover a great part of the classical design flow, which makes up for major design costs. This will be realized by the possibility to evaluate different measuring concepts qualitatively even in very early design stages by means of the magnetic field simulations upon the envisioned trajectory, independent of noise, other disturbances and measurement errors.

Also in further design phases, a stepwise refined evaluation is possible by simulating the sensor IC and its various, and inevitable measuring errors. Only after these evaluations, real position sensor devices must be set up and calibrated which can be designed from virtual concept studies already validated by the simulations.

Based on the experience presented here, further direction of development is evident: Efforts must be made to evaluate simulated signals automatically, independent from an individual designer’s experience. Corresponding criteria must be derived from practical design experience as well as theoretical considerations.

Those criteria will be indicators for symmetry, for insufficient resolution as well as for unfavourable signal-to-noise ratio or limit states of the electronic devices integrated on the sensor IC.

V. Summary and Prospects

In the framework of a joint research project by Fraunhofer IIS and industrial partners, a novel 3D Hall sensor IC has been developed, which is able to measure magnetic flux as well as its gradients and even second derivatives in 3D space, actually without any field distortions as introduced by ferromagnetic field concentrators in competing products . By means of demonstrator applications, the potential in use but also the complexity of the design problems for 3D position sensing systems was shown with preliminary HallinOne® sensor IC prototypes. For design support and refinement of such systems, a simulation and design environment with a graphical user interface has been developed and presented.

This widely platform-independent design environment software supports especially the early design stages, concept and feasibility studies. It is extensible to alternative principles of measurement and sensor types and to multi-body systems. It is planned to develop a toolbox of position decoder algorithms for standard problems, which can be exported to FPGA or similar platforms. Design support for non-standard cases is also offered on a bilateral basis. Sensor models will be complemented by algorithms for self monitoring and calibration.

The design environment is currently not available for sale, but Fraunhofer EAS is offering design services for industrial customers who plan to apply magnetic position sensor systems based on recently available HallinOne® sensor ICs manufactured by Micronas AG and, soon, by AMS. Support for custom Hall sensors can be easily integrated. The design tool will be further developed and refined according to industrial demands.

Acknowledgment

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