

# Development of a Ferrofluidic Inclinometer exploiting a Vision-based Readout Strategy

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## Summary:

This paper presents an innovative inclinometer exploiting ferrofluids as a seismic mass with tunable properties via an external magnetic field. Tilt readout is performed through a Vision-based technique, by tracking the ferrofluid displacement under the balance of magnetic and gravitational forces. The system features non-contact measurements, robustness against mechanical shocks and low-cost. Experimental results have shown an accuracy of  $\pm 0.39^\circ$  and a resolution better than  $0.08^\circ$  over the operating range  $[0^\circ, 16^\circ]$ .

**Keywords:** Ferrofluid, Inclinometer, Computer-Vision, Image processing, Contactless measurement.

## Background, Motivation and Objective

Ferrofluids (FFs) are colloidal liquids consisting of nanoscale ferromagnetic particles coated with surfactants and dispersed in a carrier fluid. They exhibit super-paramagnetic behavior under a magnetic field while maintaining their fluidity [1]. Their physical properties, like volume and viscosity, can be modified by changing the magnetic field; this tunability allows ferrofluids to mimic spring-mass systems, enabling the development of advanced inertial sensors (such as accelerometers, inclinometers, and gyroscopes) with real-time adjustable performance [2].

FF-based inclinometers are more reliable and shock-resistant compared to traditional approaches because they employ a ferrofluidic aggregate as the seismic mass. In the event of mechanical shocks or extreme tilting, the ferrofluidic mass may exceed its displacement limit without incurring damage, and normal operation is restored when conditions return to their original state. Ferrofluidic inclinometers exploiting various electrical readout methods have already been demonstrated in [3], [4], and [5].

This paper presents a novel FF inclinometer that makes use of a Vision-based readout approach. Above already mentioned features, key advantages of this method include: *i)* the ability to tune properties and performance via an external magnetic field by using FF as the seismic mass; *ii)* a Vision-based readout that eliminates the need for physical contact and electrical connections with the sensing element; *iii)* a low-cost fabrication using cheap technologies and components.

## Description of the New Method and System

The tilt sensor features a glass tube filled with a saturated solution of deionized water and sodium chloride (NaCl), and a ferrofluidic mass. The ferrofluid seismic mass has been realized by pouring 30  $\mu\text{l}$  of Ferrotec® EFH3 ferrofluid into 15 ml of salt-saturated solution. This material was selected for its high saturation magnetization (65 mT) and low viscosity (12 mPa·s). A W-10-N neodymium magnet, mounted on a screw, generates the external tuning magnetic field which also give to the FF mass the characteristic spike-like shape. By adjusting the distance between the magnet and the glass pipe, the field intensity over the ferrofluid is varied. Magnetic field values over distance have been measured through an A1324 Hall-effect magnetic sensor, by Allegro Microsystem Inc.

The target tilt is detected by tracking the displacement of the ferrofluidic mass, which balances magnetic (retaining) and gravitational forces in a steady state. FF mass shift is monitored by a low-cost, embedded Vision system. The proposed readout approach is aimed at estimating the displacement of the FF mass from the rest position due to the target tilt, from an acquired image of the FF drop. Image acquisition and processing are carried out using a Pi Camera Module v2.1 connected to a Raspberry Pi 4 Model B.

A suitable experimental setup has been realized in order to assess the proposed measurement strategy. The following parts can be distinguished in Fig. 1-a, -b: 1) glass vial containing the FF; 2) ferrofluidic mass; 3) magnet; 4) magnetic field tuning screw; 5) target tilt screw;

6) GY-521 module, featuring an InvenSense MPU-6050 inertial sensor, used as reference for tilt values.

Acquired images go through a sequence of digital filters aimed at improving the effectiveness of parameters estimation, as shown in Fig. 1c, including: *i)* image cropping to the region of interest; *ii)* conversion to grayscale; *iii)* image blurring through a Gaussian filter to reduce random noise and improve FF contour recognition; *iv)* thresholding: enhance the contrast in the image and improves FF recognition; *v)* identification of the bounding rectangle surrounding the FF shape. Then, the geometric quantities defined in Fig. 1-d, are evaluated in order to estimate the FF mass displacement: the dimensions of the bounding rectangle and its aspect ratio,  $W$ ,  $H$  and  $W/H$ , respectively; the horizontal and vertical displacement of the FF center of mass ( $C$ ) with respect to the vertex of the triangular reference marker ( $V$ ),  $\Delta X$  and  $\Delta Y$ , respectively; the distance of the mid-point of the FF shape base ( $M$ ) to the vertex ( $V$ ),  $ED$ . A dedicated study has demonstrated that  $\Delta X$  shows the better correlation with tilt angle, with respect to other parameters. The above-mentioned quantities are natively estimated in pixels, thus in order to convert them to real dimensions, the pixels-to-millimeters conversion coefficient has been estimated by measuring the base and height of the reference marker. The estimated conversion coefficient value is  $31.8 \cdot 10^{-3} \text{ mm/px}$ .

## Results

The system response has been investigated by estimating the geometric parameters at different tilt angles and for different values of the applied magnetic field. The operating range limit is represented by the tilt angle value that leads the FF

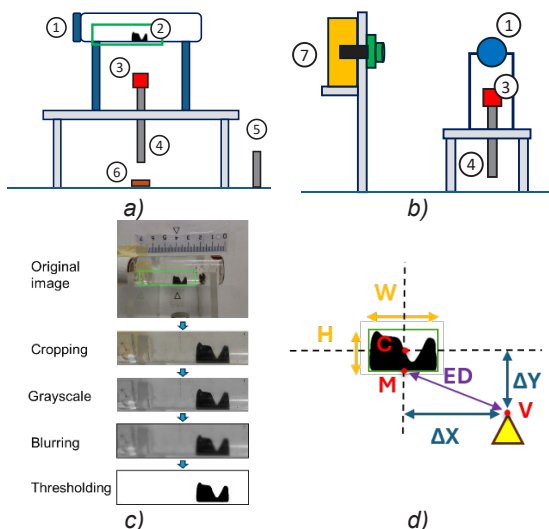


Fig. 1. Schematization of the experimental setup: a) front view; b) side view. c) Example of image processing d) graphical representation of the parameter.

mass escaping from the retaining force. For each magnetic field and tilt angle couple of values, 10 images have been acquired. Experimental results in terms of the mean value and standard deviation (error bars) of the parameter  $\Delta X$  over 10 acquisitions, as a function of the tilt angle,  $\theta$ , for different values of the magnetic fields are reported in Fig. 2. It can be observed that, as the magnetic field decreases, the system responsivity increases while the operating range narrows. The system response in case of 5.78 mT, which corresponds to a distance of 3.3 mm between the magnet and the glass vial, represents the better tradeoff between operating range, responsivity and accuracy values. By fitting experimental data with a 2<sup>nd</sup>-order polynomial, the following relation is achieved:

$$\theta = -0.048\Delta X^2 + 2.117 \Delta X + 0.073$$

The estimated uncertainty in the  $3\sigma$ -limit is  $0.39^\circ$ , while the resolution, reported on the right axis of Fig. 2, is  $0.08^\circ$  in the worst case.

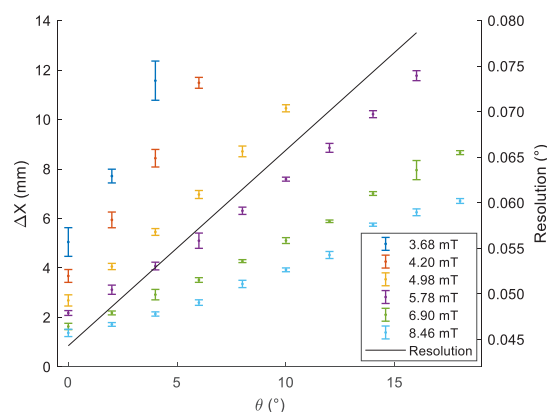


Fig. 2. Estimated value of  $\Delta X$  vs tilt angle and applied magnetic field (left axis). Estimated resolution for the case 5.78 mT (right axis).

## References

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