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MEMS fluxgate magnetometer for parallel robot application

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Abstract An advanced real-time workspace monitoring for parallel kinematic machines including tasks like self-calibration and exception handling demands integrated sensors measuring the angular position of the robot joints. This work introduces a single-axis MEMS fluxgate magnetometer developed for the specified application. The sensor is composed of high aspect ratio helical coils with generating and sensing functions around an electrodeposited nickel–iron core featuring ferromagnetic behavior. The core is designed in racetrack geometry causing an excellent directional sensitivity of the sensor for measuring the magnetic orientation of permanent magnets which rotate on the joint shaft. This approach allows the real-time detection of the required joint angle and the simplified analytical solution of direct kinematics.

1 Introduction

Fluxgate magnetometers are inductively working sensors composed of excitation and sensing coils around a ferromagnetic core for detecting vector magnetic DC and low-frequency fields. Several core shapes are known performing different behavior. Informative and comprehensive surveys on fluxgates can be found in (Göpel et al. 1989; Primdahl 1979; Ripka 1992). The MEMS fluxgate developed at the Institute for Microtechnology is designed in so-called racetrack geometry for highest directional sensitivity regarding the magnetic field vector. The ferromagnetic core material is periodically saturated by AC voltage excitation. The excited magnetic flux induces a voltage in the sensing coil. Via superposition of internal and external field vectors at core level, the induced signal is influenced by an external DC magnetic field. The corresponding signal part of the sensed AC voltage is the second harmonic, which is electronically analyzed and provides the required information about magnetic magnitude and field direction, respectively. MEMS fluxgate magnetometers feature the advantage of being small in size, weight and wattage. Fluxgate cores with a thickness of several microns mostly receive better magnetic properties and lower noise effects compared to ferromagnetic thin film layers (Primdahl et al. 1989; Ripka 2003). The presented single-axis micro-fluxgate has an electrodeposited 10 μm thick racetrack-core. It is applied as angular position sensor for a parallel robot.

In comparison to serial robots, parallel machines are characterized by fixed drives and closed kinematic chains composed of passive rods and joints. They perform high acceleration and velocity due to low mass and high stiffness of the passive elements. Taking full advantage of the structural capabilities of parallel kinematics demands additional machine-oriented control tasks, e.g., self-calibration, real-time workspace monitoring and exception handling. For simplifying the corresponding algorithms, position sensors, ideally contactless working, are integrated in the structural components (Hesselbach et al. 2005; Boese et al. 2009). The measured data leads to the analytical solution of direct and inverse kinematic models for realizing the required control-tasks. A high resolution and repeatability of these sensors are exceedingly important for high performance and accuracy of the parallel robot.

The introduced micro-fabricated fluxgate is combined with a permanent magnet and integrated in the passive joints of a parallel machine with HEXA-structure. Details

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about the HEXA-robot have been discussed in (Büttgenbach et al. 2005; Hesselbach et al. 2005; Kirchhoff et al. 2009b). The magnet is fixed on the joint shaft and rotates its magnetic direction during robot movement. This angular position sensor system builds an excellent solution for the described specifications. This work reports on fabrication, electrical analysis and characteristics of the MEMS fluxgate magnetometer.

2 Fabrication details and fluxgate design

The MEMS fluxgate consists of electrodeposited helical copper coils (see Fig. 1) around an electro deposited nickel–iron (NiFe) core in racetrack geometry. The electroplating of the coil bottom conductors as well as the deposition of the NiFe core takes place in AZ9260 moulds. The copper conductor height averages 20 μm, the core height amounts 10 μm. The core is embedded between SU-8 insulation layers (see Fig. 2). The remaining sections of the three-dimensional coils are electroplated in only one sequence using the negative working electrodepositable (ED) photoresist Intervia 3D-N. The electrophoresis process for applying the ED resist and relevant process parameters are described in (Kirchhoff et al. 2008). The Intervia 3D-N is stripped in an acid solution bath, which is warmed and treated with ultrasonic for an exhaustive and fast stripping process. After electroplating the helical conductors and etching the copper seed layer, the fluxgate is covered by SU-8 for protecting purposes, excluding the contact pads. The complete sensor is about 60−80 μm thick and built up on a 630 μm thick ceramic substrate.

The excitation coil consists of two identical parts connected in series (see Fig. 3). A horizontal magnetic flux (parallel to the substrate) is generated, when the fluxgate is excited. The sensing coil is wound around the two parallel

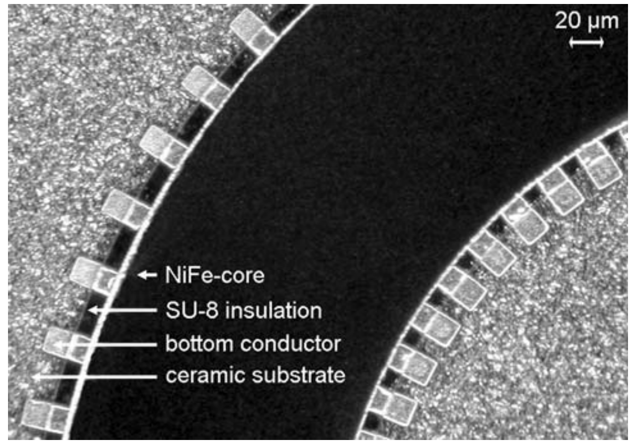


Fig. 2 Darkfield micrograph of the core upon the first SU-8 insulation layer

racetrack-core sections. Due to the fact that the magnetic flux passes the parallel sections in opposite directions, the excitation itself induces marginal signal in the sensing coil. An external field with a vector parallel to the core level amplifies and reduces the flux, respectively. In this way, the induced sensor signal is influenced and gains even harmonics corresponding with the external field. The induced voltage signal is zero, when the direction of the external field is vertical to the parallel core sections. If the field direction turns 90°, the output signal reaches maximum values.

3 Electrical circuit

The electrical circuit for driving the fluxgate and processing the sensor signal is dimensioned for the parallel robot application and shown in Fig. 4. The HEXA-robot

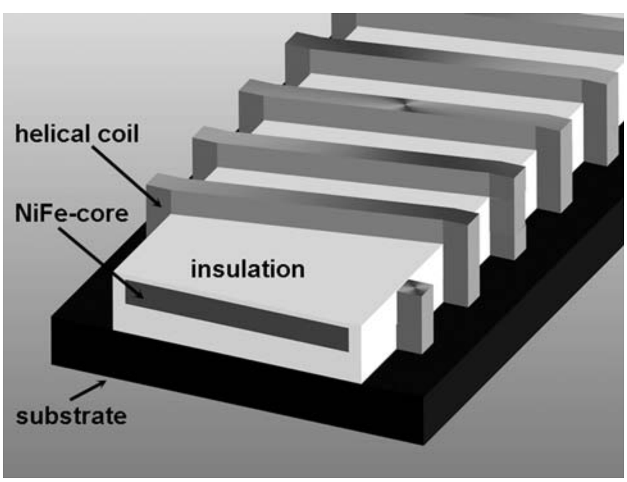


Fig. 1 Schematic of the cross section of the sensor

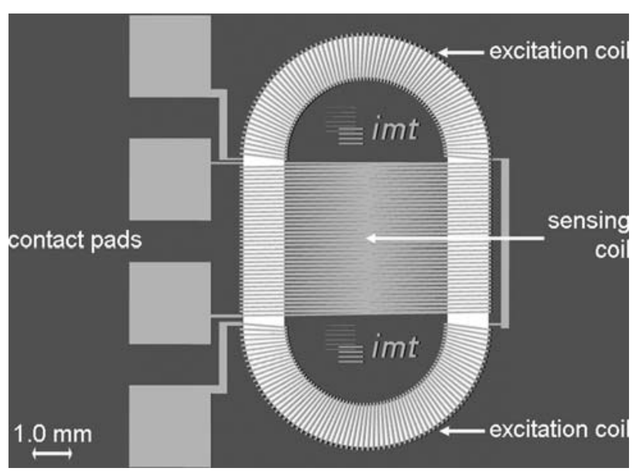


Fig. 3 Schematic of the fluxgate with excitation and sensing coils

controller unit, which employs a power supply of ±12 V, also powers the fluxgate electronics.

The square wave 20 kHz excitation signal is generated by means of a microcontroller (0 to +5 V, TTL level). To convert the TTL signal to an analogue −5 to +5 V excitation voltage, the signal is processed by a differential amplifier. The sensor signal amplitude is in the range of several mV and depends on the external field vector at level of the magnetic flux within the core. The signal parts, which represent the DC external field, are the even harmonics according to Fourier transform theory. For implementation to the 16-bit A/D converter of the robot controller unit, the sensor output signal must be in the range of −5 to +5 V DC. The functions of the analyzing electrical circuit are detecting, demodulation and amplifying of the second harmonic, which has double excitation frequency (40 kHz). A band-pass filter screens the second harmonic; it is amplified and connected to a phase sensitive rectifier with a 40 kHz reference signal. After filtering and amplifying by an active RC low-pass amplifier, the analogue DC signal ranges from −5 to +5 V as required for the parallel robot application.

The electrical circuit is assembled with low-noise ICs and several capacitors for noise reduction. Shielded cables and connectors are installed to avoid noise injection. Several parameters, e.g., gains and critical frequencies, of the electric circuit can easily be adjusted to different fluxgate types. Varying properties of the single sensors can be volitional (e.g., core height or numbers of windings) or non-volitional, mostly fabrication tolerances.

4 Characterization

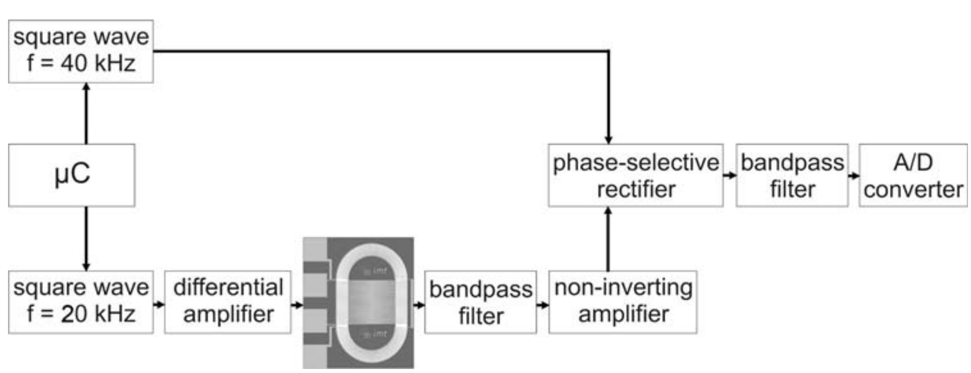
Figure 5 shows the test set-up for experimental investigation of the fluxgate. The micro magnetometer is located in a sensor fixture, which is mounted on a high-precision *xyz* linear stage driven by DC motors. The electrical connection of the fluxgate is realized by four test probes for an easy sensor exchange. The sensor can be adjusted with a resolution of 1 µm in all directions above the permanent magnet, which is fixed on a rotary platform and produces a magnetic field of approximately 800 nT. The distance between magnet and sensor is adjusted to 1.5 mm, similar to the situation in the passive joints of the HEXA robot (Franke et al. 2008; Kirchhoff et al. 2009a).

The rotary stage turns the magnet with a resolution of 0.001°. The DC motor controller for the stages is connected to a PC via USB. A visual C# program allows intuitive activation and movement of the stages and provides programming of motion-sequences (Kirchhoff et al. 2009b).

Figure 6 shows a typical characteristic of the presented micro fluxgate magnetometers. Maximum output voltage values (+5, −5 V) are reached at 90° and 270°, which mean a parallel orientation of the field direction relative to the parallel core sections. Zero-crossing of the output voltage at 180° derives from vertical magnetic orientation relative to the parallel core sections. In the linear span of the characteristic between 150° and 210° a sensitivity of 6.8 V/° is reached. 16-bit A/D conversion with a voltage range of 10 V and a measurement range of 180°, respectively, leads to a resolution of 153 µV corresponding to 0.003°. As the test-setup is not shielded, parasitic induction and noise effects caused by surrounding electro-magnetic fields impair this theoretical value. The calculated resolution based on the measured data amounts 10 mV corresponding to <0.2°. To identify the achievable resolution of the angular sensor, measurements in a shielded chamber will be subject of further studies.

The fluxgate operation principle is based on the magnetic behavior of the electrodeposited ferromagnetic NiFe core. The presented sensor characteristic (Fig. 6) belongs to sensor types with copper seed layers for the core electro deposition. The elemental composition of the cores has been identified to $Ni_{0.83}Fe_{0.17}$ by EDX analysis. The analyzing of coercive field strength $H_C < 150$ A/m and magnetic saturation flux $\Phi_S > 5.0$ nWb has been performed with a hysteresis loop tracer (SHB Instruments, Inc.). The detected values show the ferromagnetic behavior of the core structures with rectangular shapes of the hysteresis curves.

Fig. 4 Electrical circuit for providing the excitation and analyzing the output signal



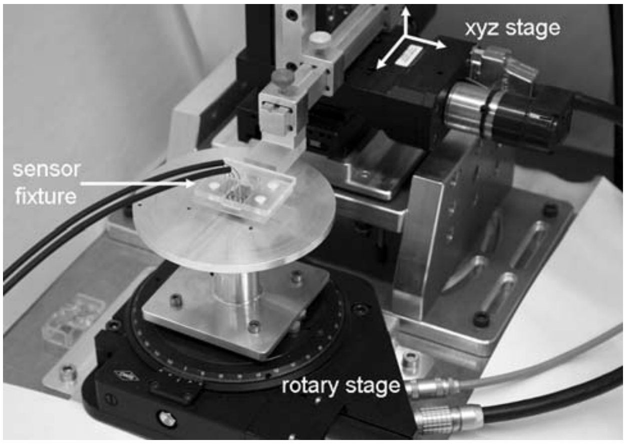


Fig. 5 Test set-up with *xyz* linear stage, rotary stage and sensor fixture

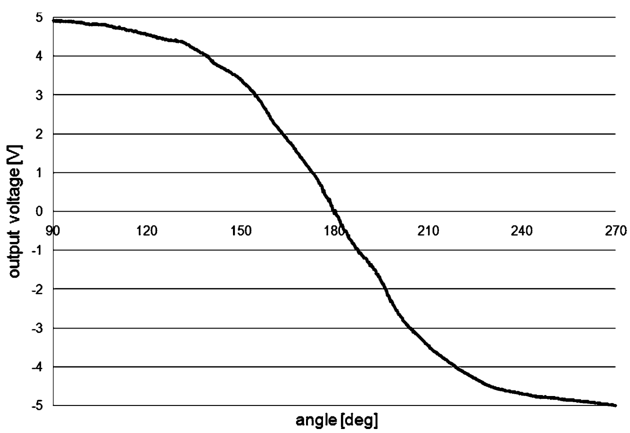


Fig. 6 Output voltage as a function of the angle

Despite the satisfying core characteristic, continuing research will probably review the core fabrication process by applying NiFe seed layers and magnetic annealing processes for an optimization of the magnetic properties. Preliminary studies presented in (Jordan et al. 2009) promise excellent results in this topic.

5 Conclusion

Single axis MEMS fluxgate magnetometers for a special parallel robot application are presented in this work. They build the basis of angular position joint-sensors applied for advanced real-time workspace monitoring. The fabrication process based on MEMS-technologies and the sensor design are introduced. The electrical processing of the sensors depends on the second harmonic demodulation and is adapted to the requirements of the application. Finally, the test set-up for the characterization and the typical characteristic of the angular sensors in the range of 180° as well as properties of the NiFe cores are presented.

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