SEARCH COIL MAGNETIC ANTENNA
(BOBMARLEY)
SAVRONIK

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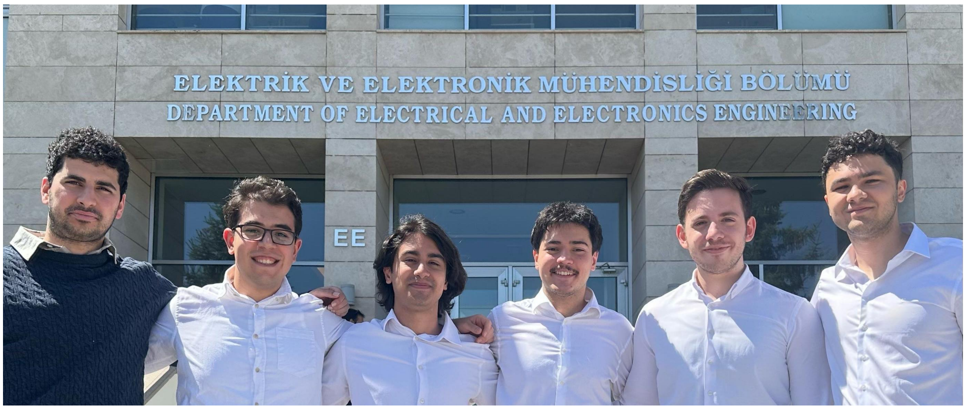

Abstract. This project aims to develop a search coil type magnetic antenna and a supporting front-end circuit to sense magnetic fields in the 600–900 Hz frequency range. The search coil antenna is also one type of magnetic sensor that can work in sub-KHz frequencies, and this project offers a system to detect the magnetic field change in the environment for the specified frequency band for proximity sensory applications. This system includes a segmented coil antenna, a Printed Circuit Board (PCB) with amplification and filtering stages, and a MATLAB Graphical Unit Interface (GUI) for real-time analysis. For the antenna design, a segmented coil design was optimized for better detection capability while considering thermal noise effects. The final prototype is capable of detecting low-frequency magnetic signals within a 5-meter radius with 97%

PROJECT DESCRIPTION

Search coils are inductive sensors widely used in various fields such as geomagnetic field measurements (magnetotellurics), magnetometers in spacecrafts [1-3]. Compared to traditional Flux-gate and Hall effect magnetic sensors that lack the required sensitivity in close range, search coils are, especially, a suitable option for proximity fuse sensor [4] applications in torpedoes. In this project, we address the challenge of detecting weak low-frequency (600-900 Hz) magnetic fields by developing a search coil antenna that have a sensing capability within a 5-meter range, in collaboration with Savronik. The sensor includes a segmented high-turn-count coil antenna with high magnetic permeability core, an analog front-end circuit for amplification, and filtering of the received signal, analog-to-digital converter, and implementation of a graphical unit interface (GUI) on MATLAB for the visualization. In the final product, we achieved a compact, and highly sensitive magnetic sensor with a sensitivity of 2500 V/T within a range of 5 meters.

MILESTONES

1. **Research and Analysis:** Different type of low-frequency magnetic antenna designs are examined, and list of components are arranged.
2. **Antenna Design:** A magnetic coil design is modeled in CST to get maximum magnetic flux receiving around high permeability material.
3. **Receiver Circuit Design:** Using circuit schematic simulation tools, possible topologies are analyzed in order to satisfy frequency response specifications.
4. **GUI Design:** MATLAB GUI and firmware are developed to visualize the receiving magnetic signals.
5. **Antenna Manufacturing:** The antenna model is implemented by winding segmented coils around a high-μ material rod.
6. **PCB Manufacturing:** A Printed Circuit Board layout is designed, and fabricated, and lumped circuit elements are soldered.
7. **Prototype Implementation:** The antenna, PCB, and GUI are installed together, and the operating system is analyzed.

DESIGN DESCRIPTION

The project consists of three main sections: the antenna, analog front-end circuit, and computer interface. The design methodology, simulations, and manufacturing steps are explained in detail for each section.

Antenna: A search coil is an antenna with high magnetic permeability (μ) core material surrounded by windings. The high permeability core used in this project has a relative permeability (μ_r) of 10,000, which is considerably higher than most of the ferrite materials. Due to its high permeability, the magnetic field around the antenna is confined into high-μ core. Windings are designed to be have more density around the center where the magnetic field intensity is the highest, in order to enhance the received electromagnetic wave [5].

The main challenge with such a coil design is that the magnetic field distribution around the core is not uniform, and the maximum length of the copper wire around the core is limited due to the thermal noise of its resistance [6]. Therefore, a computational analysis was necessary for the optimization of the antenna model. In this optimization process, the magnetic field distribution around the core was simulated on CST with a linear magnetic field being introduced in the system. The resulting magnetic field distribution was then post-processed in Python to calculate the optimized winding distribution around the high-μ rod.

A non-uniform distribution was achieved by dividing the antenna into segments. The segmented model approach reduces the capacitance value of the antenna in order to increase the sensing efficiency. Also, the segmented antenna model was found to be more convenient in terms of manufacturing. After the design process, the coil is wound around a custom-made plastic case which was printed with a 3D-printer. The wire diameter is chosen as 200 μm, and there are approximately 19,200 windings. Inductance and resistance values were recorded for different winding segmentations, with the final design achieving approximately 6 H inductance and 650 Ω resistance using a modular, 3D-printed coil body.

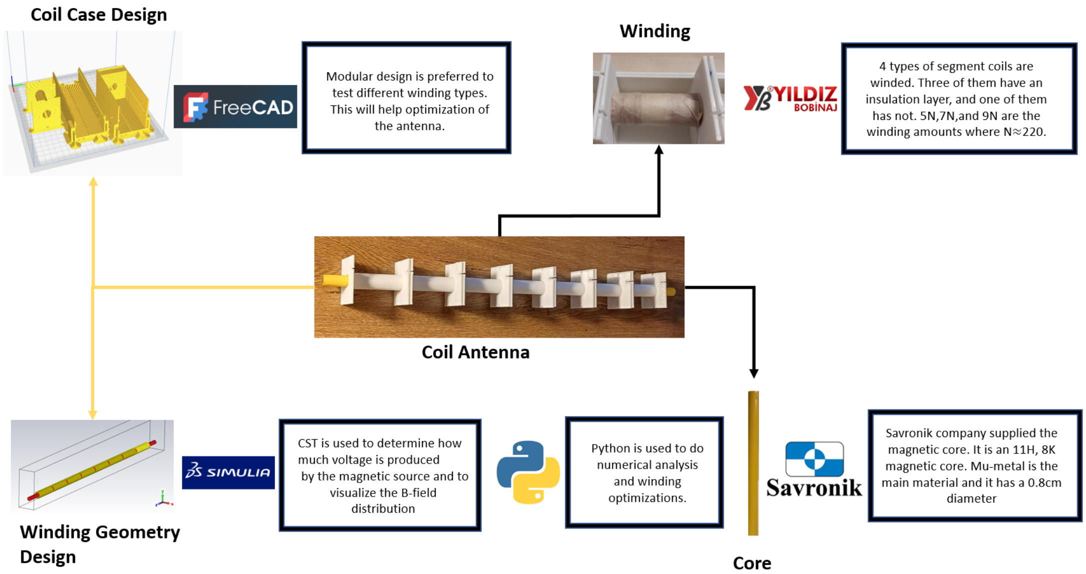

Figure 1: Antenna design overview.

PCB: Analog front-end circuit of the search coil system consists of three main parts: amplifier, band-pass filter, level-shifter, and voltage limiter.

Firstly, in the amplifier part of the circuit, an amplification ratio of 100 (40 dB) is achieved, while obtaining a low noise figure. There are four cascaded parts of the amplifier. Initially, an input buffer is realized in order to provide a lower input impedance for the following blocks. The inductance of the antenna is tuned with a shunt capacitor for a higher power transfer to the amplifier circuit [7]. Then, there are pre-amplifier, and amplifier blocks that provide 40 dB amplification. Finally, there is an output buffer OPAMP to isolate the amplifier from the filter.

Secondly, an 8th order active band-pass filter with 600-900 Hz cut-off frequencies is designed. Butterworth topology was determined due to its flat pass-band characteristics. An attenuation level of 15 dB is acquired around 100 Hz out of the band limits.

Thirdly, a level-shifter circuit was necessary, since the Analog-to-Digital converter used in the system (STM32 ADC module) allows a voltage swing between 0-3.3 V. Therefore, a 1.65 V DC bias is introduced to the received AC signal through a BJT circuit.

Finally, A voltage limiter circuit using a 4.7 V Zener diode was integrated to protect the ADC input. All PCB components were soldered and tested, and two functioning prototype boards were manufactured in the Bilkent University lab.

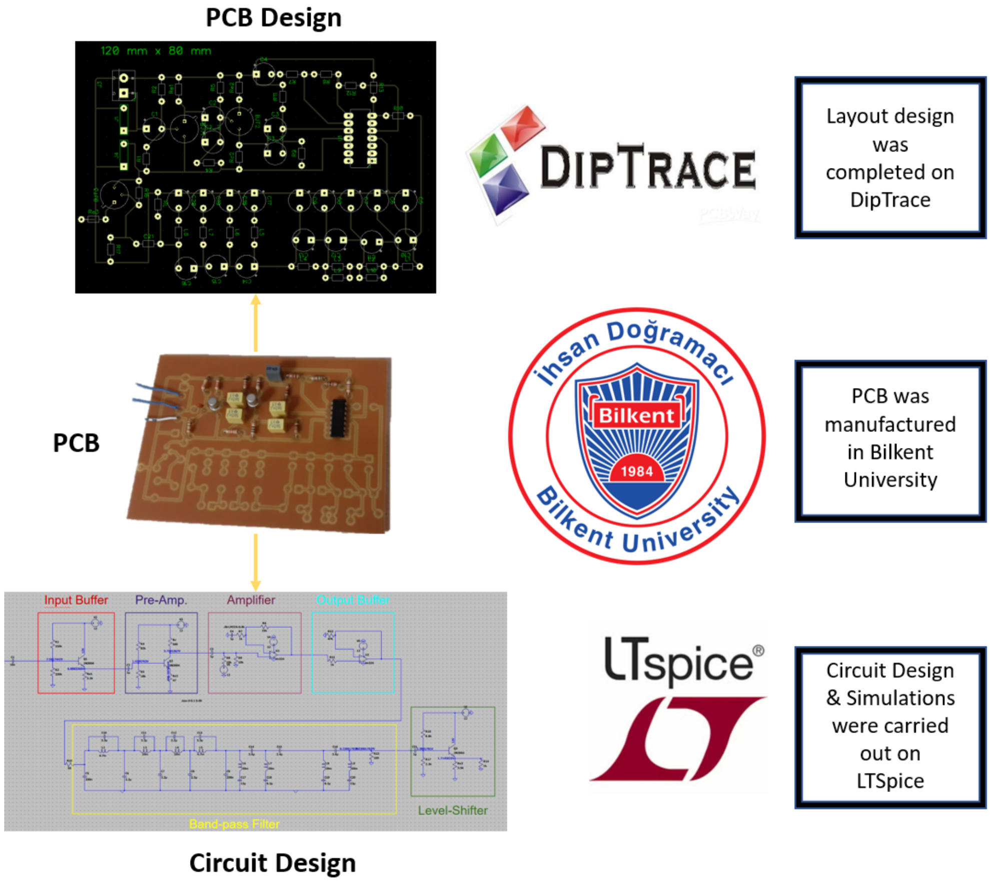

Figure 2: Circuit design overview.

GUI: The MATLAB GUI allows users to visualize and analyze signals in real time, with both time-domain and frequency-domain plots. Using simple “Start” and “Stop” buttons, users can begin and end data streaming with ease. When streaming starts, the live time-domain signal appears in the upper-right plot. Pressing “Stop” saves the signal automatically with an index, which can later be used to retrieve the data for further analysis.

Users can enter the saved signal’s index, select a specific time range, and click the “Show” button to display that segment in the bottom-left plot, while the full signal remains visible above for context. A Fourier Transform is then applied to the selected segment, and the GUI highlights the top 5 dominant frequencies alongside the frequency-domain plot to help identify key components or noise in the signal.

The system is powered by the NUCLEO-G431RB microcontroller, featuring a 12-bit ADC sampling at 23.5 kHz. Data is efficiently transmitted to MATLAB via UART using optimized serial communication for fast and accurate signal acquisition.

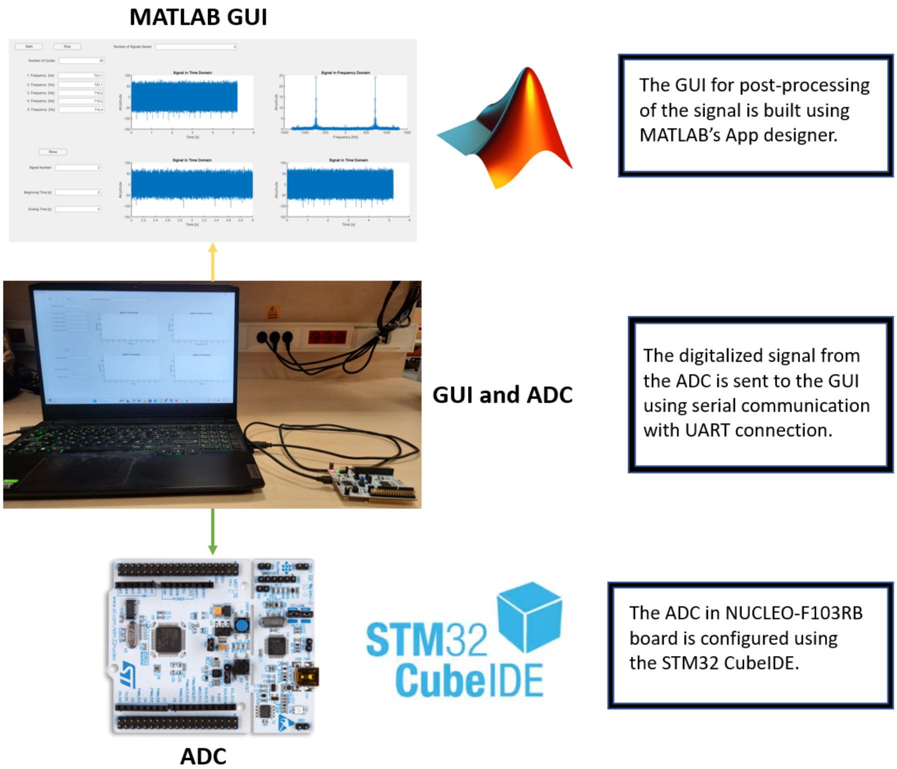

Figure 3: GUI design overview.

RESULTS AND PERFORMANCE EVALUATION

After integrating all modules, receiver accuracy and range were tested using a waveform generator and oscilloscope. Testing was conducted under controlled conditions at distances of 1 m, 3 m, and 5 m, for various input signals ranging from 0.5 Vpp to 10 Vpp and frequencies of 650 Hz, 750 Hz, and 850 Hz. Results were recorded for both serial and parallel orientations. The system exhibited reliable signal detection with minimal error at close range and maintained acceptable performance across the tested spectrum. These results validate the antenna's sensitivity and the effectiveness of the amplification and filtering stages. The antenna reliably captured 750 Hz modulated signals.

- **Range:** 5 meters
- **Sensitivity:** 2500 V/T
- **Bandwidth:** 600–900 Hz
- **Gain:** 46 dB total

GUI output remained stable under different interference conditions. Performance exceeded the 90% accuracy benchmark, achieving >97% in most of the test conditions.

Input	5 m	3 m	1 m
10 Vpp / 650 Hz	1.44	0.97	4.64
5 Vpp / 650 Hz	1.4	0.98	4.63
1 Vpp / 650 Hz	1.63 (2)	1	1.23
0.5 Vpp / 650 Hz	1.4 (2)	0.92	1.24
10 Vpp / 750 Hz	0.11	0.6	4.67
5 Vpp / 750 Hz	0.11	0.76	4.64
1 Vpp / 750 Hz	0.81	0.56	0.78
0.5 Vpp / 750 Hz	0.06	0.27	0.53
10 Vpp / 850 Hz	0.32	0.04	4.63
5 Vpp / 850 Hz	0.31	0.75	4.60
1 Vpp / 850 Hz	0.17	0.18	0.47
0.5 Vpp / 850 Hz	0.17	0.87	0.47

Table 1. Test Results in Serial Orientation

Input	5 m	3 m	1 m
10 Vpp / 650 Hz	1.4	1.23	4.61
5 Vpp / 650 Hz	1.67	1.23	4.33
1 Vpp / 650 Hz	1.66	0.78	1.23
0.5 Vpp / 650 Hz	1.46	0.83 (2)	1.23
10 Vpp / 750 Hz	0.05	0.54	4.68
5 Vpp / 750 Hz	0.12	0.3	4.62
1 Vpp / 750 Hz	0.12	0.51	0.55
0.5 Vpp / 750 Hz	0.28	0.79	0.58
10 Vpp / 850 Hz	0.47	0.71	4.60
5 Vpp / 850 Hz	0.47	0.72	4.49
1 Vpp / 850 Hz	0.47	0.72	0.71
0.5 Vpp / 850 Hz	0.47	0.16	0.47

Table 2. Test Results in Parallel Orientation

Explanation: The values in the tables indicate the percentage error from the transmitted signal frequency as detected by the receiver system. Colors represent different outcomes:

- **Green:** The system successfully detects the correct frequency within the 3% accuracy margin.
- **Yellow:** The correct frequency is detected, but it is not the most dominant frequency component in the signal. The order of dominance is indicated in parentheses.
- **Orange:** The system detects the correct frequency slightly out of the the 3% accuracy margin, which is due to the signal clipping.

CONCLUSION AND FUTURE WORK

The developed magnetic antenna system effectively meets the defined performance criteria for low-frequency magnetic sensing in the 600–900 Hz range. Future work will focus on enhancing portability by integrating a battery-powered system, increasing environmental robustness through waterproof casing, and expanding the software interface to support multi-sensor data acquisition and analysis.

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BEHIND THE SCENES