NEWTON Deliverable D3.2

Preliminary design report for the electronic control block

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Abstract: This document reports the preliminary design of the Control Unit (CU) of the NEWTON instrument. The electronic Control Unit is the responsible of the control, acquisition and processing of the signals of the sensor unit. It contains a microcontroller that performs these tasks and generates the different frequency signals for the susceptometer and the magnetometer.

Keyword list: Planetary Science missions, magnetometry, complex susceptibility, multi-sensor system, Mars, the Moon, control unit, lock-in, signal processing, susceptometer, magnetometer.

Executive Summary

This NEWTON WP3 deliverable D3.2 entitled "Preliminary design report for the electronic control block" describes the preliminary design of the control unit developed for the three prototypes of NEWTON instrument.

With the aim of maximizing the impact of novel NEWTON technology, different prototypes will be developed within the project. Two prototypes (named prototype 1 and 3) will be developed for planetary application, while a slightly (reduced) adapted version of prototype 1 (named prototype 2) will be developed in order to demonstrate the spin-off of the technology between space and non-space fields. The three prototypes share the same architecture while they provide different performance capabilities adapted to different scenarios. The key building blocks of the three prototypes are the same, i.e. Power Distribution Unit (PDU), the electronic Control Unit (CU) and the Sensor Unit (SU).

With regard to the CU, it is the responsible of the control, acquisition and processing of the signals of the sensor unit. This deliverable describes the preliminary design of the CU for the three prototypes. In addition to this, this document also includes information about the electronics included in the SU.

This document is structured in different sections. Section 2 reports the architecture of the three prototypes developed within the NEWTON project as well as it describes the main differences between them. Section 3 describes the preliminary design of the CU for the three prototypes of the NEWTON instrument as well as preliminary validation tests. Section 4 describes the actions planned for the next stage of the project. During this following phase, the final design of the NEWTON instrument will be developed and reported in the next WP3 deliverables which are planned to be delivered in April 2018. Finally, Section 5 presents a summary of the content included in this document as well as the main conclusions obtained from it, and Section 6 provides the referenced bibliography.

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Abbreviations

AC	Alternating Current
ACK	Acknowledgement
ADC	Analog-Digital Converter
B	Magnetic Induction
CRC	Cyclic Redundancy Code
CU	Control Unit
D	Deliverable
DAC	Digital to Analog Converter
DC	Direct Current
EU	European Union
INTA	Instituto Nacional Técnica Aeroespacial “Esteban Terradas”
IRM	Isothermal Remanent Magnetization
LSB	Least Significant Byte
MSB	Most Significant Byte
NRM	Natural Remanent Magnetisation
PC	Personal Computer
PDB	Printed Circuit Board
PDU	Power Distribution Unit
R	Resistance
SCLK	Serial Clock
SDI	Serial Digital Interface
SDO	Serial Data Output
SPI	Serial Peripheral Interface
SU	Sensor Unit
TRL	Technology Readiness Level
TTI	Tecnologías de Telecomunicaciones e Información
TTL	Transistor-Transistor Logic
UART	Universal Asynchronous Receiver-Transmitter
UPM	Universidad Politécnica Madrid
USART	Universal Synchronous and Asynchronous Receiver-Transmitter
UT	University of Trier
WP	Work Package

1. INTRODUCTION

Magnetic characterization is essential to know the past and present of planetary objects. To make magnetic prospections in-situ requires a magnetic susceptometer (it's real: χ' and imaginary: χ'' parts) to determine the magnetic structure recorded during the formation of the studied rocks. The previous measures with vector magnetometers to know the total magnetic field (B) and its components (Bx, By, Bz), complete a total study of the planetary exploration.

NEWTON project develops a new portable and compact multi-sensor instrument for ground breaking high resolution magnetic characterisation of planetary surfaces and sub-surfaces through the combination of complex susceptibility and vector measurements. The new instrument includes magnetometer, portable susceptometer, power supply system immune to radiation and a frequency generation system. The goal of the NEWTON project is to achieve a demonstration prototype in a relevant environment (TRL6) in order to make the multi-sensor instrument suitable for boarding in a planetary exploration rover in the short term.

With the aim of maximizing the impact of novel **NEWTON** technology, different prototypes will be developed. Two prototypes (named prototype 1 and 3) will be developed for planetary application, while a slightly (reduced) adapted version of prototype 1 (named prototype 2) will be developed in order to demonstrate the spin-off of the technology between space and non-space fields. This will allow the consortium to simultaneously investigate 1) ground breaking potential for the measurements of parameters of main importance in planetary magnetism with implications to the geological history of the planets by introducing susceptometer technology and new technologies that are immune to radiation in the designs and 2) integrate and explore synergies to industrial spin-off.

The three prototypes share the same architecture while they provide different performance capabilities adapted to different scenarios. The key building blocks of the three prototypes are the same, i.e. Power Distribution Unit (PDU), the Control Unit (CU) and the Sensor Unit (SU). This deliverable describes the preliminary design of the electronic Control Unit, and it also includes information about the electronics included in the SU.

2. ARCHITECTURE OF THE NEWTON INSTRUMENT

In this section the main features of the architecture of the different prototypes are described highlighting the fundamental differences between them. As already mentioned, NEWTON project is developing three different prototypes for different applications and scenarios, with the aim of maximizing the impact of novel NEWTON technology. The main features of these prototypes are:

- **Prototype 1:** This prototype is designed for planetary exploration missions with the particular case of Martian and Moon's system with an envelope adapted to a rover-mounted payload. This prototype performs in-situ measurements of the susceptibility in a planetary environment combined with vector Natural Remanent Magnetization (NRM) data. This prototype will work in a sweep of continuous frequencies within the range from 1 kHz up to 100 kHz.

- **Prototype 2:** This prototype is a reduced version of prototype 1 implemented on a hand-held device for a rapid and preliminary analysis of surface during prospections on Earth. This prototype performs in-situ measurements of the susceptibility at discrete frequencies. It will be employed to potentiate the impact of NEWTON technology not only in space sector, but also on Earth for civil engineering applications.

- **Prototype 3:** This prototype is an advanced system for the in-situ analysis and full magnetic characterization of drilled samples in the medium term missions with more powerful rovers or to be part of base stations with the particular case of Martian and Moon's systems. This prototype performs in-situ measurement of the susceptibility, demagnetization and isothermal remanent magnetization (IRM) acquisition experiments.

As previously indicated, the three prototypes share the same architecture while they provide different performance capabilities adapted to different scenarios. The key building blocks of the three prototypes are the same, i.e. Power Distribution Unit (PDU), the Control Unit (CU) and the Sensor Unit (SU). The SU is at the same time divided in the sensor head, which includes magnetometer and susceptometer, and the proximity electronics.

This document reports the preliminary design of the Control Unit, and it also includes information about the design of the electronics included in the SU. D3.1 [1] describes the preliminary design and optimization process of the magnetic head including susceptometer head and magnetometer, while D3.3[2] reports the preliminary design of the Power Distribution Unit (in case of Prototype 1 and 2 it also includes an amplifier located in the SU). FIGURE 2 and FIGURE 3 show the architecture of the different prototypes and the corresponding documents where their building blocks are reported.

The preliminary architecture of the three prototypes was initially defined and included in the NEWTON deliverable D2.1 [3]. Now, as part of the activities developed within WP3, the architecture has been updated and re-defined. D3.1 [1] includes a detailed description of the architecture of NEWTON prototype 1, prototype 2 and prototype 3 while it also reports the main difference among prototypes. It is recommended to the reader go through section 2 of D3.1 before continuing reading this document.

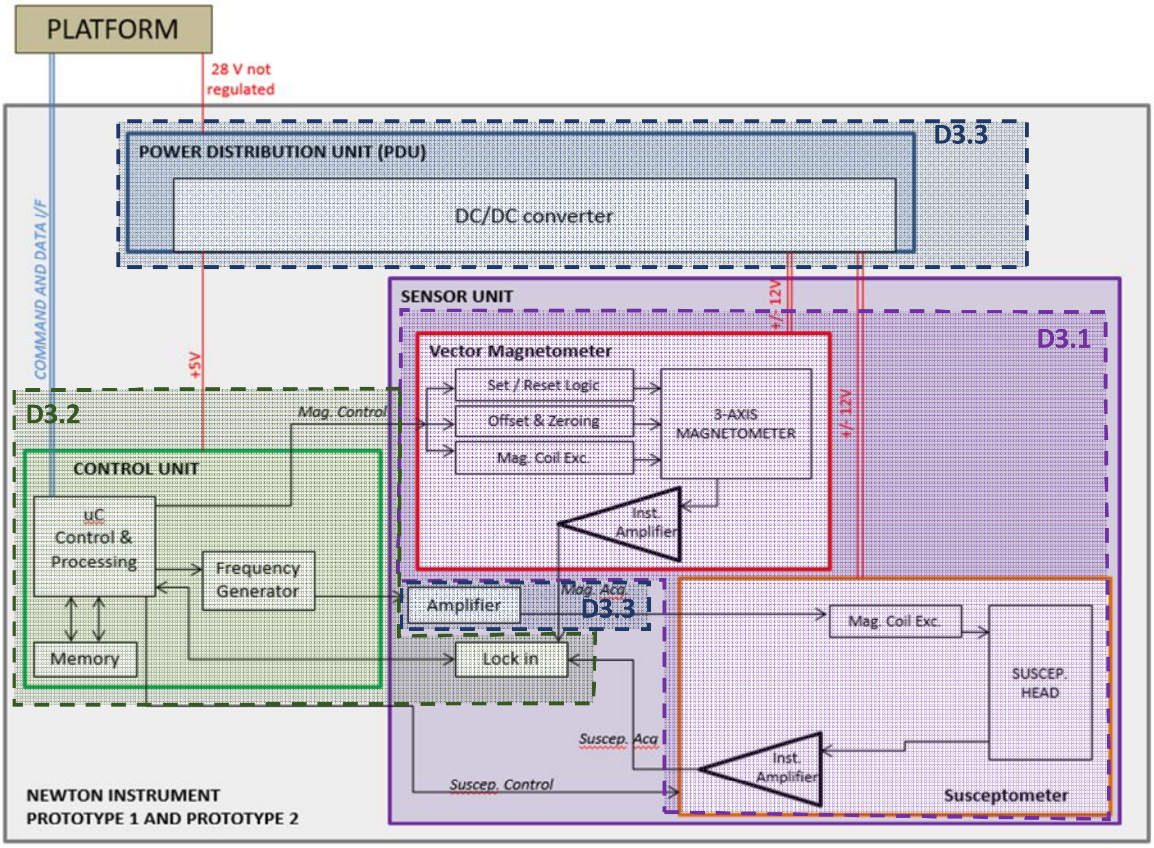


FIGURE 1. Block Diagram of the NEWTON muti-sensor instrument for prototype 1 and prototype 2.

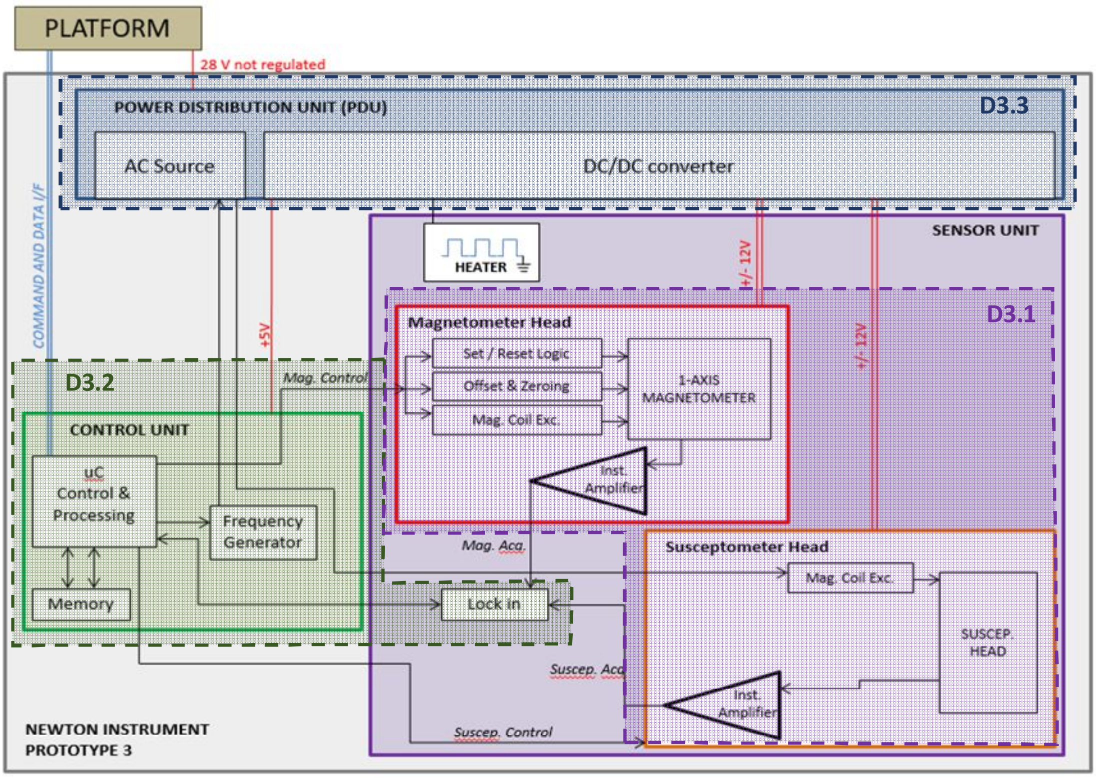


FIGURE 2. Block Diagram of the NEWTON muti-sensor instrument for prototype 3.

3. PRELIMINARY DESIGN AND VALIDATION OF THE ELECTRONIC CONTROL BLOCK

This section describes the preliminary design of the Control Unit (CU) for the three prototypes developed within NEWTON project. Moreover the preliminary validation activities are also reported in this section.

The electronic Control Unit is the responsible of the control, acquisition and processing of the signals of the Sensor Unit. It contains a microcontroller that performs these tasks and generates the different frequency signals for the sensor unit. This functionality is the same for the three prototypes of NEWTON multi-sensor instrument, i.e. Prototype 1, Prototype 2 and Prototype 3. In addition to this, in the case of the prototype 3, the control unit has additional functionality for the full magnetic characterization of the samples.

3.1. EXCITATION AND MEASUREMENT SYSTEM (Prototype 1, Prototype 2 and Prototype 3)

3.1.1. Requirements

The electronic devices included in the Control Unit must operate under specific conditions. These operational conditions are detailed described in the section 3.1 of the D3.1. [1].

3.1.2. Preliminary Design

3.1.2.1. General functionality

The Control Unit generates the two signals that serve to measure the samples of the rocks to which the Sensor Unit approaches. One of these signals will be used for the excitation of the sensor and the other one will act as reference for the measurement system which is a lock-in.

The signal coming from the sensor is amplified in the analogue domain by means of using a gain chain adjustable to x3, x9 and x27. Once amplified, the signal is corrected by a full-wave rectifier implemented by a synchronous demodulator and passed through a filtering stage composed of a second-order Sallen-Key active filter and another active first-order filter. By doing so, it is achieved a continuous signal proportional to the phase shift between the sensor output signal and the reference signal.

FIGURE 3 shows a general outline of the control system.

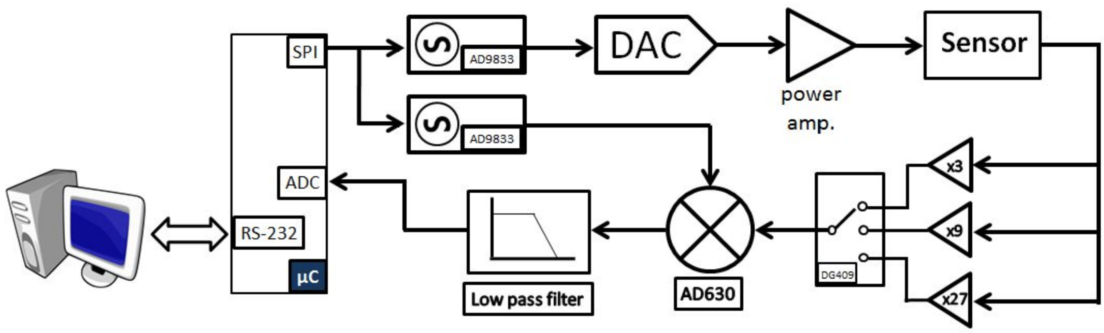


FIGURE 3. General block diagram of the control unit.

This functionality is common for the three different prototypes developed within the project and it will be part of the modes of execution that will be defined to carry out more complex measures in the case of prototype 3.

As already indicated, the Control Unit is the responsible of the control, acquisition and processing of the signals of the Sensor Unit which includes a susceptometer and a vector magnetometer. In this preliminary design stage, its excitation and measurement system has been developed. During the next stage of the project, the functionality of the Control Unit will be advanced in order to include the control of the magnetometer. In the case of prototype 1 and prototype 2 the selected magnetometer consists of a three axes magnetometer based on anisotropic magnetoresistance (AMR). In this project HMC2003 commercial magnetometer (by Honeywell) will be used. The transducers of such device are HMC1001 and HMC1003 and they have an electronic control system already integrated for an immediate integration in the prototypes. In the case of prototype 3, the susceptometer is based on two designs for different rage of frequencies [1].

3.1.2.2. Parts of the system

Each of the elements that are part of the Control Unit are described below. The Unit can be divided into two parts: on the one hand, the control system used to generate the signals that excite the sensor and act as a reference respectively, and on the other hand the measurement system that amplifies the sensor signal, rectifies and filters this signal. Then the signal is converted to a digital data in order that control board can work with this signal. In addition to this, the preliminary design includes a communication module to communicate with a user PC.

3.1.2.2.1. Control System and signal generation.

The core of the system is a microcontroller. PIC16F887 [4] has been selected for the preliminary design based on the previous experience this can be an efficient solution tacking into account the requirements defined in the project. The most relevant parts to fulfill the functionality are: the RS-232 Serial Communication Module (UART), the SPI serial communication module and the analog to digital converter (ADC).

The two control signals are generated by two Analog Devices [5] programmable wave generators which are controlled by SPI. The functional block diagram of these wave generators is shown in FIGURE 4. As it is known, this protocol is serial and consists of 4 lines: SDI, SDO, SCLK and OE. In this case, since the device only supports input data, the SDO line does not exist and the input data line is replaced by SDATA. The OE signal is renamed FSYNC and serves to select which device to use.

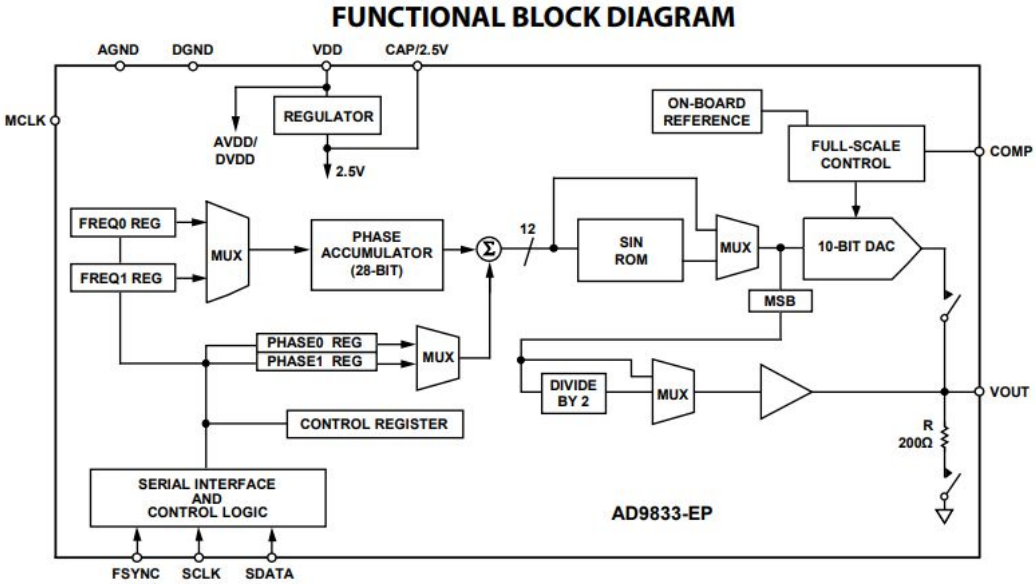


FIGURE 4. Functional block diagram of AD9833.

The data is sent from the µC to configure the output of each of the two oscillators. Different parameters, i.e. waveform (square, square with half of period, triangular or sinusoidal), frequency of the signal and phase of the signal can be loaded sending a control word as shown in FIGURE 5.

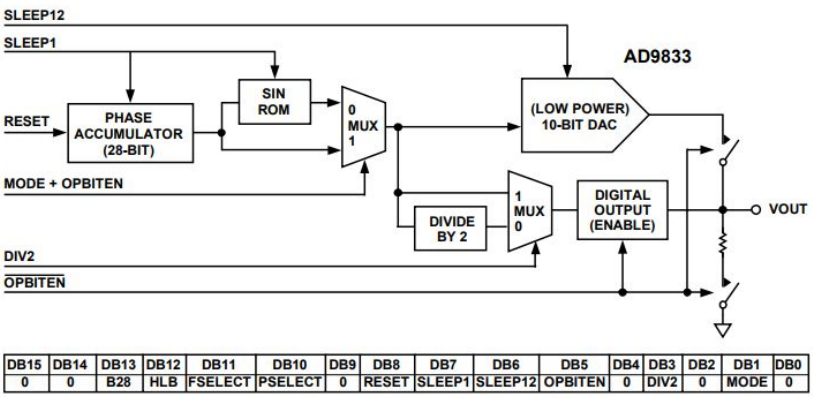


FIGURE 5. Configuration word for AD9833.

As already indicated, two oscillators have been mounted in order to generate both, the excitation and the reference signal. The excitation signal has very low output amplitude at the output of the oscillator. In order to control the gain of this signal, it is passed through an analogue to digital converter controlled by SPI which is the AD5452 [6]. The functional block diagram of the AD5452 is shown in FIGURE 6.

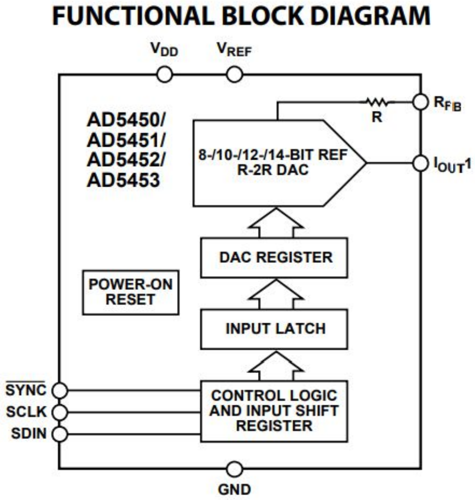


FIGURE 6. Functional Block Diagram of the AD5452.

The control of the gain of the signal is done by means of sending the control word shown in FIGURE 7 . This control word consists of 12 bits with two additional configuration bits.

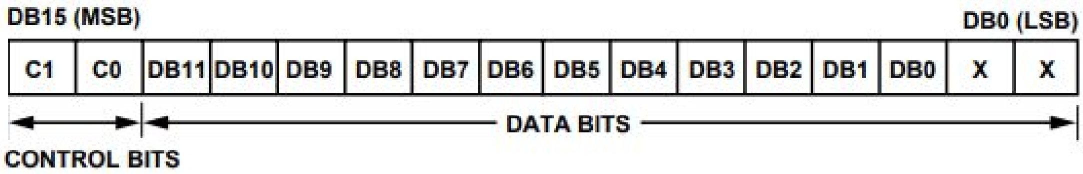
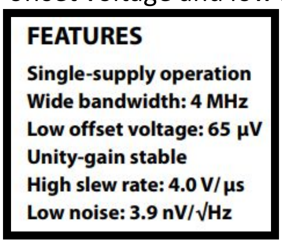


FIGURE 7. Configuration work of the AD5452.

The communication protocol used in this type of devices contains a signal called in this case, SYNC that is used to make the selection of the used device. This signal must be low when the control signals are being sent. An output configuration in four quadrants has been chosen for the signal in order to take advantage of the negative margins of the output signal. The output in 4 quadrants is realized with two operational amplifiers rail-to-rail, OP484 [7]. As it is shown in FIGURE 8, the main advantages of these amplifiers are that they have a large bandwidth with low offset voltage and low slew rate.


FEATURES

Single-supply operation
Wide bandwidth: 4 MHz
Low offset voltage: 65 μV
Unity-gain stable
High slew rate: 4.0 V/μs
Low noise: 3.9 nV/√Hz

FIGURE 8. Features of the operational amplifier OP484.

The system described in this point allows to obtain the output signal with controllable frequency phase and amplitude. Then, said signal is passed through a power amplifier before exciting the sensor head.

3.1.2.2.2. Measurement system and data acquisition.

When the excitation signal is generated, it goes to the sensor to proceed with the measurement. Then the output signal from the sensor secondary passes through an instrumentation amplifier to convert the signal into differential. The signal obtained when a sample approaches to the sensor unit is subtracted from the signal obtained when there is no sample, and then passes through the adjustable gain stage. After that, the output signal is amplified in a controlled way by selecting amplification X3, X9 or X27. This stage is composed of 3 OP484 operational amplifiers (as indicated above) in non-inverting amplification configuration, so that each of them amplifies by 3. Thus, with the three amplifiers in series, the maximum amplification indicated above will be achieved. This stage is controlled by an Intersil DG409 [8] analog switch whose block diagram is shown in FIGURE 9.

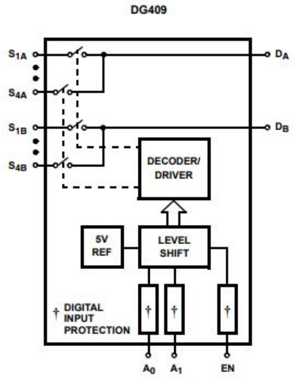


FIGURE 9. Functional Block Diagram of the DG409.

As can be seen in FIGURE 9, the control interface consists of three digital signals, two control signals, and one enable (EN). Depending on the configuration of the bits A_0 and A_1, the inputs from 1 to 4 will be selected and redirected to the outputs D_A or D_B, according to the truth table depicted in TABLE 1.

TABLE 1. Truth table of DG409.

TRUTH TABLE DG409

A_1	A_0	EN	ON SWITCH
X	X	0	NONE
0	0	1	1
0	1	1	2
1	0	1	3
1	1	1	4

In our case, the outputs corresponding to the set of switches B and the output 1 of the switch A are canceled since they are not used. The D_A output is brought to the input of the synchronous demodulator, once it is already amplified.

The theoretical based of the proposed measurements in based on the measurement of the phase shift between the sensor output signal and the reference signal. For this, a rectification of the sensor output signal will be performed with the reference signal, which will be a square TTL, without continuous level. The rectification is a multiplication of the two signals, so a synchronous demodulator, shown in FIGURE 10 is used.

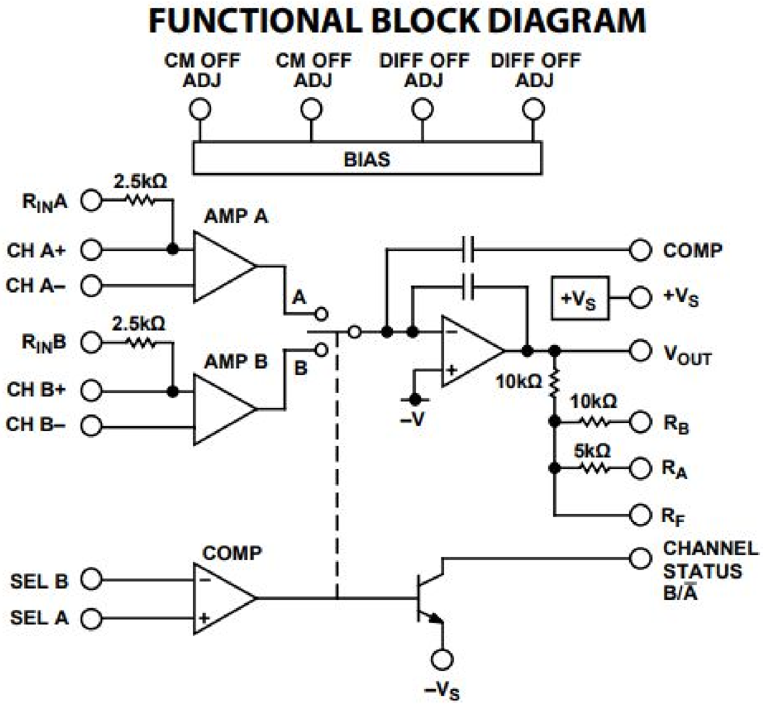


FIGURE 10. Functional Block Diagram of the AD630.

The configuration used in this card is given by the manufacturer and it corresponds to the so-called "Lock-in Amplifier" which is precisely the mathematical operation that is searched. The internal setup for the Lock-in amplifier functionality is shown in FIGURE 11.

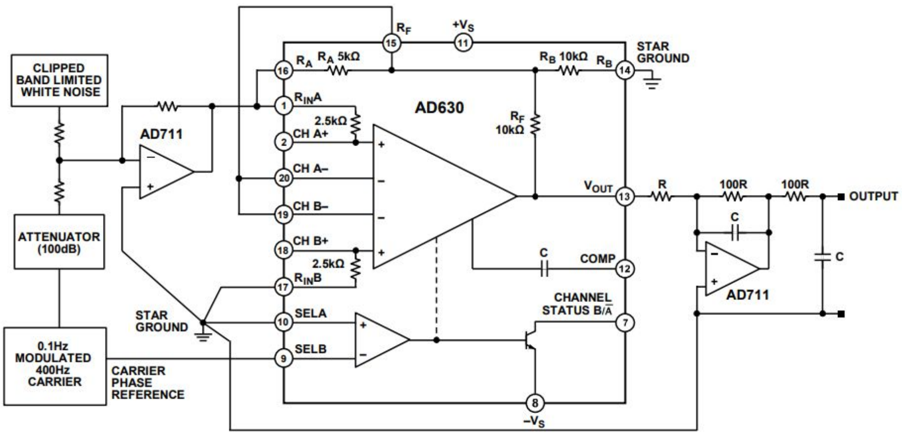


FIGURE 11. Internal setup for Lock-in amplifier functionality.

In our case, the first operational amplifier will be an OP484 and the subsequent filter stage will correspond to two active filters: one of second order and one of first order implemented also with OP484.The output of the second filter is connected to the microcontroller input (ADC) [9] so that the continuous signal proportional to the offset of the sensor output signal and the reference signal is measured and converted into a digital data for its later indicted.

The ADC is, by default, the one that includes the µC. It has 10 bits so the resolution of the conversion step (LSB) is:

$$LSB = \frac{5}{1023} = 4{,}88mV \tag{3.1-1}$$

This limits the sensitivity of the system. The minimum detectable phase change is one whose rectification generates a difference in the continuous level of the signal of at least 4.88mV. Preliminary measures have been taken to verify this and, in principle, the change in the resonance frequency of the sample with less susceptibility is sufficient for the system to be able to see the phase change.

The control system described in this section has been preliminary validated. After performing these initial tests, a second lock-in (or even a third lock-in in the case of prototype 3) may be required. Additionally, some new lines to use ADCS of the μC may be added. This will be analysed during the next stage of the project when the final design of the Control Unit will be developed.

3.1.2.3. Explanation of the codes used in the system.

It is important to highlight that, the work reported in this document is part of the preliminary design of NEWTON instrument. Therefore the software designed at this stage is intended for checking the correct operation of the system. At the user application level it is easy to implement the operating modes or actual measurements protocols, although for the final design, the ultimate goal will be to implement as much code as possible in the microcontroller.

The overall control of the system is performed between the microcontroller program and the user application. The communication between this application, which was initially developed for MATLAB, and the code of the microcontroller, is using a set of commands implemented in the RS-232 serial protocol.

With regard to the microcontroller code, it is implemented in assembler and it includes the handling of the SPI serial port, the UART for communication with the PC via RS-232 and the ADC for the conversion of the input data. In order to operate the microcontroller, a series of commands whose structure is fixed (in terms of the fields that compose it) and of variable size are implemented, depending on the arguments associated to the order that is precise.

Therefore, the structure of the orders is shown in FIGURE 12.

FIGURE 12. Frame structure.

Although the structure shown in FIGURE 12 probably changes during the instrument development, the principle parts are described in the following:

- **Head**: the first byte contains a 0x55 in hexadecimal (01010101 in binary) which is the most suitable code to test, at a physical level, any type of transmission failure. The other two data contained in the header are the identifiers of the transmitting element of the order and the one assumed (if the communication is correct) is the receiver.
- **Order**: (and arguments) the first byte is the size of the arguments (number of arguments that the order has), the order itself and the arguments of it (information that the order needs to be executed).
- **Tail:** this is a specific data code that serves to indicate the end of the plot. In principle, it would be sufficient to indicate the size of the command argument, but this data signal may also help to improve transmission errors as it may help certain CRC decoders.

- **CRC**: (Cyclic Redundancy Code) This is a byte of information that serves to check the correct transmission of the frame, and its reception. In this preliminary stage, the mathematical function that is used for this CRC is a simple XOR of all the bytes of the frame. A more robust controlling modewill be implemented in the future.

The microcontroller receives the frame and extracts the information of the order and depending on this information, the microcontroller executes the corresponding code.

For the moment, the following orders have been implemented:

- Order 10 changes the frequency of the AD9833 generator to be chosen. The order arguments are the frequency data that must be loaded into the device register.
- Order 11 changes the amplitude of the output signal of the AD9833 generator, modifying the DAC conversion register. The order arguments are the data that will be loaded into the conversion register.
- Order 14 changes the phase of the output signal of the selected generator. The order arguments are the phase data to be loaded into the AD9833 conversion register.
- Order 15 change the gain of the signal from the sensor to x3
- Order 16 changes the gain of the signal from the sensor to x9
- Order 17changes the gain of the signal from the sensor to x27.
- Order 18 performs a measurement with the ADC, stores the converted data and sends it through the serial port to receive the PC.

As mentioned before, these are the basic commands to check the correct functioning of the board. During the next stage of the project, new orders will be implemented with the idea that the user application will have less weight in the data collection process, and that weight will be reversed in the microcontroller code.

The microcontroller code is programmed with two interruptions: interrupting the UART for receiving data through the serial port and interrupting the ADC to execute code associated with ADC conversion. Each of the data received through the serial port is processed each time the UART is interrupted until the entire frame is processed and the order and its arguments can be processed. The other data that is received through the UART is the confirmation of reception of data when "Mode 1" is active. This mode acquires data continuously through the ADC and sends them to the user application. Each time the data is received, the PC sends a confirmation word and the µC interprets that it as a validation to continue acquiring data. Therefore, in the UART interrupt attention routine, it must be discerned when the data is being received as an order or when the data is being received as a delivery confirmation.

During the next stage of the project, it will be implemented a system of response to communication initiated by the PC. In this sense, the µC programming will be compatible with the programming of the advanced features of the prototype 3.

3.1.3. Interfaces

3.1.3.1. Hardware interfaces

As already indicated, the control system of the sensor head described in previous section is common for the three prototypes, i.e. Prototype 1, Prototype 2 and Prototype 3. This control system is complemented with the two additional stages described in this section. The two elements to consider as stages before and after the signal passing through the sensor are shown in FIGURE 13. The first stage will be a stage of amplification of the output signal of the DAC, before entering the primary windings of the sensor. The second will be a differential step which subtracts the two signals from the secondary windings to convert the signal at the output of the sensor into a unipolar signal before re-entering the controller card.

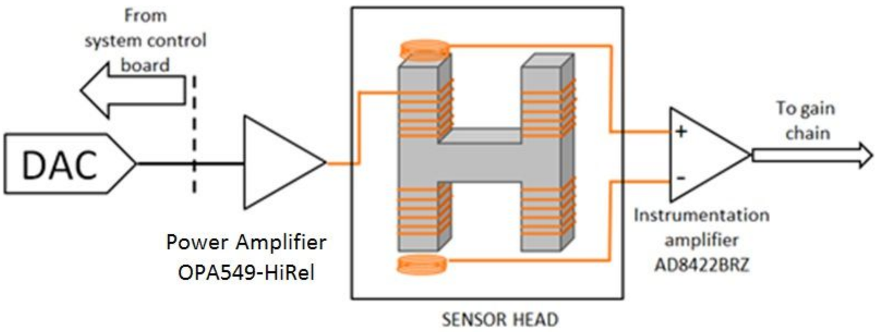


FIGURE 13. General system setup for hardware interfaces.

- **Power amplifier OPA549-HiRel.[10]**

After the output of the DAC, which constitutes the amplitude control of the excitation signal, a power amplifier is connected to amplify the signal in order that it can generate a high magnetic field in the sensor. The amplifier chosen is the Texas Instruments OPA549-HiRel. It is an operational amplifier with the following features:

FEATURES

- **High Output Current:**
  - **8-A Continuous**
  - **10-A Peak**
- **Wide Power Supply Range:**
  - **Single Supply: 8 V to 60 V**
  - **Dual Supply: ±4 V to ±30 V**
- **Wide Output Voltage Swing**
- **Fully Protected:**
  - **Thermal Shutdown**
  - **Adjustable Current**
- **Output Disable Control**
- **Thermal Shutdown Indicator**
- **High Slew Rate: 9 V/μs**
- **Control Reference Pin**
- **11-Lead Power Package**

FIGURE 14. Main features of the OPA549-HiRel amplifier.

The configuration chosen is in non-inverter mode as shown in FIGURE 15.

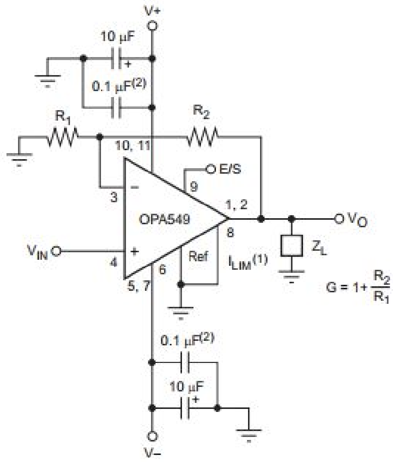


FIGURE 15. Setup for OPA549-HiRel amplifier.

The operation graphs of the OPA549-HiRel amplifier establish that for the maximum (approximate) operating frequency both, the gain and the voltage vs. frequency parameters are valid. FIGURE 16 shows the frequency range that is being used for the instrument. This range goes from 10KHz to almost 100KHZ (around 90KHz, in fact). As can be seen, there are gain values ranging from 60dB to 30dB which allows the generation of a signal with enough power to be able to excite the sensor.

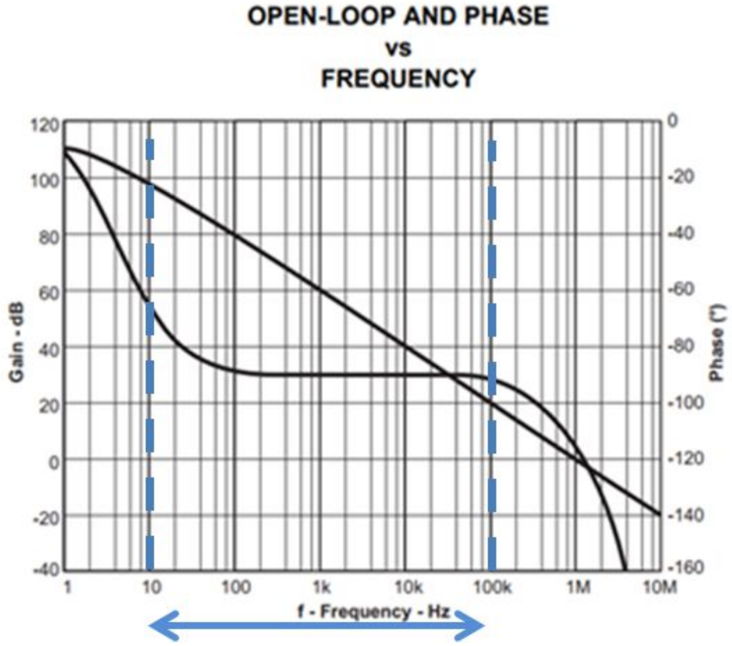


FIGURE 16. Gain and phase response of the OPA549-HiRel amplifier.

The other graph that defines the operation of the amplifier is shown in FIGURE 17:

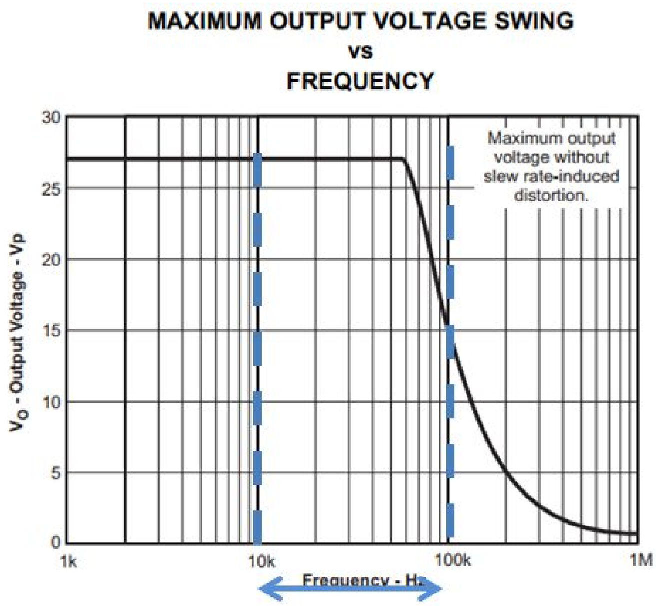


FIGURE 17. Output voltage vs frequency.

The maximum output voltage is 27V for frequencies below 60KHz. In addition, the current limitation can be controlled simply by connecting a resistor to the output of the amplifier as a load as depicted in TABLE 2. Therefore, in the best case, and for a current of 2,5 A (well above the required value) could be reached powers of at least: 2.5A x 15V = 37.5W. This is just an example of the behavior of the device that we could achieve.

TABLE 2. Relation between input resistor and behaviour of OPA549-HiRel.

OPA549 CURRENT LIMIT: 0 A to 10 A

DESIRED CURRENT LIMIT	RESISTOR(1) (R_{CL})	CURRENT (I_{SET})	VOLTAGE (V_{SET})
0A(2)	I_{LIM} Open	0 µA	(Ref) + 4.75 V
2.5 A	22.6 kΩ	158 µA	(Ref) + 3.56 V
3 A	17.4 kΩ	190 µA	(Ref) + 3.33 V
4 A	11.3 kΩ	253 µA	(Ref) + 2.85 V
5 A	7.5 kΩ	316 µA	(Ref) + 2.38 V
6 A	4.99 kΩ	380 µA	(Ref) + 1.90 V
7 A	3.24 kΩ	443 µA	(Ref) + 1.43 V
8 A	1.87 kΩ	506 µA	(Ref) + 0.95 V
9 A	845 Ω	570 µA	(Ref) + 0.48 V
10 A	I_{LIM} Connected to Ref	633 µA	(Ref)

- <u>**Instrument amplifier AD8422BRZ [11]**</u>

The output stage of the sensor is carried out with a differential stage which is included within the AD8422BRZ instrumentation amplifier. This model has been chosen because based on previous experience it provides several benefits over other possible solutions as indicated in FIGURE 18.

FEATURES

Low power: 330 µA maximum quiescent current
Rail-to-rail output
Low noise and distortion
  8 nV/√Hz maximum input voltage noise at 1 kHz
  0.15 µV p-p RTI noise (G = 100)
  0.5 ppm nonlinearity with 2 kΩ load (G = 1)
Excellent ac specifications
  80 dB minimum CMRR at 10 kHz (G = 1)
  2.2 MHz bandwidth (G = 1)
High precision dc performance (AD8422BRZ)
  150 dB minimum CMRR (G = 1000)
  0.04% maximum gain error (G = 1000)
  0.3 µV/°C maximum input offset drift
  0.5 nA maximum input bias current
Wide supply range
  4.6 V to 36 V single supply
  ±2.3 V to ±18 V dual supply
Input overvoltage protection: 40 V from opposite supply
Gain range: 1 to 1000

FIGURE 18. Features of AD8422.

Especially, AD8422 provides significant benefits with respect to the gain control by a resistance and the maximum operating frequency with G = 1. With this regard, FIGURE 19 illustrates how the amplifier behaves for different frequencies.

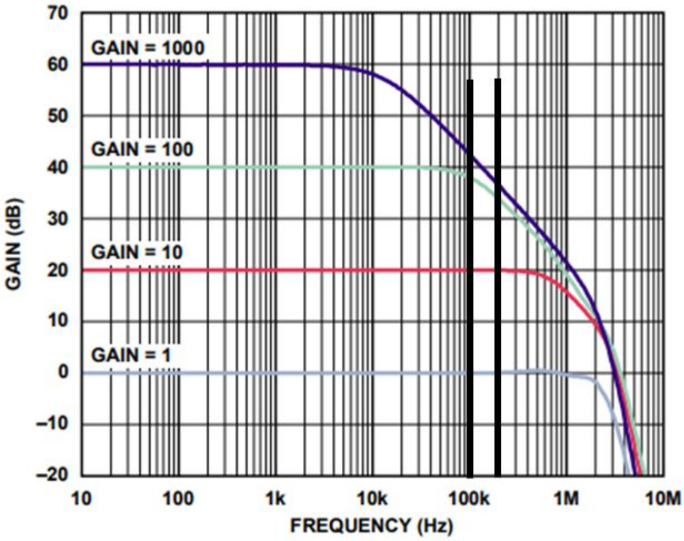


FIGURE 19. Gain response vr frequency of the AD8422.

If the maximum operating frequency of the susceptometer is set at 100KHz, a gain of 10 can be achieved. The gain, as any other instrumentation amplifier, is set to the value of the resistance (R_G) connected to the inputs. The formula that governs the calculation of the gain is:

$$R_G = \frac{19.8\,\text{k}\Omega}{G-1} \tag{3.1-2}$$

At this stage of the instrument development, it has been decided to employ a variable resistor to control the gain and make the output stage more adaptable to the gain stage of the control board. By tuning the resistor between 20 to 2 KΩ, we can obtain gains in the range of 2 to 10.

3.1.3.2. Possible Modifications to measuring interfaces design

At this stage, it has been analyzed different solutions in order to find the most adequate configuration of the NEWTON instrument. With this regard, FIGURE 20 shows some possible modifications which could be developed in order to improve the performance of the control system.

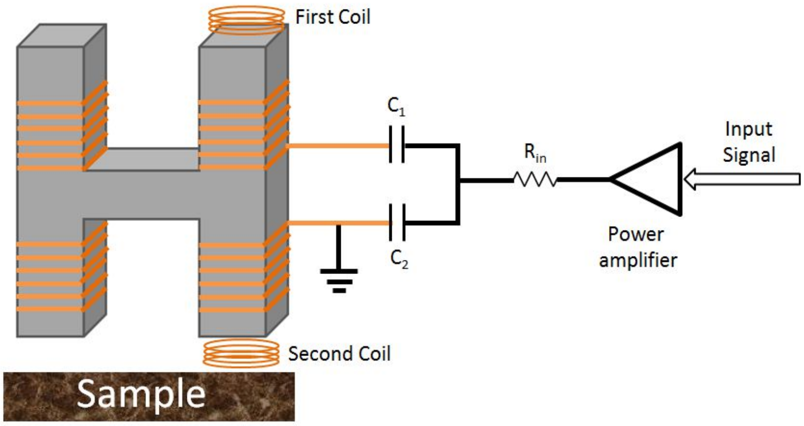


FIGURE 20. Possible modifications to the measuring interfaces.

As can be seen, the sensor head has two secondary windings, one of which is placed in front of the sample and the other is always in the air. The input signal excites a double resonance circuit with the sensor head primary acting as a coil.

FIGURE 21 illustrates how the proposed measures would be taken on the general scheme.

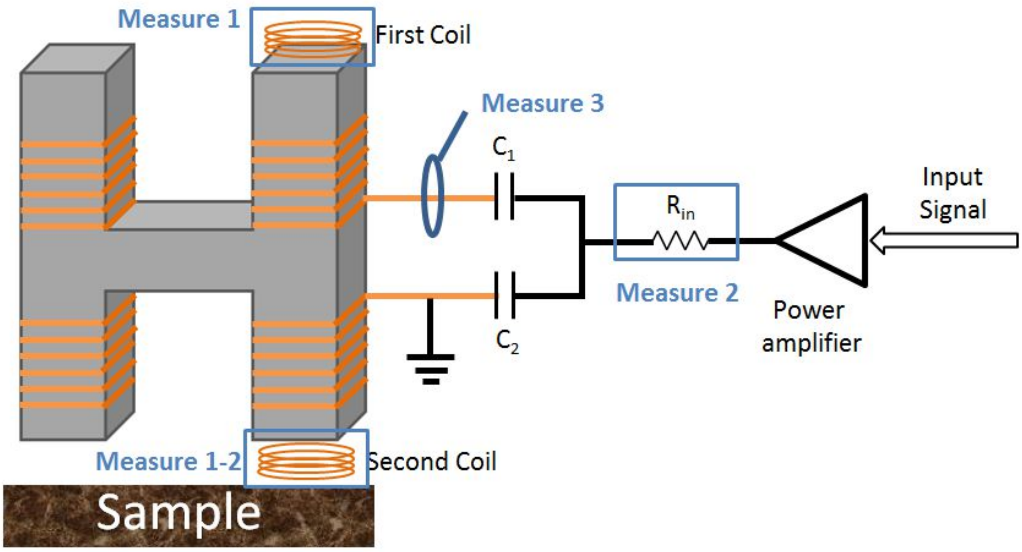


FIGURE 21. General block diagram of the proposed measurements.

The modified measures that are proposed:

- **<u>Measurement in secondary coils of the sensor head</u>**: The measurement obtained in the secondary coils will be used to compare the gap between the flow of the core in the presence of the sample and the air (FIGURE 22). The deviations of this flow generate a phase difference measured with the lock-in system installed on the board associated with said sensor and implemented with AD630 setup. To do this measurement there are two possibilities: a) each of the secondary coils is connected to an instrumentation amplifier and the outputs of these amplifiers are connected to another instrumentation amplifier, so that the output is the difference of the signal with and without sample as shown in FIGURE 22, or b) to use operational amplifiers in emitter followers configuration, instead of instrumentation amplifiers in the first stage and another operational amplifier in differential mode for the second stage.

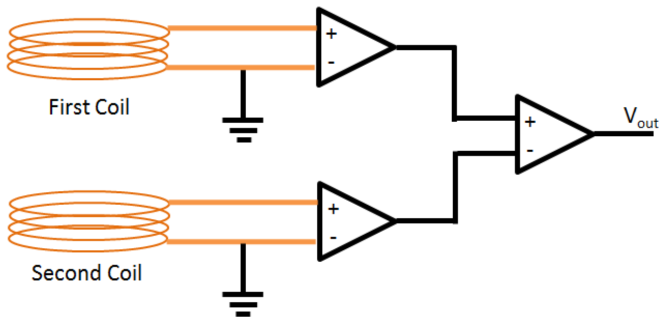


FIGURE 22. Differential measurements with the secondary sensor coils.

- **<u>Measurement at the ends of the input resistance</u>**: this measurement will be done in order to obtain the input current necessary by the primary. At the ends of the resistor an instrumentation amplifier will be connected which will give the potential drop and (knowing the value of the resistance) the current. This measurement will be alternated with a measurement of the secondary winding. This does not have the sample next to it and will be able to characterize the phase of the input current that is modified by the presence of the sample. This signal will be taken as the reference in a subsequent signal lock-in process.

- **Measurement of the current by the primary winding**: this is a calibration measure that will be performed with specialized laboratory instruments using to current measures.

The benefits provided by the implementation of the proposed measurements will be analyzed during the next stage of the project, with the aim of improve the performance of the overall system.

3.1.3.3. Graphical User Interface

As already described in section 3.1.2.3, the user application has been developed using MATLAB and serves as a platform for the user to easily manage the system. Currently, the implemented functions are simply used for the validation of the hardware parts in laboratory. During the next stage of the project, the functionality of the user application will be increased.

FIGURE 23 shows the main interface for the user application.

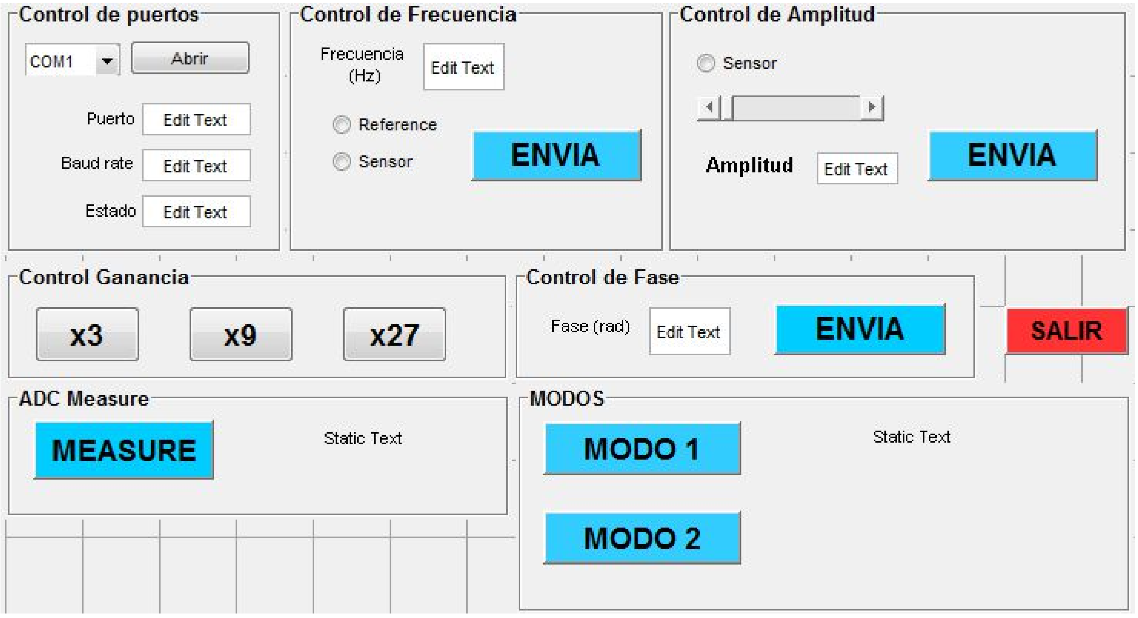


FIGURE 23. Principal interface for the user application.

The main blocks that integrate the graphical user interface are:

- **Port Control (control de puertos):** This part of the main panel controls the opening of the serial port that is used for communications with the µC. It contains a drop-down menu where all port references are listed. When the "Open" button is pressed, the port is opened and information about the port name, its baud rate and its status (open or closed) appears.

- **Frequency Control (control de frecuencia):** Its purpose is to control the frequency of the output signal of the oscillators. It is possible to select which of the two oscillators is chosen to load the new frequency data. When "ENVIA" is pressed, the frame with the indicated information word is generated and sent through the serial port.

- **Amplitude control (control de amplitud):** The amplitude control works similar to the frequency control block. In this case, the conversion register of the DAC is loaded with the data corresponding to the chosen amplitude of the output. Once again when "ENVIA" is pressed, the transmission frame is generated with the data to be loaded and sent via serial port.

- **Gain Control (Gain Control):** it controls the gain of the receive chain. The signal coming from the sensor (from the secondary sensors) is amplified by the gain indicated with this command. It is composed of other 3 suborders whose execution serves to change the output of the analog switch by modifying the gain on the reception signal.
- **Phase control (phase control):** It controls the phase of the output signal of the AD9833. In this case, the data loaded with this command stores in the data records of the devices, changing the phase of the sensor signal. This code is one that is likely to be modified or even removed in the final application for ultimate system control. Although now it has been decided to leave for the initial tests.
- **ADC measure:**. This part of the code controls a single measurement with the ADC. When the command is sent, the executable code remains waiting until it receives a data, at which time it processes the information and displays it on the screen with the final conversion to volts.
- **Modes:** At present, the two modes of operation of the system will be used during verification, mainly to check the sensitivity that the board has. This code will be modified, or even eliminated, when the definitive system management codes are implemented during the final design stage.

Mode 1: It measures the output of the lock-in in an array of phases. A new phase is introduced, and a certain number of measures are made on the result of the lock-in operation, to then make the average of all of them. This mode was created to make a characterization of the system sensitivity, so that the phase change in the sensor signal was simulated with a change in the AD9833 registers. Some of the results obtained in this way are shown in FIGURE 24. This graph shows the measure of the lock-in versus the phase. The slope of the line that appears will be the sensitivity of the system.

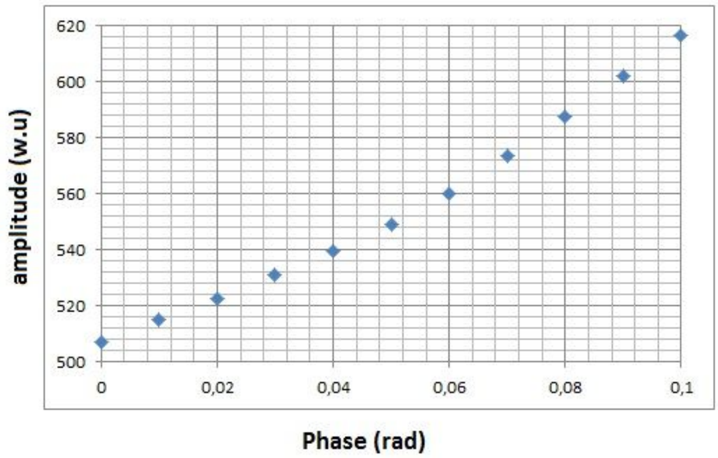


FIGURE 24. Sensibility of the measurement system.

Mode 2: This mode launches a set of measurements using as indicated phase data in the text box of the phase control. It stores the results in a txt file. These data are extracted from the ADC and its conversion to voltage.

3.1.4. Manufacturing and Validation

The FIGURE 25 shows some captures obtained from each of the stages of the control system. Image 1 corresponds to the output of the generator of the reference signal. The image 2 corresponds to the signal that excites the sensor. Image 3 shows the result of the multiplication of the two previous signals, and 4 is the result of the enclosure. A blue line can be seen which represents the level of continuity that is what enters into the ADC converter. Different examples can then be seen with different DC levels depending on the offset of the two input signals: the sensor and the reference signal.

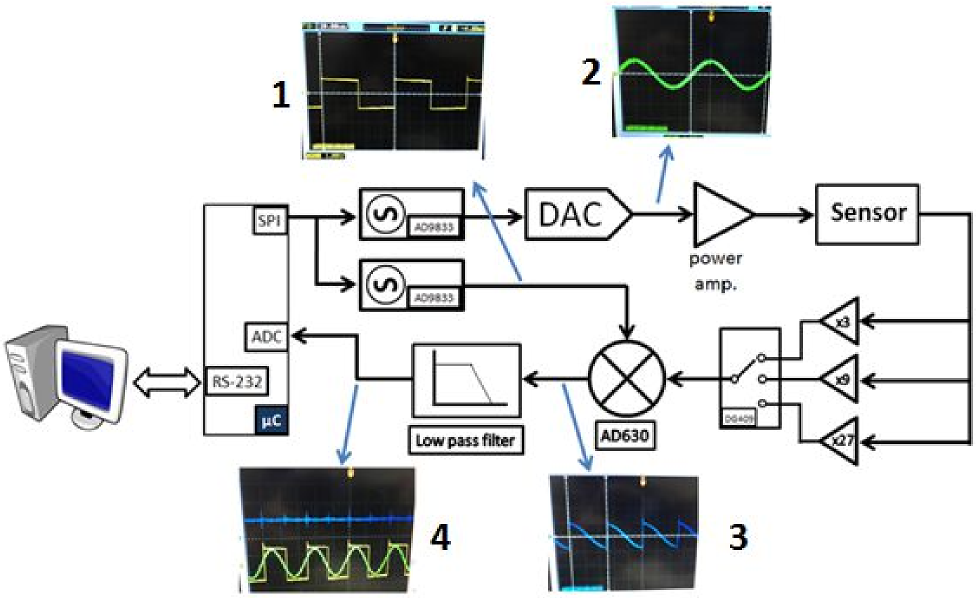


FIGURE 25. Response of the complete control system

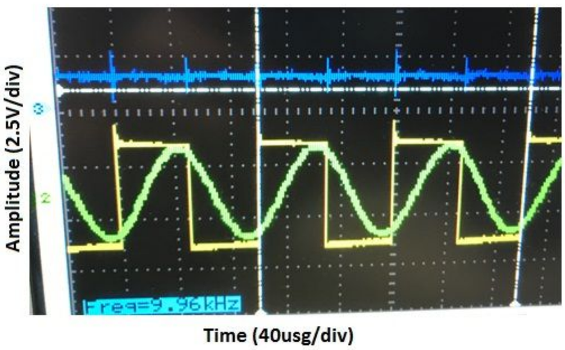


FIGURE 26. Demodulated output. Example 1.

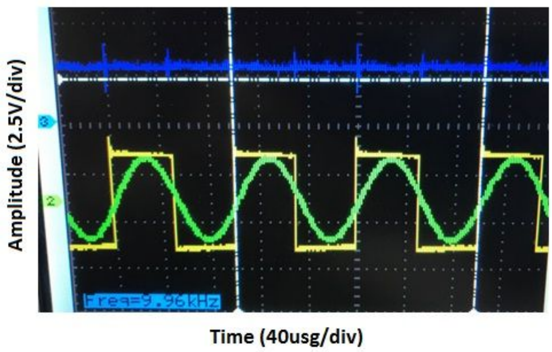


FIGURE 27. Demodulated output. Example 1.

3.2. ADVANCED CONTROL SYSTEM (Prototype 3)

This section describes the advanced control functionality included in the Control Unit of the NEWTON Prototype 3. This advanced system is dedicated to perform magnetic susceptibility measurements of samples in a portable system. There are two kinds of measurements: low frequency range and high frequency range. In this section we will describe the system able to perform the magnetic measurement and to generate the signal used to produce the exciting field. The sample magnetization is performed by measuring the magnetic flux induced in the secondary coil system described in D3.1 [1] .The signal generated in the secondary is proportional to the derivative of the magnetic flux, so it must be integrated to attain the magnetic flux and therefore the samples magnetization. To perform any magnetic measurement, changes in magnetic flux induced in the secondary coils must be produced. These changes can be done by varying the exciting field or by displacing the sample inside of the secondary coil system. In both cases the exciting field or sample position must be known or measured. In the following section both, the hardware and software of the whole device are described. An additional PCB will be used for the implementation of the advanced control system of the Prototype 3.

3.2.1. Requirements

An analysis about susceptibility measurements requirements can be found in section 3.2 in D3.1 [1]. The initial set-up for the magnetic measurements is also described in the same section.

3.2.2. Design of the Electronic Control Block for the prototype 3.

FIGURE 28 shows the schematic of the electronic circuit designed for the prototype 3.

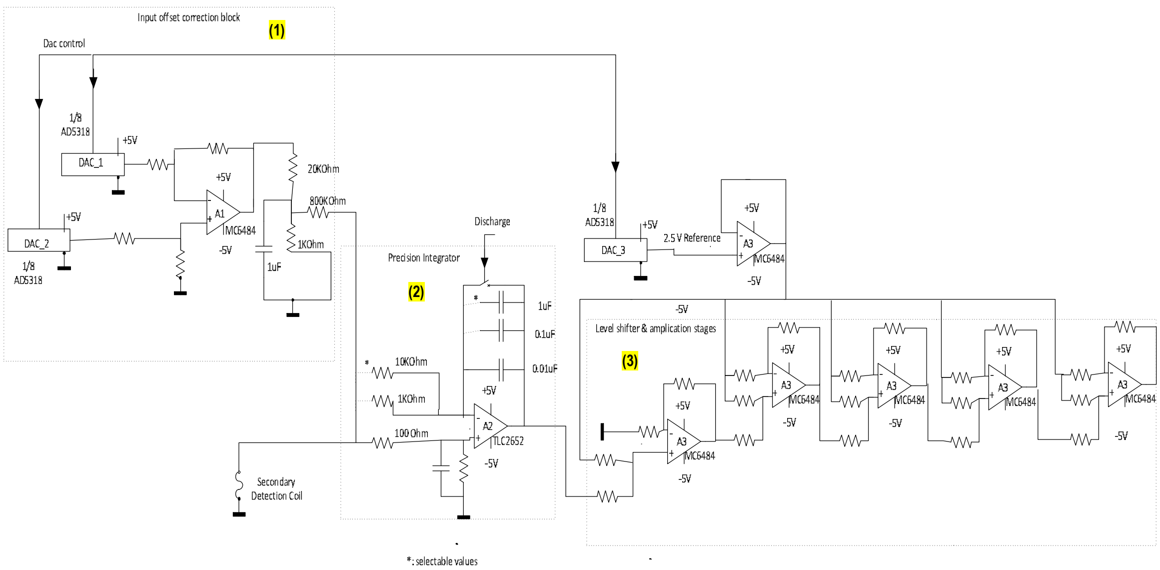


FIGURE 28. Schematic of the electronic control circuit for the prototype 3.

The integrator design is shown in the ***Precision Integrator block (2)***. It is impossible to cover the measurement range with a single RC set in the integrator. So we will use a set of different resistances 1-100 KΩ and a set of high quality capacitors 0.01-3 µF. The output in the integrator is V= Φc/(RC), the maximum sensitivity will be 10^5 V/Wb and the minimum 10 V/Wb. This will be enough to cover the whole range. The sensitivity of the whole system also depends on the number of turns of the secondary coil. In principle the coil geometry will always be the same and its self-induction can be evaluated, semi experimentally, as function of the number of coil turns. The self-induction of the secondary coil produces a spurious phase in the integrator that depends on the frequency.

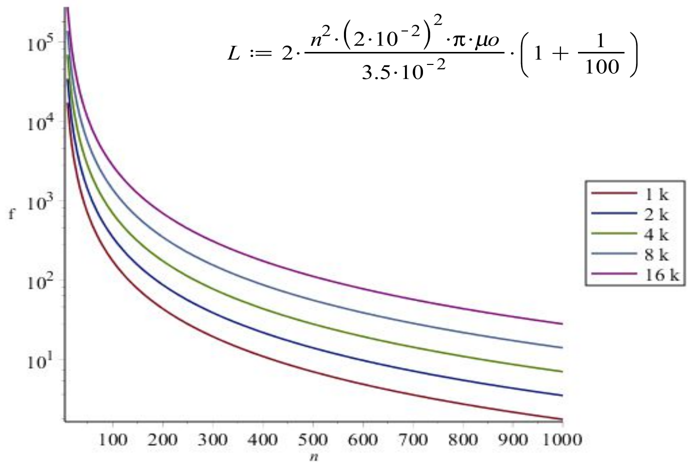


FIGURE 29. Frequency vs the number of turns.

FIGURE 29 shows the frequency vs the number of turns to have a phase lower than 10-3. If we select an input resistance of 1 KΩ and 200 turns, the maximum working frequency is 100 Hz. The feedback capacitor is charged by the operational amplifier output and its current is limited to 40 mA, so large capacitors cannot be used at high frequency. FIGURE 30 shows the maximum capacitor which is allowed for each frequency.

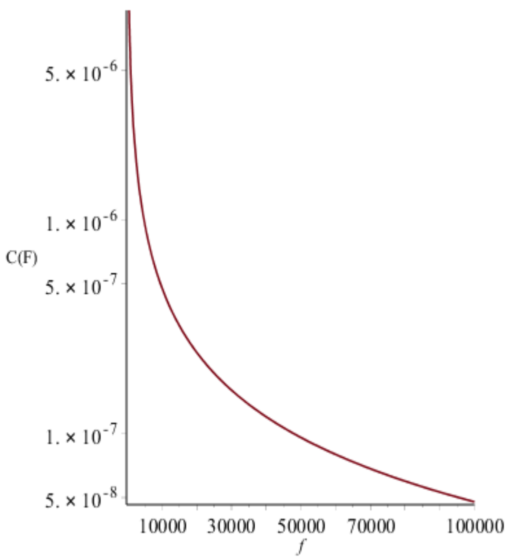


FIGURE 30. Maximum capacitor value allowed for each frequency.

To solve these problems, besides this manual adjustment of sensitivity, there is a chain of amplifiers [12] connected to 4 ADCs [13-14] of the µ-controller [4]. This automatically adjust the sensitivity range (***Level shifter & amplification stages block*** **(3)**).

The main problem of the integrator is the drift because of the DC open loop. The sources of the drift are the Peltier voltage that appears in welded conductors and the current bias of the operational amplifier. We have been very careful with the conductor distribution looking for a symmetric configuration. Therefore we have also selected an appropriate operational amplifier [15]. We can estimate an uncompensated drift current in the order of 100 pA so for 1 µF capacitor in de feedback, the output voltage drift is in the order of 10^{-4} V/s.

To compensate the thermal drift we have designed the ***Input offset correction block*** **(1)** consisting on two 10 bits DACs [13-14], connected to a differential amplifier to attain +/- 5V at the output. Tension divider and a capacitor are used to filter and stabilize the current used to compensate drift.

After performing a drift compensation the output can be out of the middle of the dynamic range so an offset tension supplied by another DAC is used to adjust the integrator output level at the correct voltage (***Level shifter & amplification stages*** **(3)**).

H field measurements:

To measure the field H we use a differential amplifier as input and 3 more amplifiers [15] in cascade to obtain four different gain amplitudes. The offset level is controlled by 10 bits DAC (see FIGURE 31).

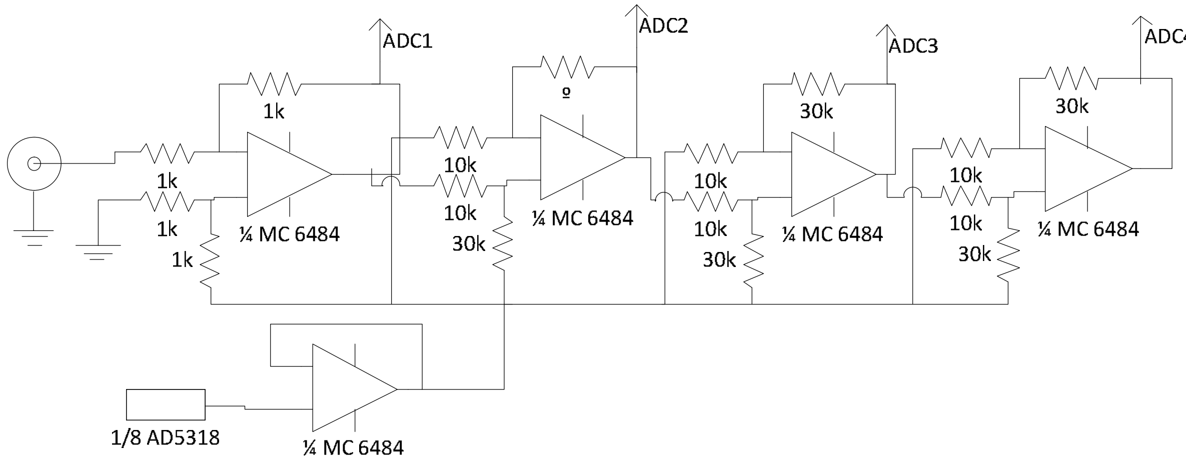


FIGURE 31. DAC to control the offset level.

The H field is produced by a power amplifier controlled by the circuit shown in FIGURE 32. Two 10 Bits DACs which are connected to a differential amplifier generate output voltages between+5/-5 V.

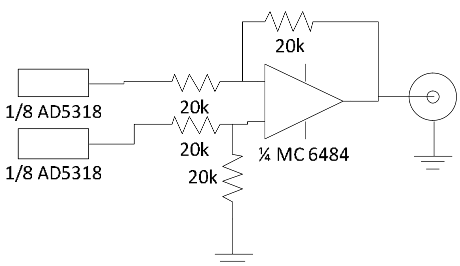


FIGURE 32. Power amplifier used to generate the H field.

For very low frequency measurements it will be necessary to displace the sample inside the secondary coils to reduce thermal drift. A stepper motor is used driver by an L298 [16] directly connected to the circuit microcontroller as shown in FIGURE 33.

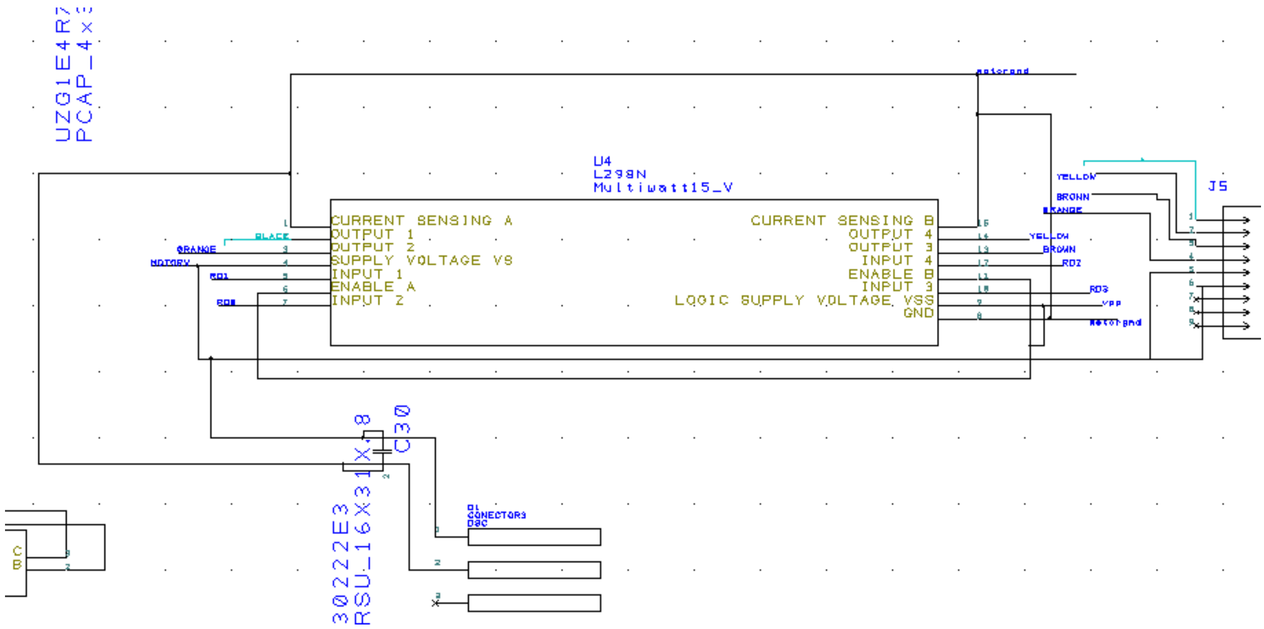


FIGURE 33. Configuration of the stepper motor to displace the sample.

<u>Microcontroller:</u>

FIGURE 34 shows the microcontroller that drives all the different blocks mentioned above. It has the possibility of serial communication through RS232 [17] or RS422 [18] to have the possibility of connecting several devices to a single serial output of the host. In the next stage of the project a 128K SPI memory will be added.

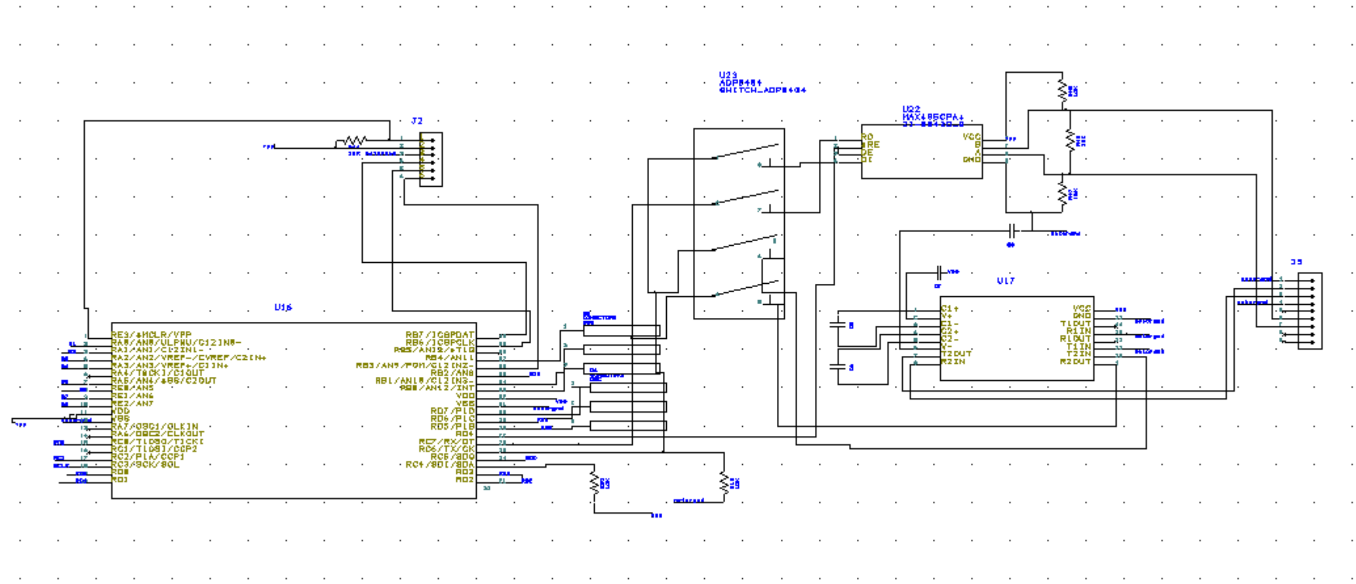


FIGURE 34. Microcontroller integrated in the control unit of the prototype 3.

FIGURE 35 shows the PCB manufactured as part of the preliminary design stage.

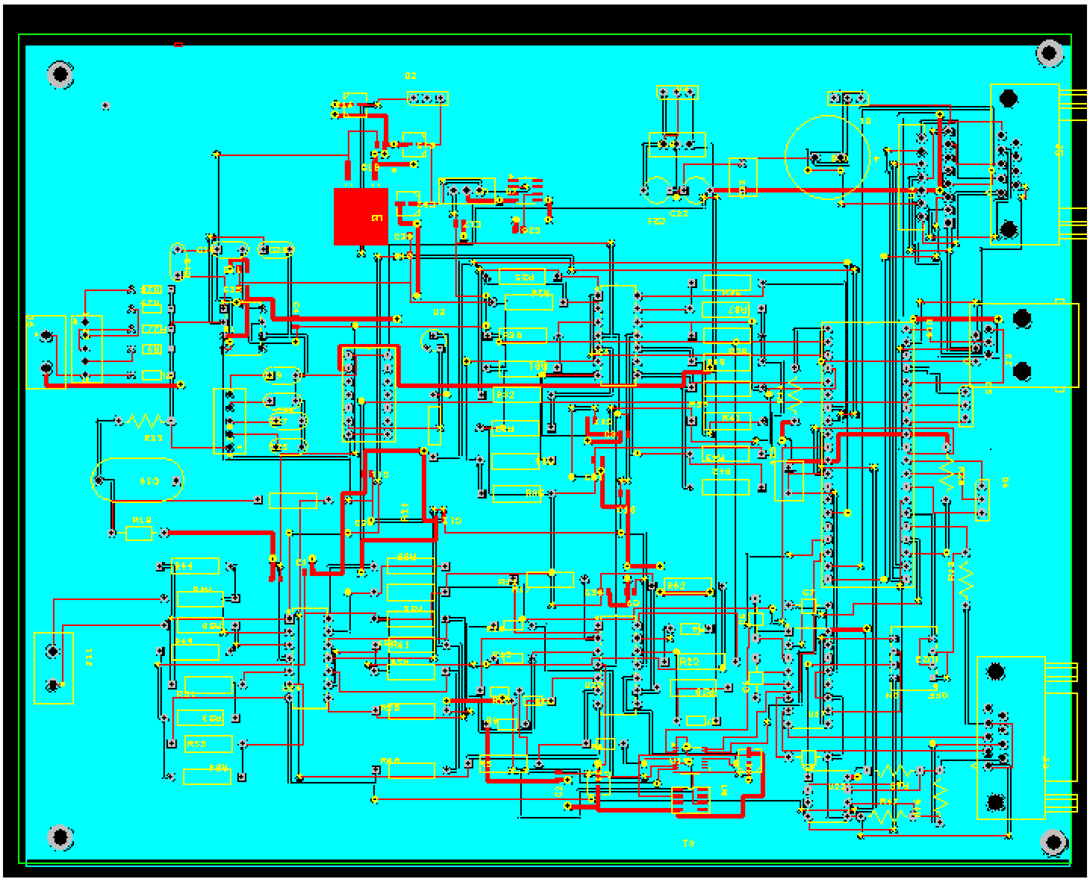


FIGURE 35. Manufactured PCB for the control unit of the prototype 3.

3.2.3. Interfaces

The control system is based in a master slave configuration. In this preliminary design, the master is a pc with windows 10 as operative system and visual net for the control consoles. Any way to assure an adequate portability, the different slaves control is performance trough serial connection RS232 or RS422. The RS232 is used for some tests or in the case of a single slave. Anyway, the overall communication protocol is compatible with both serial communication systems. The communication between master and slave is based in a setup of orders (from 0 to 255) that will be executed by the slave after reception. The slave answer can be just after the execution of the order, or after the reception of the order by the slave, if the order must be executed continuously, i.e. periodic displacement of the sample, the generation of an AC signal etc. The slave always answers to the order with a head in which appears the number of the received order except in the case of error in the reception or in the execution, in both cases the answer will be the order 255 plus de number of the error.

3.2.3.1. Communications protocol

The control systems are managed from a microcontroller integrated in the own card that has code programmed, based on a series of orders that are sent through the serial interface, from a control PC or a final user application. The command protocol is based on a series of transmission frames with a fixed structure and encapsulated information so that a device (in this case a µC) can read it and extract the information it needs to execute specific code. The communication ends when the receiver of the frame answers with an ACK or confirmation of the correct reception. In the case where the receiver does not receive the frame correctly or does not understand any of the fields that compose it, it will respond with an error frame, forcing the PC to resend the frame and restart the communication.

It should be noted that the system is designed in such a way that the master of the communication will always be the PC and the slave the µC. Knowing this, the µC will always answer an order commanded by the PC, and will never start a data transmission without the PC sending it.

3.2.3.2. Structure of control frame.

FIGURE 36 shows the structure of the control frame. It is organized in: head, order, order body, error control (CRC) and tail

FIGURE 36. Structure of the control frame.

Each of the parts are composed of fields that are fixed in the definition of the frame (are necessary for the frame to be safe and reliable). The fields are shown in more detail in FIGURE 37.

FIGURE 37. Fields that compose the control frame.

The following describes each of the fields that are part of the communication frame:

- **0x55:** This code in hexadecimal is in binary: 01010101. It has utility in detecting transmission errors or related to transmission times, delays, etc. If such a code is received well, there will be no problems associated with communication, in terms of distortions, loss of information due to problems in the channel, etc.
- **T.W (To Who):** This byte indicates to whom the message is addressed. It is the identifier of the communication receiver.
- **F.W (From Who):** This byte indicates who the message is from. It is the identifier of the communication transmitter.
- **Length (MSB):** Most significant byte of the two fields that indicate the size in bytes (within the frame) of the command and arguments. The total size will always be the number of arguments plus 1, because the order byte is implicit.
- **Length (LSB):** Least significant byte of the two fields that indicate the size in bytes (within the frame) of the command and arguments. The total size will always be the number of arguments plus 1, because the order byte is implicit.
- **Order:** Byte identifier of the command that has to execute the receiver, or that alludes to the response sent by the receiver as well received order or request to forward the frame for that order. It can have values between 0x0 to 0xFE (inclusive). The code 0xFF is the code associated with error.
- **Arguments (from 1 to n):** Arguments associated with the order. They are usually the data that the order needs to be executed, but in the error indication frames they allude to the error that has occurred itself.

- **CRC:** Cyclic redundancy code. It is the byte resulting from the error checking function in the transmission of the frame. Generally it is usually the result of an XOR, although you can think of a more complex and reliable system.
- **0x00:** Code that marks the end of the frame.

3.2.3.3. Structure of answer frames.

There are two possible responses sent by the µC to the PC: one validation of the frame sent to start the communication and another as a negative response to said sending or error notification. The structure of both frames is shown below:

ACK frame:

FIGURE 38. Structure of the ACK frame.

In this case, as can be seen in FIGURE 38, the frame is identical to the transmission. The only change is the order of the T.W and F.W. These two bytes change the order because now the frame transmitter is the previous receiver. The advantage of sending the frame with this unique change is that the CRC is the same, so when checking the transmission errors, the process is remarkably simplified.

Error frame:

FIGURE 39 shows the structure of the error frame.

FIGURE 39. Structure of the error frame.

In this case, the order field decreases to a single argument which is the error identifier. The frame notifies that an error has occurred by the order field, which becomes fixed value, 255 (0xFF) leaving the first argument of the command to indicate the particular error.

Switch on and test connection software module

This module allows establishing the connection between master and slave by pressing the button Connect, as shown in FIGURE 40. The master and slave names and port name must be given initially.

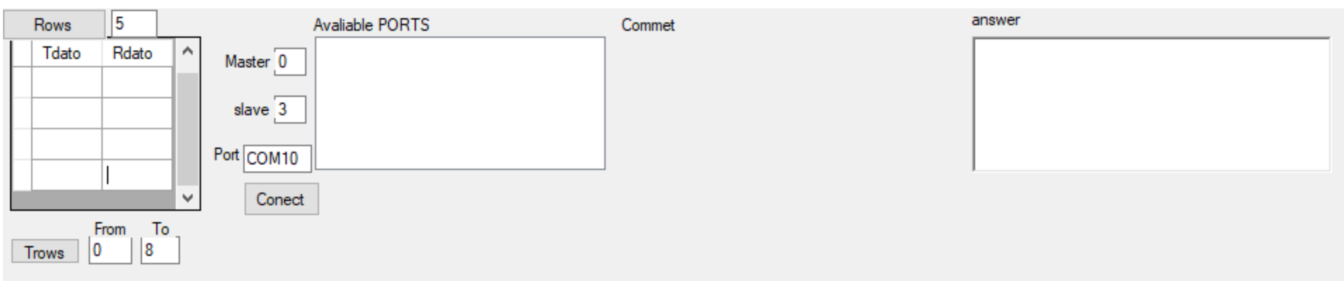


FIGURE 40. Graphical User Interface for the connection between master and slave (I).

If the selected port is not adequate, it appears the available ports and a comment suggesting the next action as FIGURE 41 illustrates.

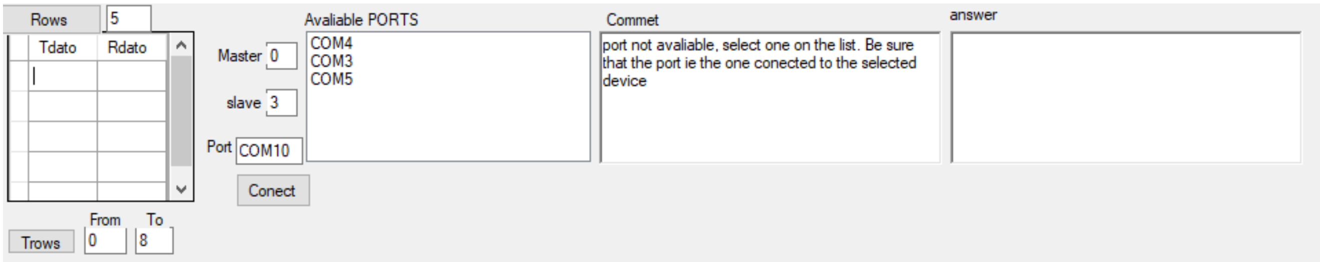


FIGURE 41. Graphical User Interface for the connection between master and slave (II).

If the slave is connected an order list appears instead of the Serial PORT selection from which an adequate one can be selected (FIGURE 42). In the left column of the grid appears the bytes sent to the slave. The answer appears in the right column. For test or to prove communications the left column can be written at any time and by pressing rows button, written bytes are sent to slave .

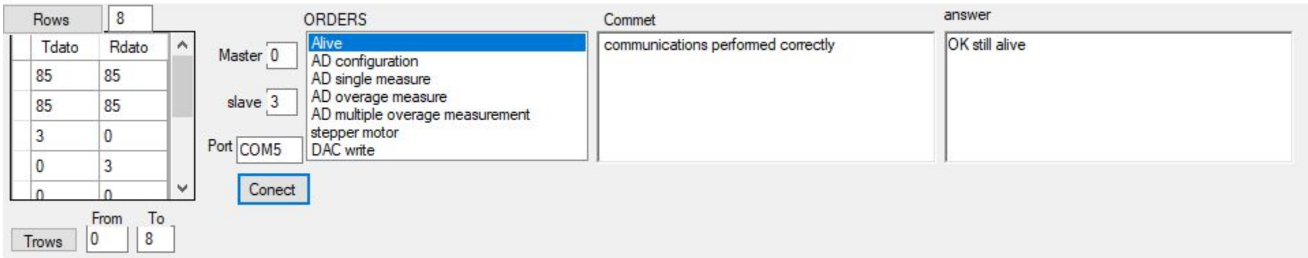


FIGURE 42. Graphical User Interface for the connection between master and slave (III).

<u>Order control software module</u>

Once connected, any order of the list can be selected- A grid with the parameters of the order options appears, after an adequate fulfill, the user can send the order to the slave by pressing the button "Transmit". Then the slave respond is shown in the answer box and if there are data they appear in the "Received data" grid as it is shown in FIGURE 43.

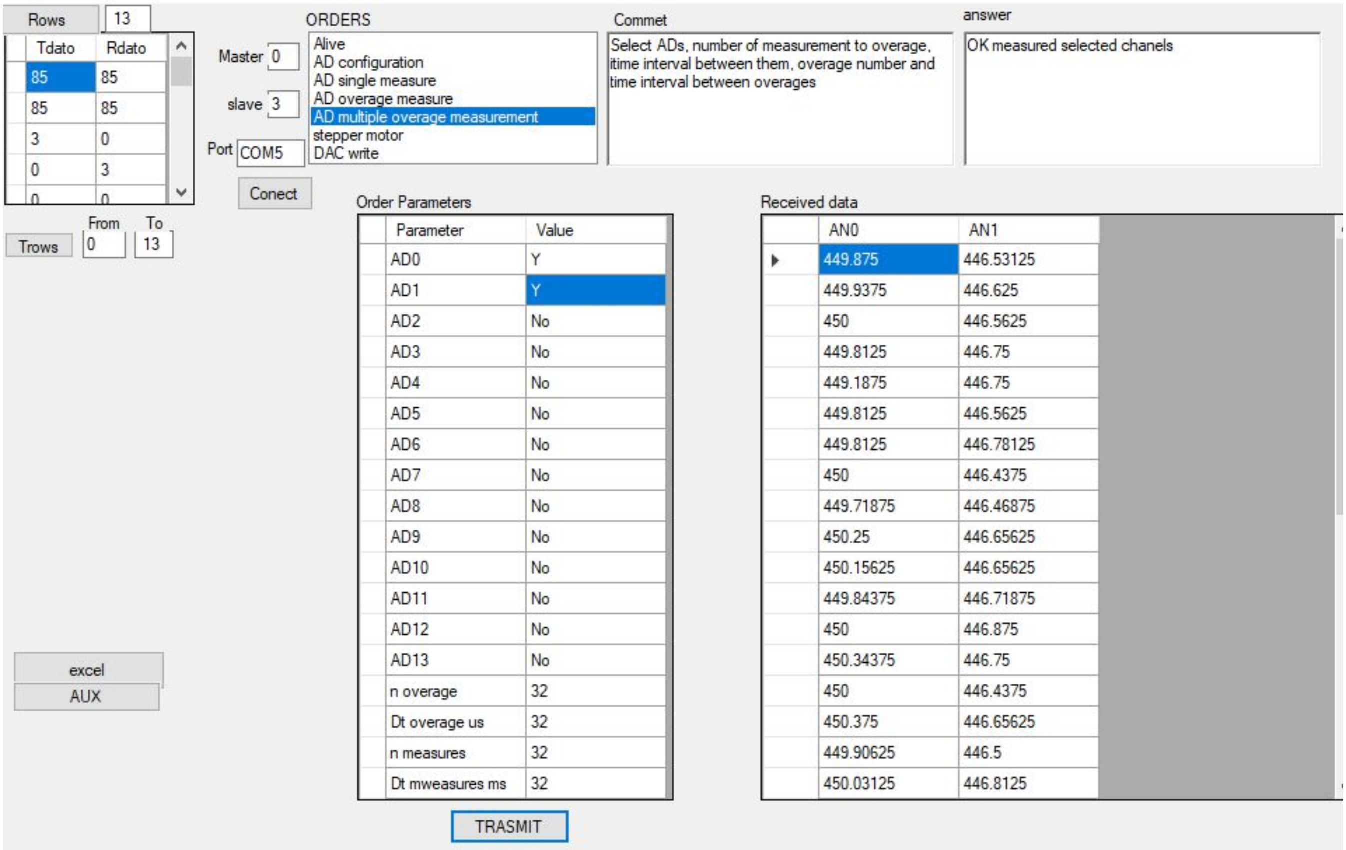


FIGURE 43. Graphical User Interface for the connection between master and slave (IV).

By presing excell button all data in the grid received data is trasfered to an Excel document.

Microcontroller program

We have used the PIC 16F887. The Microcontoller program is written in an assembler. It has the following modules:

- **Configuration module:** The data to configurate the µcontroller are stored in the EEmemory. It is divided in two sets, the first set (2100H-2180H) can be changed and stored durig executing program. To store the used configuration a security code must be used. In the second set (2180H-2200H) the initial configuration is stored to recover the original configuration. It is usefull in the case of incorrect operation of the system. After switch-on or reset the first set is charged. Also it can be charged by an order sent by the PC. Also there is an order to store the actual configuration in the µcontroller, the orther must include a 4 bytes security number to avoid changes on initial codition made by no autorized persons. The fields inside the initial configuration are: the security number (4 bytes), the µcontroller numbe (1 byte), the used special function registers addreses and values.
- **Interruption module:** Attend to USART interruptions, SPI interruption, and timer interruption for stteper motor control. The ADCs ar contolled by poolling. If there is a frame or over run error this module send an error mensge to PC.
- **Main program:** It calls to configuration subrrutines and enter in an infinite loop, watching the state bytes and waiting for orders to execute them. The PC program sent via serial an order, and after interruption, the order is procesed by the reception module and executed by the order execution module.

- **Reception module:** After an USART interuption, this module processes and stored the received order, testing the received bytes and the parity, in case of error it sends a message with the adequate error number.
- **Order execution module:** It reads the stored received order, goes to the order subrrutine and executes the order reading the stored order body. After order execution if it is not a continuos mode, answers to the PC with data or with an acknowledge.

4. FUTURE ACTIVITIES

During the next stage of the project the final development of the three prototypes of the NEWTON instrument will be developed. With this regard, and tacking into account the outcomes gained from the preliminary design stage, the main future activities have been defined:

- To test the integrator and its connections to the ADCs as well as the Level shifter & amplification stages block.
- To develop and test the Input offset correction block for the automatic drift control.
- To test and measure the H field production by means of connecting a ramp generator to a) a power amplifier (220 AC powered) and b) a switching power supply (12 V DC powered).
- To test the sample displacement system and evaluate its performance. Now the displacement system is based on a linear gear that is driven by the stepper motor. In case of an insufficient precision a new displacement based on either a screw or belt pulley transmission will be used
- To evaluate the system to perform hysteresis loops susceptibility measurements, demagnetizing curves, etc.
- Redesign parts of the susceptometer electronic circuit to solve errors and to improve its possibilities.
- To build the complete AC susceptometer, it will be necessary to integrate both software and hardware systems of the devices developed within the project, such as lock-in amplifiers, primary and secondary coils, power amplifiers.
- To test the high frequency secondary coils connected to the developed electronics.
- To test the AC primary coils and power amplifiers connected to the developed electronics.
- To include the control of the magnetometer

As previously indicated, these activities will be developed during the next stage of the project and it will be reported in the next WP3 deliverables which are planned to be submitted in April 2018.

5. SUMMARY AND CONCLUSIONS

This document reports the preliminary design of the electronic control block for the three prototypes of NEWTON instrument. As described in section 2, the three prototypes share the same architecture and the same key building blocks, i.e. the Power Distribution Unit (PDU), the Electronic Control Unit (CU) and the Sensor Unit (SU). The electronic Control Unit is the responsible of the control, acquisition and processing of the signals of the Sensor Unit which includes a susceptometer and a vector magnetometer.

Within the Control Unit, the excitation and measurement system generates two signals that serve to measure the samples of the rocks to which the Sensor Unit approaches. It contains a microcontroller that performs these tasks and generates the different frequency signals for the sensor unit. One of these signals will be used for the excitation of the sensor and the other one will act as reference for the lock-in measurement system. This functionality is the same for the three prototypes of NEWTON multi-sensor instrument, i.e. Prototype 1, Prototype 2 and Prototype 3.

In this preliminary design stage, the excitation and measurement system of the susceptometer has been developed and partially validated. During the next stage of the project, the functionality of the Control Unit will be advanced and improved in order to include the control of the magnetometer. In the case of prototype 1 and prototype 2 the selected magnetometer consists of a three axes magnetometer based on anisotropic magnetoresistance (AMR) with an electronic control system already integrated for an immediate integration in the prototypes.

In the case of prototype 3, the functionality described above has been advanced in order to carry out the full magnetic characterization of the samples. NEWTON Prototype 3 is dedicated to perform magnetic susceptibility measurements of samples in a portable system. There will be two kinds of measurements: low frequency range and high frequency range. The sample magnetization is performed by measuring the magnetic flux induced in the secondary coil system which forms part of the Sensor Unit .The signal generated in the secondary is proportional to the derivative of the magnetic flux. Therefore it must be integrated to attain the magnetic flux and samples magnetization. To perform any magnetic measurement, changes in magnetic flux induced in the secondary coils must be produced. These changes can be done by varying the exciting field or by displacing the sample inside of the secondary coil system. With this regard, the specific activities which have been developed during this preliminary design stage are:

- It has been defined the initial structure of the control system for the susceptometer.
- It has been designed, built and partially tested the electronics of the low frequency susceptometer.
- It has been design and tested the high frequency susceptometer electronic input for acconditioning and measurement of an AC signal (Lock-in amplifier described in section 3.1).
- It has been designed and written the software platform for the system, either high level embedded PC as Low level embedded microcontroller. In addition to this, a great part of the software platform has been already tested.
- The medium intensity H field production system has been designed and partially built up.
- The high field intensity H field production has been designed and modelled.

After the initial validation tests and considering the results obtained from them, some changes must be performed in the preliminary design. The future activities are described in Section 4, the main modifications which should be considered in the next stages are:

- Increase the Microcontroller used in prototype 3 memory by adding a 128K SPI memory.

- Change the gain control of the Integrator and of the H field measurement.
- Improve the references voltages of the ADC in prototype 3
- Redesign the Lock-in amplifier including two of them (for prototype 2 and 3) in its board and some ADCs lines.

As already indicated, the final design of the electronic control will be developed in the next stage of NEWTON project. It is important to remark that new modifications or improvements must be required in the next steps of the design, so the information reported in this document may change. The final design will be reported in the next WP3 deliverables which are planned to be delivered in April 2018.

6. REFERENCES

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