POLITECNICO DI TORINO

MASTER’S DEGREE COURSE IN ELECTRONIC ENGINEERING

DEVELOPMENT OF AN ULTRA THIN REACTION WHEEL FOR MODULAR NANOSATELLITES

Eng. Cristinel Enusel

Supervisors:

Prof. Leonardo REYNERI
Prof. Claudio SANSOÉ

July, 2015

Summary

1. Introduction

Space is of important interest for many scientists around the world but due to the enormous costs, for decades remained an unaffordable issue for many of them. The launching costs are still high now days while the use of COTS (Commercial Off The Shelf) components allowed to reduce satellite implementation costs. *"A CubeSat is a type of miniaturized satellite for space research"* said Wikipedia. One of the most important characteristics of a CubeSat is its dimension that allows to be launched on the orbit with low costs, taking advantage of free space that can be found on the missile of bigger missions or by gathering more nanosatellites to divide launching costs.

Moved by the growing interest of the Universities around the globe in space research at affordable costs in 1999 California Polytechnic State University and Stanford University developed the CubeSat specifications. The main goals of the professors Jordi Puig-Suari and Bob Twings was to enable the graduate students to be able to design, build, test and operate in space a spacecraft with the similar capabilities of Sputnik, the very first spacecraft ever launched. The CubeSat has become a standard over time and lots of satellites have been built following the CubeSat idea.

1.1.PicPoT Project

Many Universities around the world have used CubeSat standard since then. One of them is Politecnico di Torino, which has realised its first nanosatellite named PiCPoT (Piccolo Cubo of Politecnico di Torino). This project was aimed to build a low cost satellite, which must fit within tight cost constrains for the launch and the actual satellite hardware. The PiCPoT was a cube of 130 mm side and 2.5 kg of weight with the external faces made by aluminium alloy type 5000AlMn. The main motivations were to give a training opportunity for the students and PhD students, create an interdisciplinary team from different departments of Politecnico, consolidate the knowledge of the team in the fields of electronic, aerospace and avionic system design, assessing the feasibility of building high-reliability satellites with cheap off-the-shelf components and the intention of building a "constellation of Italian satellites", together with other five Italian universities. The mission was transmitting and

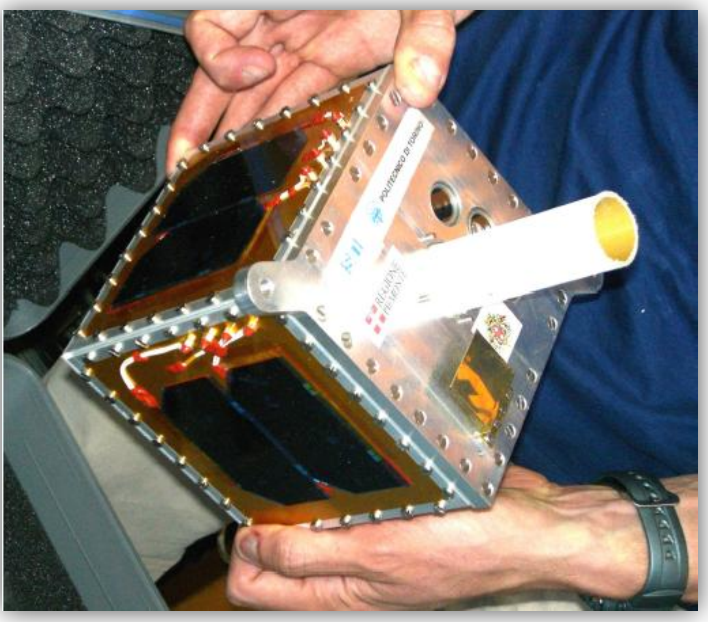


Figure 1 – PicPot nano-satellite

receiving data, shoot photos and test the off-the-shelf components, of which was built, in space conditions. The satellite had solar panels (used to power the entire system) on five sides of the cube and the sixth side was populated with antennas and cameras. This nanosatellite was never tested in space because its carrier failed few seconds after the launch.

1.2.Aramis Project

The AraMiS project is a prosecution of the PiCPoT. It's main goal is, in addition of the first project goals, the modularity. The PiCPoT was realised using an ad-hoc view, which didn't offered the possibility to reuse the designs. AraMiS project is thought with the use of independent modules, with specific independent functions, perfect interchangeable, reusable in other similar projects. Once standard modules are defined, they can be assembled into the project according with the specification of the mission, resulting in reduced projecting costs and high versatility.

The main modules, called tiles, in addition of the Inertial Attitude Subsystem Tile are the Power Management Tile and Telecommunication Tile.

1.2.1. Power Management Tile

These modules perform different functions, electrical energy generation by converting the solar light by means of the solar panels, charging this energy into the batteries and distribute it to the other systems at suitable parameters. This modules are put on the outside of the satellite because of the solar panels presence, which must be illuminated by the solar light. The Tiles are independent and managed to allow to decide which battery will be charge from which solar panel, in order to optimize the system as well as possible(clearly in a specific moment very few panels will be illuminated so only them will give power in that moment). To do that the power and data bus is used.

1.2.2. Telecommunication Tile

These modules allows the communication between the satellite and University Earth station. Uses 2 channels, the firs, on the 437 MHz band, is dedicated to the radio amateur and allow them to receive the satellite beacon, the second operates on the 2.4 GHz band. The use of two channels allows to increase communication system reliability, allowing to maintain the communications while one of radio channel is out of order.

2. 1B21_Inertial_Attitude_Subsystem

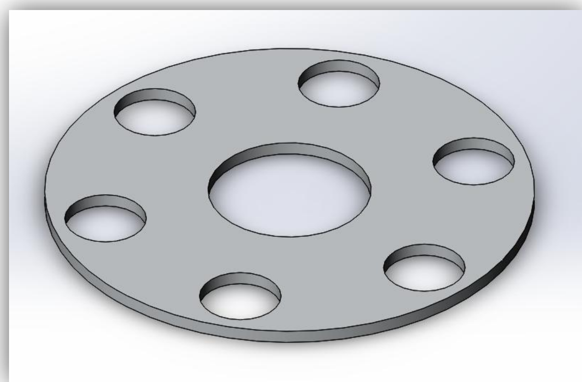


Figure 2 – Alluminum hard-disk plate

The Inertial Attitude Subsystem controls the speed, direction and the time of activity of a reaction wheel to generate an angular momentum. The mechanical details are not subject of this thesis so they will be presented only superficially. Mainly is a brushless motor realised by means of an 3.5’ hard-disk plate, modified to allow six neodymium magnets to be radial mounted. It’s a low cost solution that complies the needed proprieties: ultra-thin 4.7-6mm, light 165-190g and best magnetic and mechanical characteristics at this cost. The other elements of this brushless motor are the nine coils designed to occupy the minimum space and are 3 mm high and 18 mm external diameter with an 12 mm iron core. There are also there HALL sensors for the plates angular position sensing. The

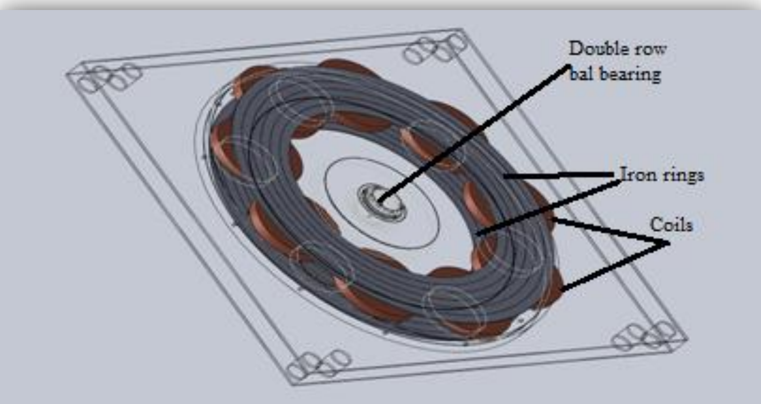


Figure 3 – Reaction wheel assembled view

motor subsystem is completed by the addition of a double row bal bearing for an easy rotation of the plate. The assembled view is shown in Figure 3 . We can see that the magnetic circuits are closed by the two iron rings placed above and below the coils and the magnetic plate. The Inertial Attitude Subsystem PCB together with the Outer Plate and the Case Body PCBs (all made in FR4 material) complete the motor construction. On the Inertial Attitude Subsystem PCB are placed all the Subsystem components including the coils and centrally is fixed the rotating plates bearing. The Outer Plate is the external part of the assembling and, as one face it’s one of the satellite face, it has two solar cells mounted on. In the centre, as with Subsystem PCB happens, the plates bearing is fixed. The Case Body is placed between the other two PCBs and allows the rotating plate movement as has a thickness greater than the reactions wheel and centrally has a slot that can easily hold it. The exploded assembly can be seen in the Figure 4.

The brushless motor just presented is driven by the actuator module called Reaction Wheel Actuator. Its function is to receive commands, and by driving the coils in specific way, to execute them. It receive

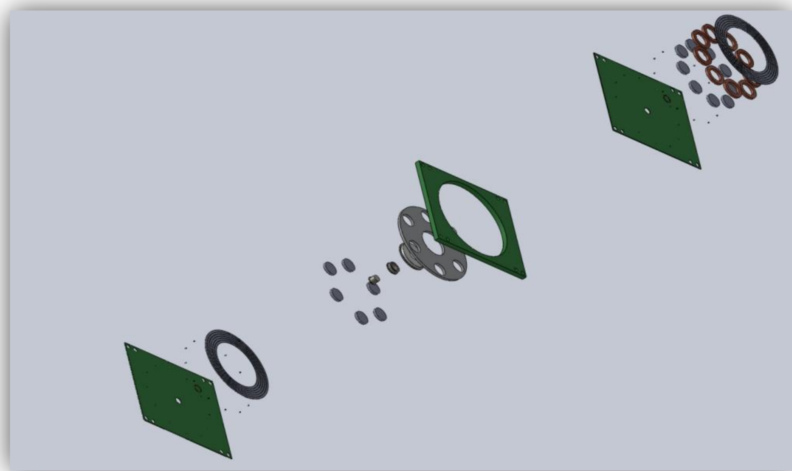


Figure 4 – Reaction wheel expolded view

signals from the motors HALL sensors, which communicate the angular position of the rotating plate. In addition of the rotating movement of the reaction wheel, the actuator, by means of specific current waveform, also generate an perpendicular magnetic field, which in interaction with the Earth magnetic field, allow a passive control of the nano-satellite attitude.

The Inertial Attitude Subsystem has also some sensors to complete the control system. They are Digital Gyroscopic, Magnetometer and temperature sensors. All the system is controlled by a microcontroller that receive commands from the data bus and execute them or return sensors data to the bus. All these elements will be analysed in detail in the next chapters.

3. B221_Magnetometer:V1 Module

The 1B221_Magnetometer_V1 module uses the HMC1002 magnetic sensor for the orientation function. The Honeywell HMC1002 magnetic sensor is an 2-axis surface mount sensors designed for low field magnetic sensing. Its sensitivity runs from tens of micro-gauss to 6 gauss, being one of the most sensitive and reliable low-field sensor in the industry. This sensor is a simple Wheatstone bridge to measure magnetic fields and only require a supply voltage for the measurement. Powered, the sensor convert any incident magnetic field in the sensitive axis directions to a differential voltage outputs. In addition to the bridge circuits, each sensor has two on-chip magnetically coupled straps, the offset strap and the set/reset strap. These straps are for incident field adjustment and magnetic domain alignment, and eliminate the need for external coils positioned around the sensors. The magnetostrictive sensors are made of nickel-iron (Permaloy) thin-film deposited on a silicon wafer. In a presence of a magnetic field, a change in the bridge resistive elements causes a corresponding change in voltage across the bridge.

3.1.SET/RESET Straps

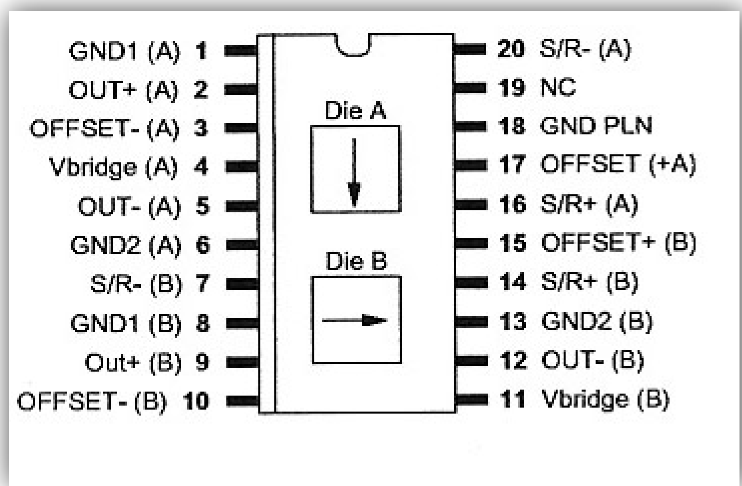


Figure 5 – HCM1002 pin configuration

Set/Reset straps are a spiral of metallization that couples to the sensor element's easy axis (perpendicular to the sensitive axis of the sensor die). Each set/reset strap has low resistance with a short but high required peak current for reset or set pulses. A set of pulse is defined as a positive pulse current entering the S/T+ strap connection. The successful result would be the

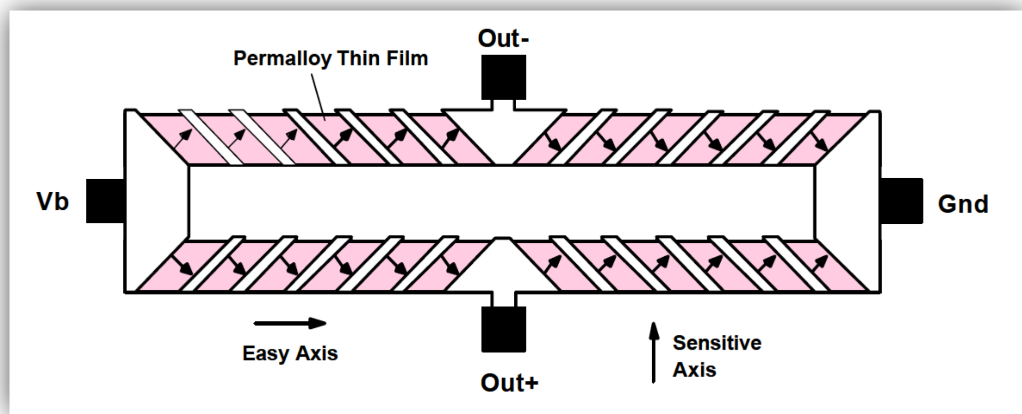


Figure 6 – Magneto-Resistive Wheatstone Bridge Elements

sensor aligned in a forward easy-axis direction so that the sensor bridge's polarity is a positive slope with positive fields on the sensitive axis results in positive voltages across the bridge output connections. A reset pulse is defined as a negative pulse current entering the S/R+ strap connection. This would align the sensor in the reverse easy-axis, with the reverted effect of the set pulse. Typically a reset pulse is sent first, followed by a set pulse a few millisecond later. By shoving the magnetic domains in complete opposite directions, any prior magnetic disturbances are likely to be completely erased by the duet of pulses.

The reason to perform a set or reset on the sensor are: 1) To recover from a strong external magnetic field that likely has re-magnetized the sensor, 2) to optimize domain for most sensitive performance, and 3) to flip the domains for extraction of bridge offset under changing temperature condition. In this project all these three cases are met due to the presence of the magnetic actuator and the difficult thermal conditions in space medium.

3.2.Magnetometer Schematic

The schematic of the physical implementation of the Magnetometer module is shown in the Figure 10. It can be seen the two axis sensor amplifiers made with the AD623ARZ single supply

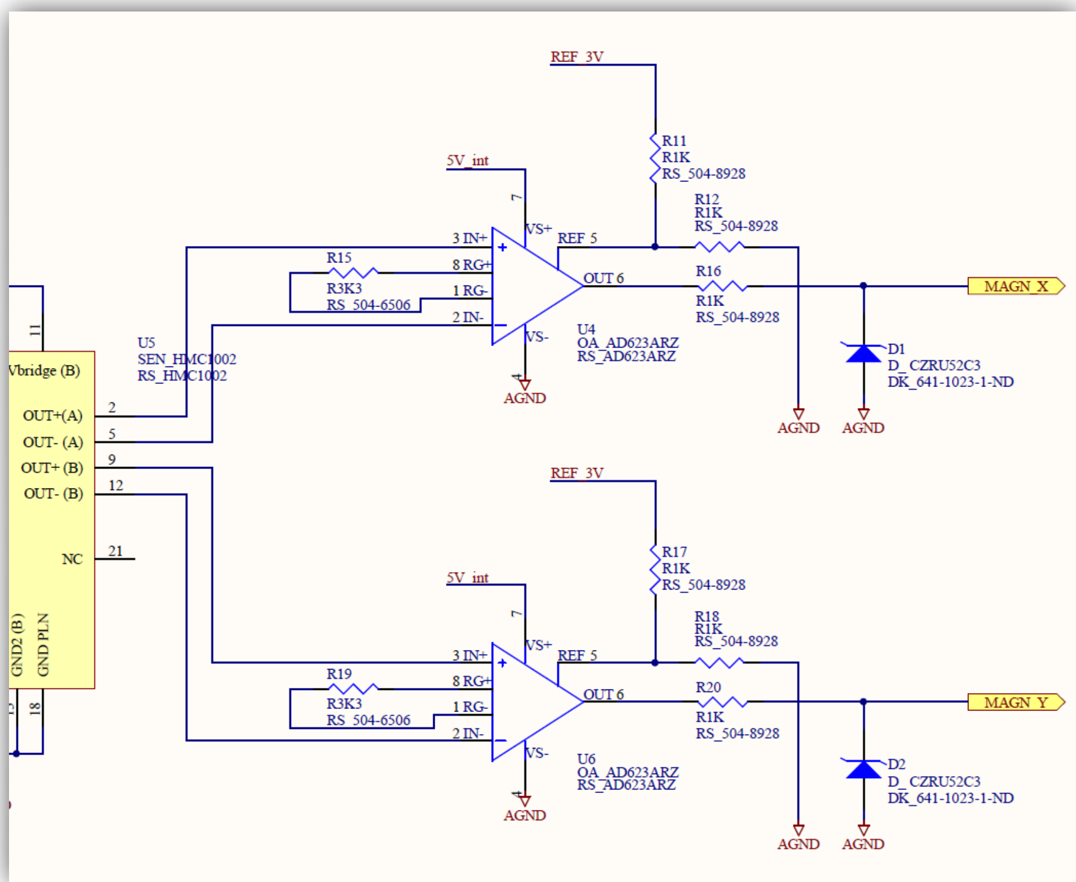


Figure 7 – Two axis sensor amplifiers

instrumentation amplifier (in detail in Figure 7). It receives the

Wheatstone bridge output in its differential inputs and outputs a single REF5 pin referenced voltage per axis. The gain is set by the resistance between pins 1 and 8 and for this project was set to 30 cca. The output 0 is set to 1.5V(half of the 3V reference source) in order to cover positive and negative signal variations.

The SET strap pulses are given by Q3 which is a double P-MOS transistor (Figure 8). When the SET signal is given (note that the SET command is active low) the 3V3 source voltage is put on the straps by means of the C6, C7 and 1.5 ohms sensors internal resistor which assure

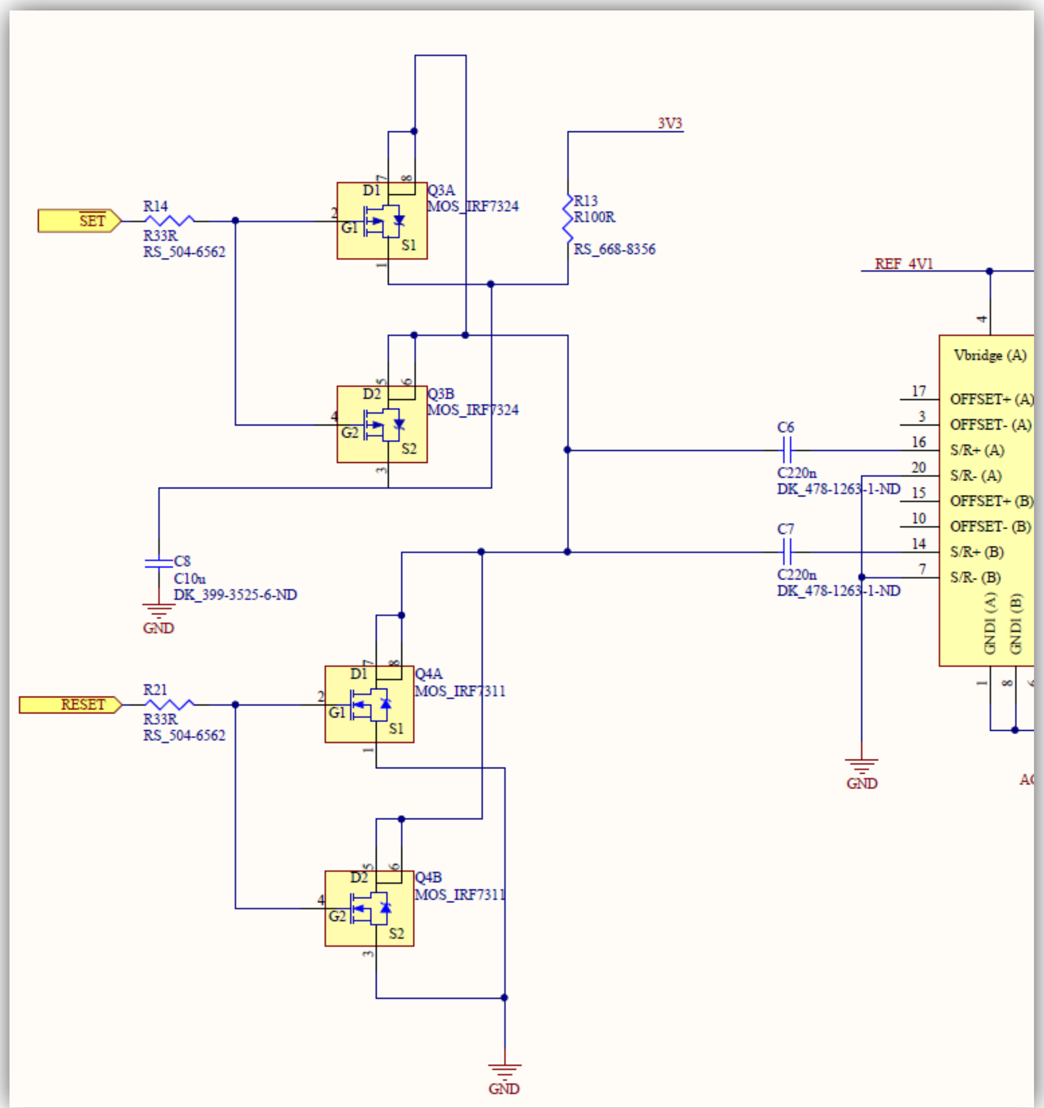


Figure 8 – SET/RESET drivers

a pulse of 0.7 us cca. C8 and R13 pass base filter ensure that the disturb do not propagate on the power line.

The RESET strap pulses are given by means of Q4, a double N-MOS transistor. When the RESET signal is given the C6 and C7 are discharged and in the S/R+ sensor pins a negative current is injected.

Another element is the LM4128 precision voltage reference. This IC gives an accurate voltage to the sensors internal Wheatstone bridge. It is powered with 5V and gives a 4.1V reference voltage. The circuit can be disabled by pulling down the pin EN.

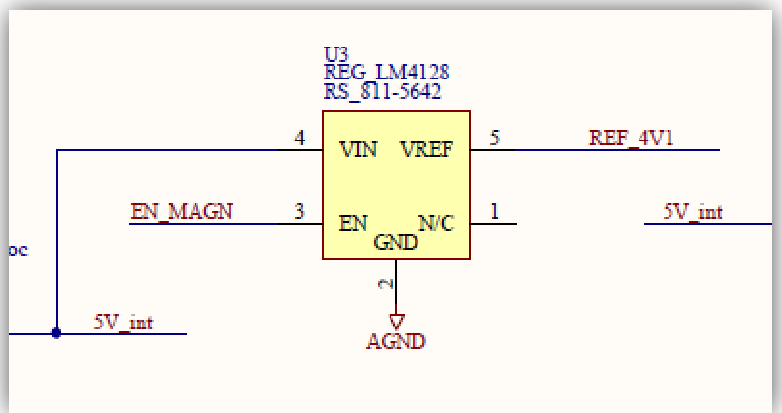


Figure 9 – Precision voltage reference

Next figure shows the complete Magnetometer schematic.

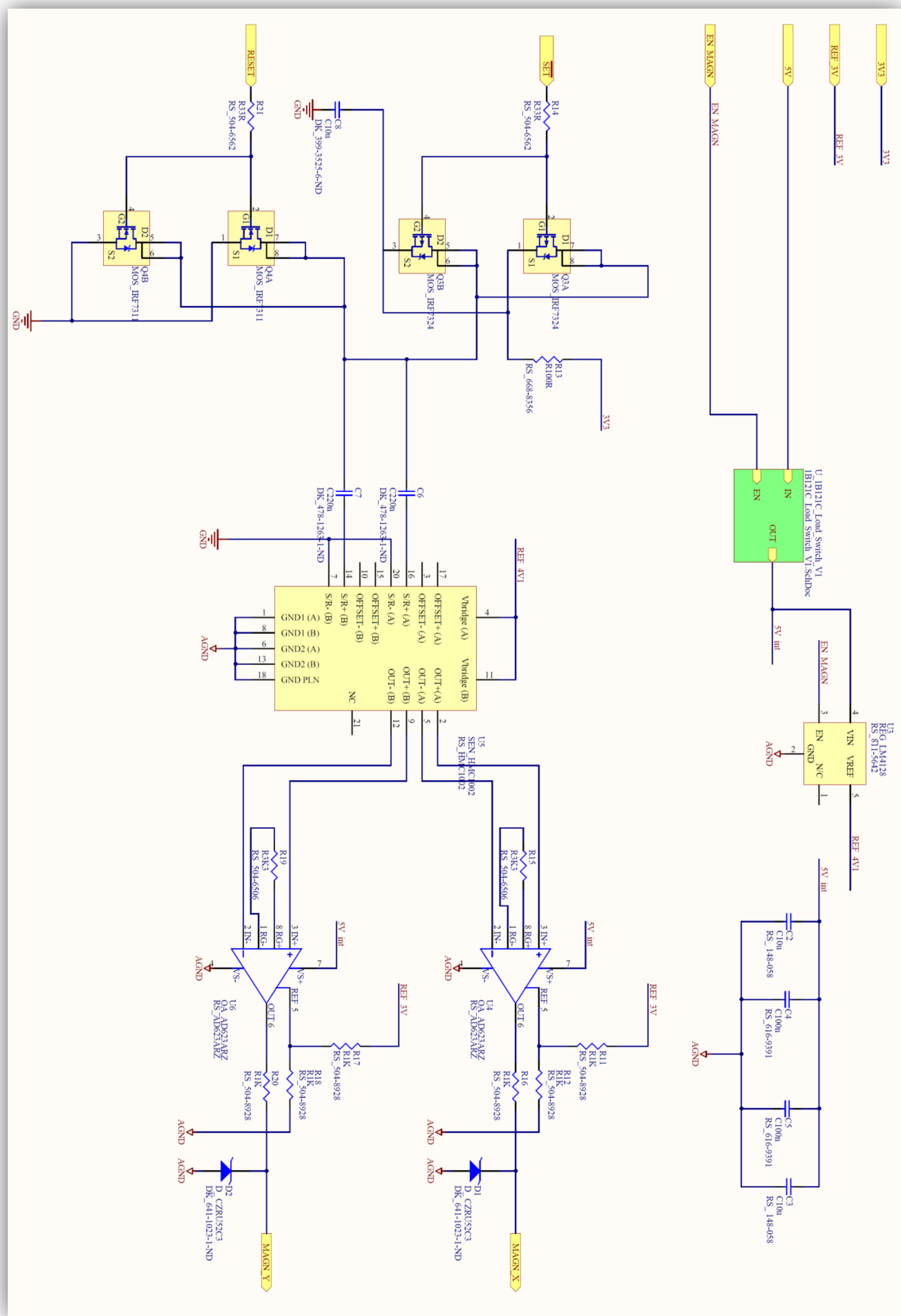


Figure 10 – Magnetometer_V1 schematic

3.2.1. Load Switch

Other last element in the schematic is the U_1B121C_Load_Switch_V1 showed in detail in the figure 11. This circuit is a high-side MOS switch and its function is to completely

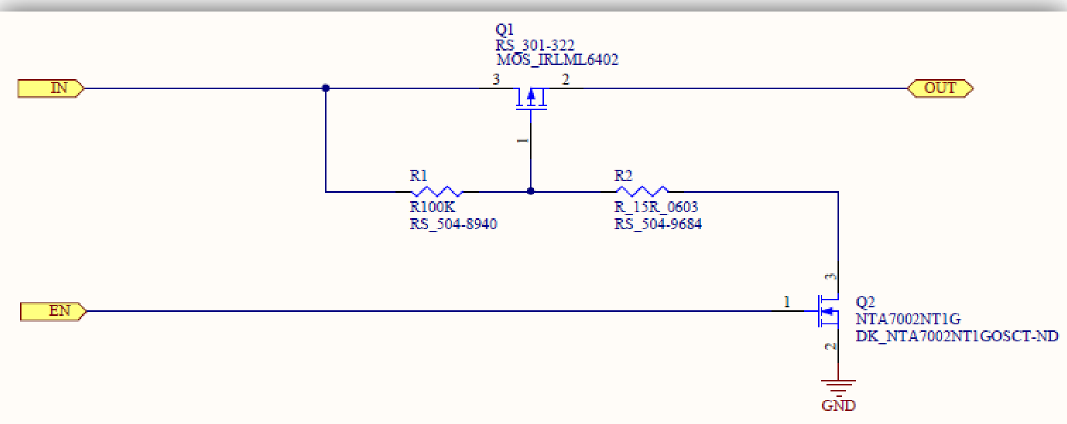


Figure 11 – 1B121C_Load_Switch_V1

remove the power to the Magnetometer module if desired. This allows the lowest power consumption when the module in off. The enable signal is given to the EN pin of the module.

3.3.Harness connection diagram

To all blocks were added an intermediate schematic level to allow the connection of the module to the harness connector to increase readability. The Magnetometer Harness connections are shown in the next figure.

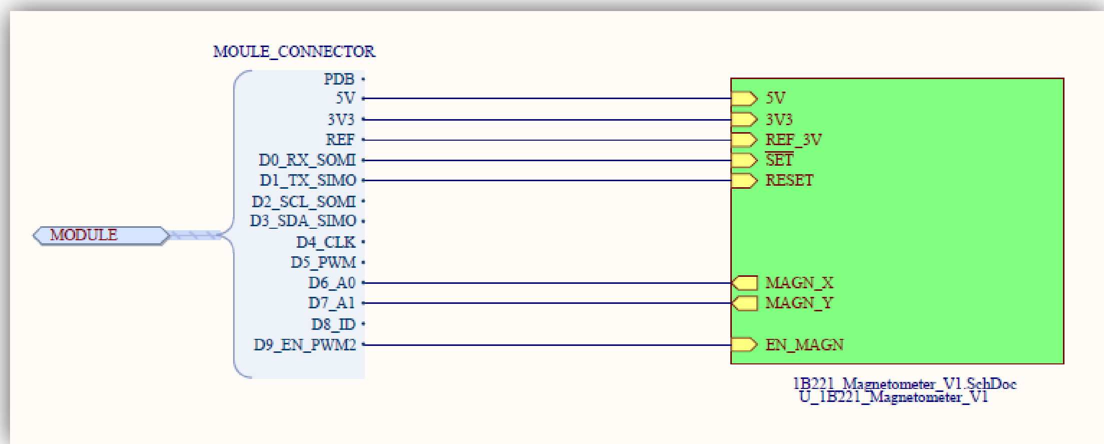


Figure 12 – Magnetometer Harness connections

4. 1B211B_Digital_Gyroscopic_Sensor Module

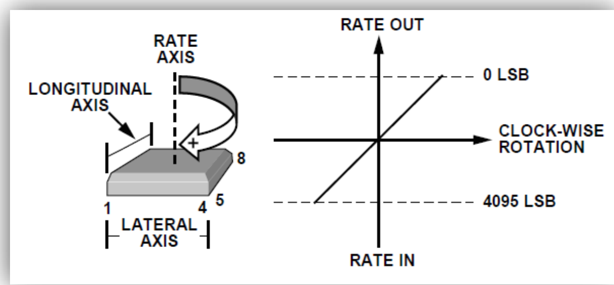


Figure 13 – Rate sensitive axis

For this module the ADIS16080 Analog Devices gyroscopic sensor was chosen. It uses a surface-micromachining process to make a functionally complete angular sensor. The digital data available at the SPI port is proportional to the angular rate about the axis that is normal to the top surface of the package. It has an internal temperature sensor and the measurement is provided through the SPI. This measurement is usually used to compensations techniques. An additional output pin provides a precision voltage reference. Two digital self-test inputs electromechanically excite the sensor to test the operation of the sensor and the signal conditioning circuits. The ADIS16080 operates on the principle of resonator gyroscope. Two polysilicon sensing structures each contain a dither frame that is electrostatically driven to resonance. This produces the necessary velocity element to generate a Coriolis force while rotating. At two of the outer extremes of each frame, orthogonal to the dither motion,

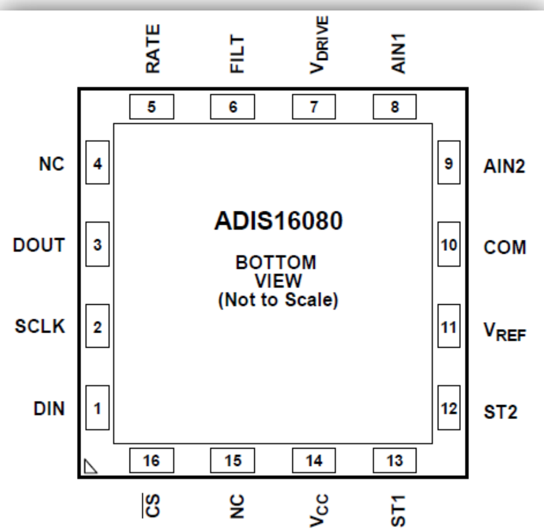
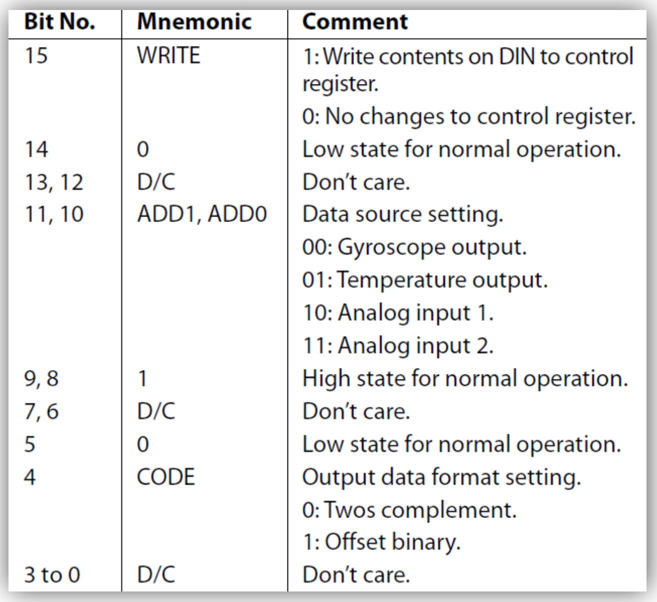


Figure 14 – ADIS16080 pin configuration

are movable fingers that are placed between fixed pickoff fingers to form a capacitive pickoff structure that senses Coriolis motion. The resulting signal is fed to a series of gain and demodulation stages that produce the electrical rate signal output. The rate signal is then converted to a digital representation of the output on the SPI pins. The dual-sensor design rejects external G forge and vibration. Fabricating the sensor with the signal conditioning electronics preserves signal integrity in noisy environments. The electrostatic resonator requires 14 V to 16 V for operation. Because only 5 V is typically available in most applications, a charge pump is included on-chip. After the demodulation stage, there is a single-pole, low-pass filter included on-chip that is used to limit high frequency artifacts before final amplification. The frequency response is dominated by the second low-pass filter, which is set at 40 Hz.

4.1.Serial Peripheral Interface (SPI)

The ADIS16080 has an external powering pin for the SPI module to simplify interfacing. The SPI port includes four signals: chip select($\overline{CS}$), serial clock (SCLK), data input (DIN) and data output (DOUT). The $\overline{CS}$ line enables the ADIS16080 SPI port and frames each SPI event. When this signal in high, the DOUT lines are high impendence state and the signals on DIN and SCLK have no impact on operation. A complete data frame contains 16 clock cycles. Because the



Bit No.	Mnemonic	Comment
15	WRITE	1: Write contents on DIN to control register. 0: No changes to control register.
14	0	Low state for normal operation.
13, 12	D/C	Don't care.
11, 10	ADD1, ADD0	Data source setting. 00: Gyroscope output. 01: Temperature output. 10: Analog input 1. 11: Analog input 2.
9, 8	1	High state for normal operation.
7, 6	D/C	Don't care.
5	0	Low state for normal operation.
4	CODE	Output data format setting. 0: Twos complement. 1: Offset binary.
3 to 0	D/C	Don't care.

Figure 15 – DIN Bit assignments

SPI port operates in full duplex mode, it supports simultaneous, 16-bit receive (DIN) and transmit (DOUT) functions within the same data frame.

The DIN control register provides controls for two operational settings: the output data source and the coding (twos complement vs. offset binary). The DIN sequence starts with a 1 for configuration sequences and a 0 for read sequences. When this bit is 0, the remaining DIN bits do not change the control register and the next sample's output data reflects the existing configuration. Data loads from the DIN pin into the ADIS16080 on the falling edge of SCLK. Once the 16-SCLK sequence is complete, the control register is updated and ready for the next read sequence. If a data frame has less than 16 SCLK cycles, the control register does not update and maintains its previous configuration. The DIN bit definitions which have either 0 or 1 assigned to them, are critical for proper operation.

4.2. ADC Conversion

The chip select ($\overline{CS}$) and serial clock (SCLK) lines control the on-board A/D conversion process. When the chip select line goes low, the DOUT line comes out of three-state mode, the track-and-hold goes into hold mode, and the ADC samples the analog input at this point. The track-and-hold returns to track mode on the 14th falling edge of the SCLK line. The serial clock drives the internal ADC conversion clock, using its falling edge for control of this process. All 16 SCLK cycles are required for a complete conversion. If a data frame has less than 16 SCLK cycles, the conversion cannot complete and does not update the output data for the next data frame cycle.

4.3. Output Data Access

The DOUT sequence starts with two zeros, one that clocks out after the falling edge of , and a second one that clocks out on the first SCLK falling edge. The next 14 bits, ADD0, ADD1 and the 12 data bits, clock out on SCLK falling edges. After the 16th falling edge, the DOUT

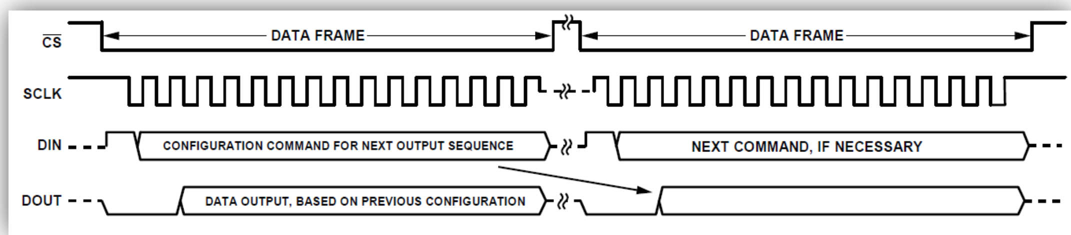


Figure 16 – Configuration and Read Sequence

line moves to a three-state mode. In the following tables the Data Coding for different data types are shown:

Temperature (°C)	Code	Bit Pattern
85	2633	0001101001001001
25 + 0.2906	2050	0001100000000010
25 + 0.1453	2049	0001100000000001
25	2048	0001100000000000
25 − 0.1453	2047	0001011111111111
25 − 0.2906	2046	0001011111111110
−40	1601	0001011001000001

Figure 17 - Temperature Data Coding, Twos Complement

Temperature (°C)	Code	Bit Pattern
85	585	0001001001001001
25 + 0.2906	2	0001000000000010
25 + 0.1453	1	0001000000000001
25	0	0001000000000000
25 − 0.1453	−1	0001111111111111
25 − 0.2906	−2	0001111111111110
−40	−447	0001111001000001

Figure 18 - Temperature Data Coding, Offset Binary

Input Level (V)	Code[1]	Bit Pattern
4.5	3686	0010011001100110
2.5 + 0.002442	2050	0010100000000010
2.5 + 0.001221	2049	0010100000000001
2.5	2048	0010100000000000
2.5 − 0.001221	2047	0010011111111111
2.5 − 0.002442	2046	0010011111111110
0.5	410	0010000110011010

Figure 19 - ADC Data Coding, Twos Complement

Input Level (V)	Code[1]	Bit Pattern
4.5	1638	0010011001100110
2.5 + 0.002442	2	0010000000000010
2.5 + 0.001221	1	0010000000000001
2.5	0	0010000000000000
2.5 − 0.001221	−1	0010111111111111
2.5 − 0.002442	−2	0010111111111110
0.5	−1638	0010100110011010

Figure 20 - ADC Data Coding, Offset Binary

4.4. Gyroscope Schematic

The Gyroscope schematic is shown in the following Figure. Together with the ADIS16080 there are two High-side switches to allow the complete power off of the module in case is not used to save energy. One switch for the 5V sensor power and the other for the 3.3V SPI power, voltage fully compatible with the system data bus. The internal schematic of the Load Switch was presented in the previous chapter. The base sensor connections were used and no analog inputs.

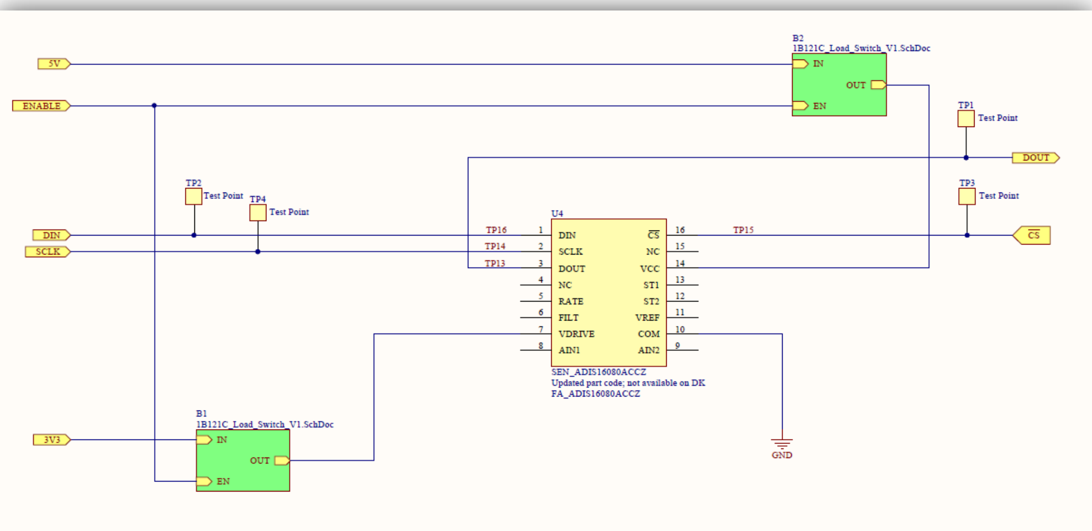


Figure 21 – Gyroscope schematic

4.5.Harness Connection Diagram

The connections to the harness modules are shown in the next figure.

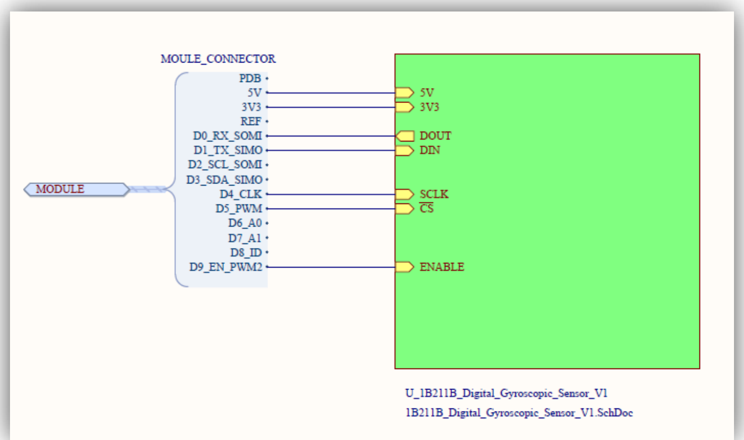


Figure 22 – Gyroscope Harness connections

5. 1B212W_Reaction_Wheel_Actuator Module

The Reaction Wheel Actuator schematic is showed in the next figure. The main component is the L6205SPD DMOS dual full bridge

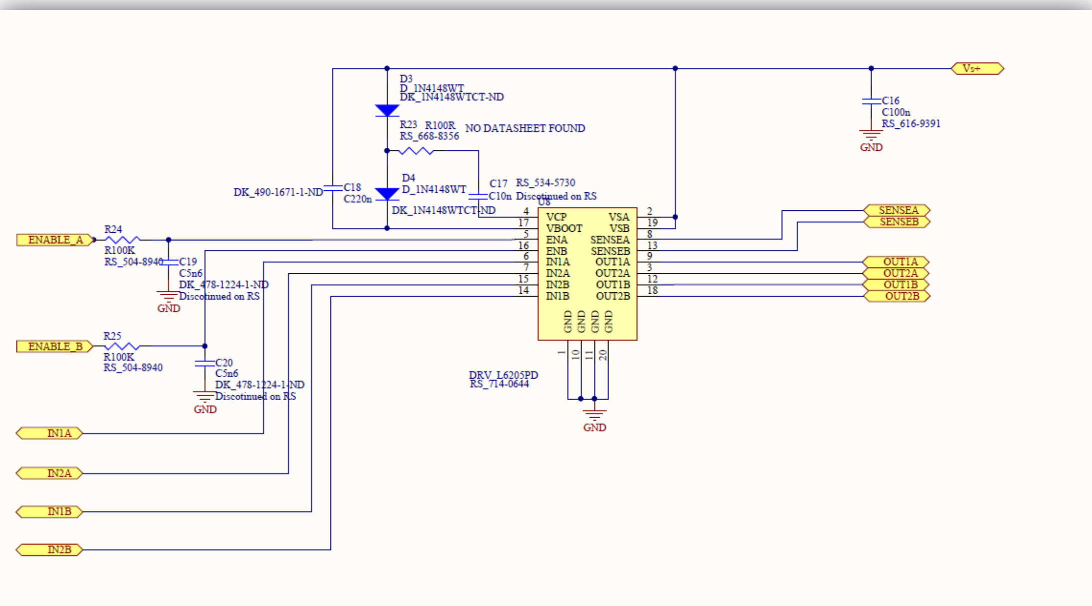


Figure 23 – Reaction wheel actuator schematic

driver. It features: operating supply voltage from 8 to 52V, 5.6A output peak current, operating frequency up to100KHz, thermal shutdown and cross conduction protection.

The PowerSO20 case was chosen for a better heat dissipation and because this package features a non-dissipative protection of high side PowerMOSFETs and thermal shutdown. Due to the absence of the air convection and so the heat dissipation based only on radiation and conduction through other elements, the minimum necessary surface is not easy to calculate. That's why in the PCB realization, this component has a thermal connection by means of 15 vias to the GND plane in order to achieve the maximum dissipation surface. The L6205 integrates two independent Power MOS Full Bridges. Each Power MOS has an Rdson=0.3 ohm with intrinsic fast freewheeling diode. Cross conduction protections is achieved using a dead time (typically 1us) between the switch off and switch on of two Power MOS in one leg of a bridge. As we can see in the schematic the L6205 driver need a charge pump to drive the N channel Power

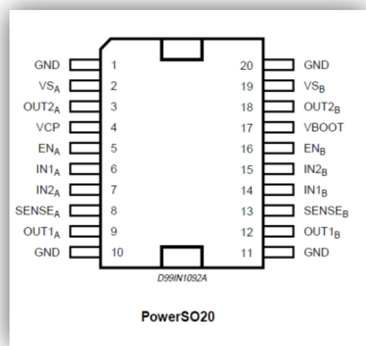


Figure 24 – L6205 pin configuration

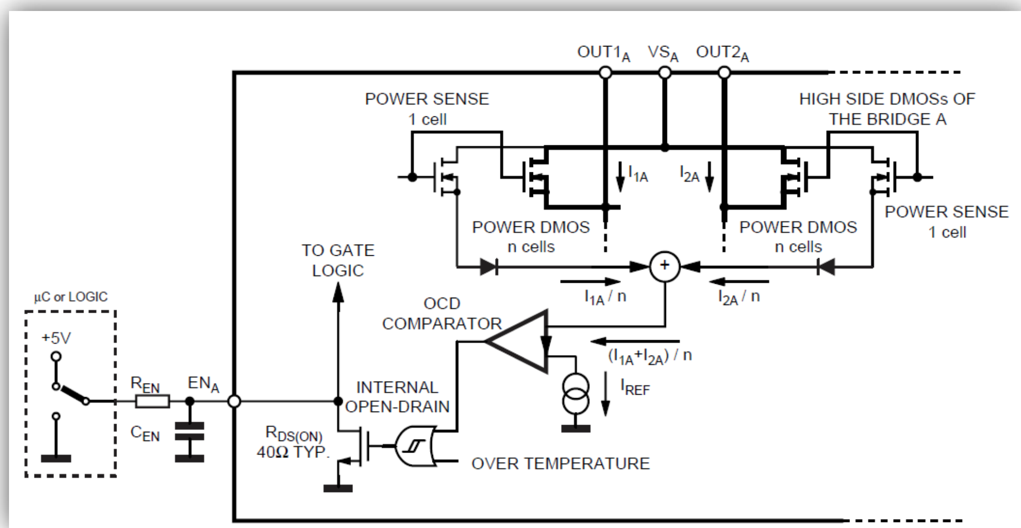


Figure 25 – Internal overcurrent protection simplified schematic

MOS for the upper transistor. This voltage is obtained through an internal oscillator and the component connected to VCP and Vboot pins. One interesting feature is the non dissipative over current protection which provides protection against a short current to ground or between two phases of the bridge. With this internal over current detection, the external current sense resistor normally used and its associated power dissipation are eliminated. A simplified schematic is showed in the Figure 25**.** To implement the over current detection a small but precise fraction of the output current is sensed from each high side power MOS. Since this is a small fraction of the output current there is very little power dissipation. This current is compared with an internal reference and, when the output current in one bridge reaches the detection threshold (typically 5.6A) the relative OCD comparator signals the fault condition. When the fault condition is detected, the EN pin is pulled below the turn off threshold (1.3V typical) by an internal open drain MOS with a pull down capability of 4mA. The delay time before turning off the bridge when an over current has been detected depends only by C19 and C20 (with the 5.6nF the delay is typical 1uS) and the delay time before recovering is given by R24 and R25 together with C19 and respectively C20 (with 100K and 5.6nF is typical of 250uS). The thermal protection for preventing the device destruction in case of junction over temperature. The L6205 has an temperature sensor integrated in the die and the device switch-off when junction temperature reaches 165°C with 15°C hysteresis (typical values).

In this application the driver is used in four half bridge configuration in order to drive three phases of the brushless motor and common of the star connection. This allow to generate the perpendicular magnetic field at occurrence, for the passive control of the asset. The four half bridges are driven by INA1, INA2, INA3 and INA4 signals and the ENABLE_A and ENABLE_B signals enable/disable the driver output. The L6205 driver has two current sensing pins. These pins are used to control the output current and as we can see in the schematic next upper level a current sensing circuit is connected.

5.1.Low Side Current Sensor

This circuit convert the current injected in IIN_NEG pin in a proportional voltage output. It uses MAX4091 rail to rail operational amplifier which amplifies the voltage on the R4 (0.1 ohm) by a factor of 75.

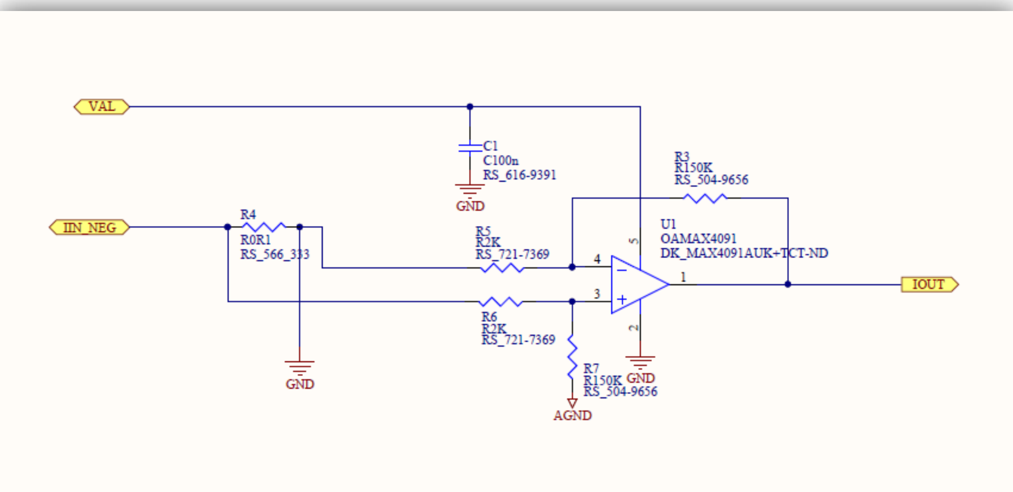


Figure 26 – Low side current sensor schematic

5.2.Harness Connection Diagram

The connections to this module are more complex as there are more than two PWM signals to be used. The intermediate level has also four signals for the connection with the Ultrathin Reaction Wheel module. The diagram is shown in the next figure.

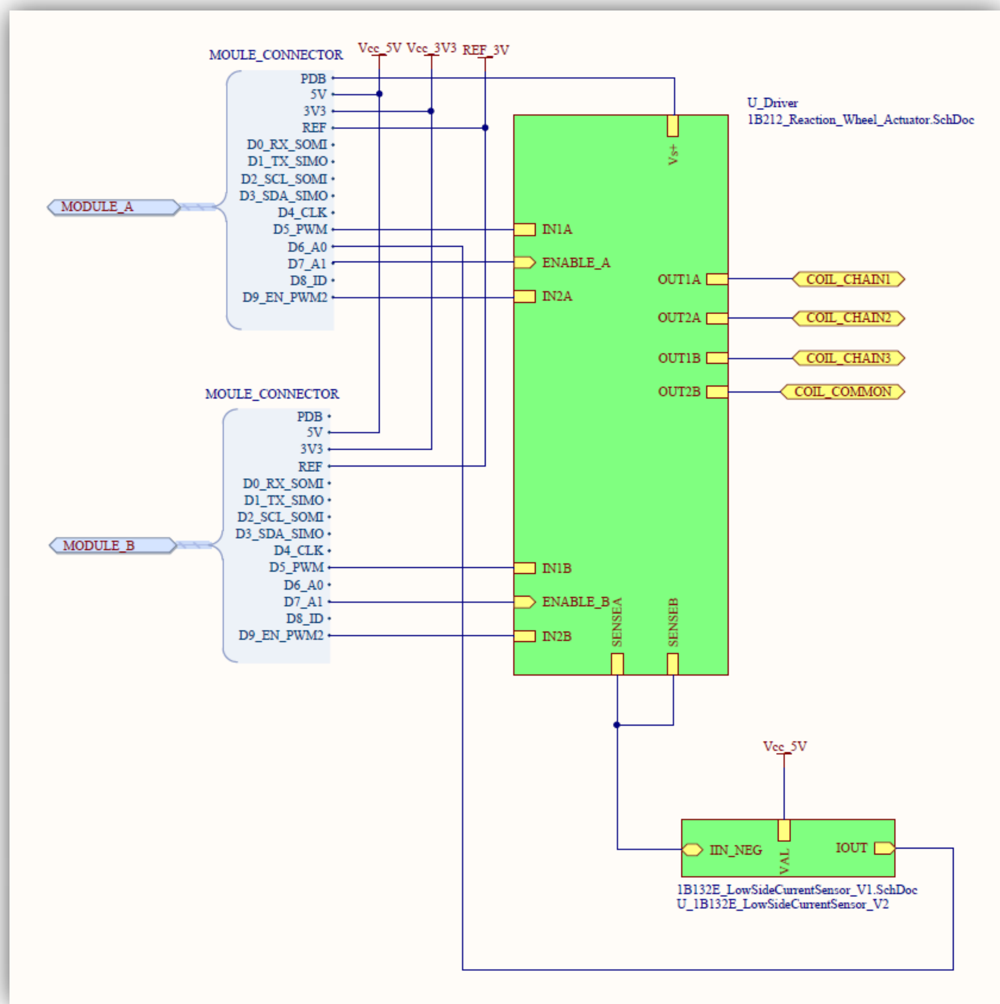


Figure 27 – Reaction wheel actuator Harness connections

6. 1B213_Ultrathin_Reaction_Wheel

The Ultrathin Reaction Wheel circuit is the connection level between the mechanical and the electrical elements. It houses the magnetic coils for the magnetic fields generation and the HALL sensors, which senses the wheel position by detecting if the neodymium magnets stays over them or not.

6.1. AH1888_ZG-7 HALL Sensor

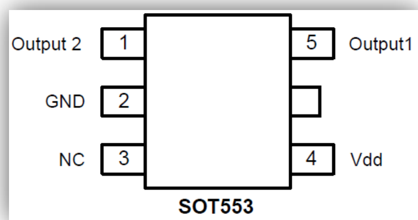


Figure 28 – AH188 pin diagram

The AH1888 sensor is micro power Omni-polar Hall Effect switch IC. It was designed for portable and battery powered equipment. It is based on two sensitive Hall Effect plates and chopper stabilized architecture and provides a reliable solution over the whole operating range. This IC was chosen because of its low power consume as was designed to operate over a supply range of 1.65 to 3.3V and consumes only12.6uW with a supply of 1.8V. As is an Omni-polar sensor it switches on with either south or north when the magnetic flux is larger than operate point. The output is turned off when flux density is lower than release point and remains off if there is no magnetic field. It has two outputs, one pulls low when switched on and the two is inverted.

The sensors are placed to control the step motor to 120° magnetic circuit as the motor is three phases one. In the next figures are presented the three steps and the relative magnetic fields. As we can see in the schematic, due to the space lack, the HALL sensors were not placed in successive positions but each one into a different magnetic groups. Of course respecting the 120° magnetic. The sensing angle of the HALL sensors can be only esteemed and, for this reason, will be experimentally

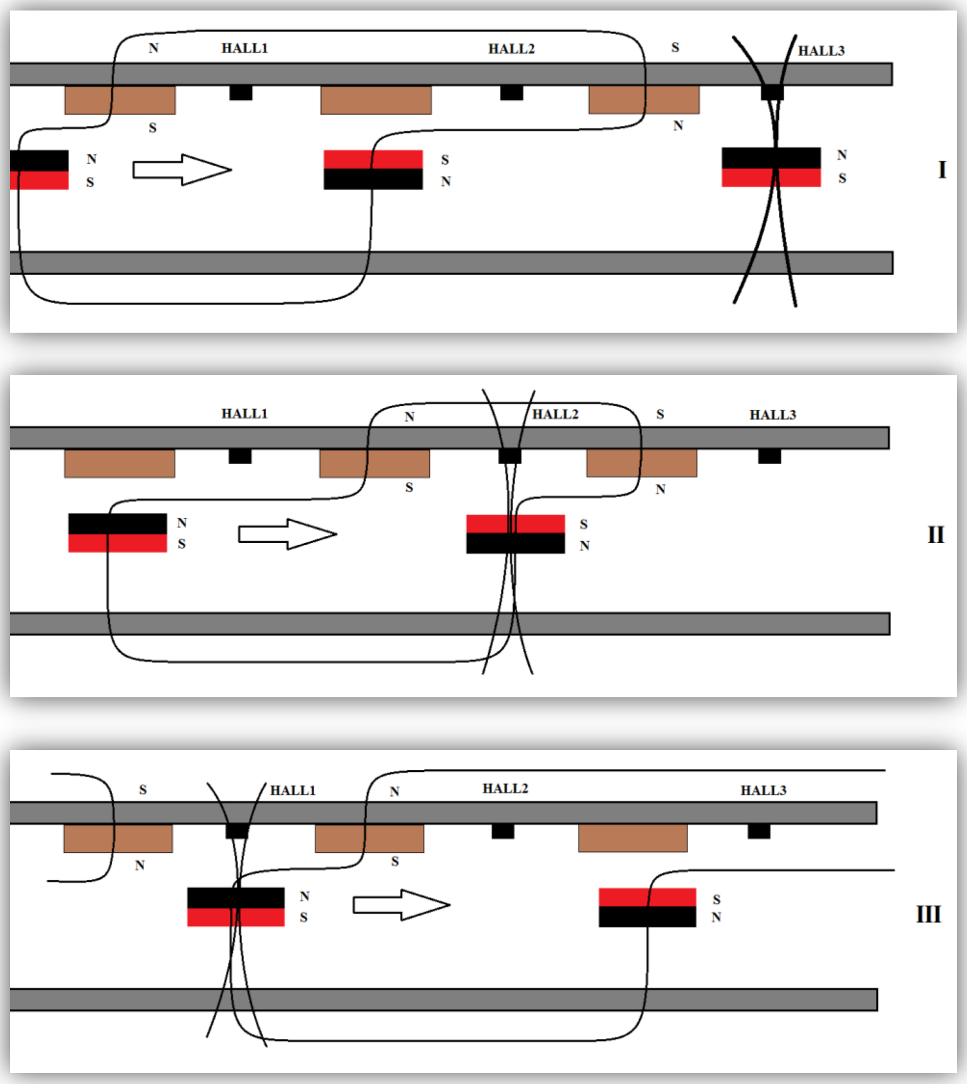


Figure 29 – The three steps and the magnetic fields

determinate and controlled by microcontroller software.

6.2.Magnetic Coils

As the space on the board is reduced the coils were designed to occupy less possible. In order to do that they were wrapped without any support to reduce to minimum their volume. They were made manually using a electric drill to achieve an acceptable precision. Were made two cylindrical aluminium disks (shown in the figure) and an Teflon ring mounted on a threaded pin. The internal ring was made in Teflon to achieve a little elasticity, which later will help to easily extract the coil from it. Moreover the internal ring and the adjacent cylinders surfaces are sprayed with silicone oil every time before starting to wind. Initially all the components are screwed on. Then the left most cylinder is unscrewed from the pin and the wire is blocked between it and the central ring. Once all the system is blocked, it is rotated axially and the wire winds on the central ring. In the meanwhile the wire is constantly

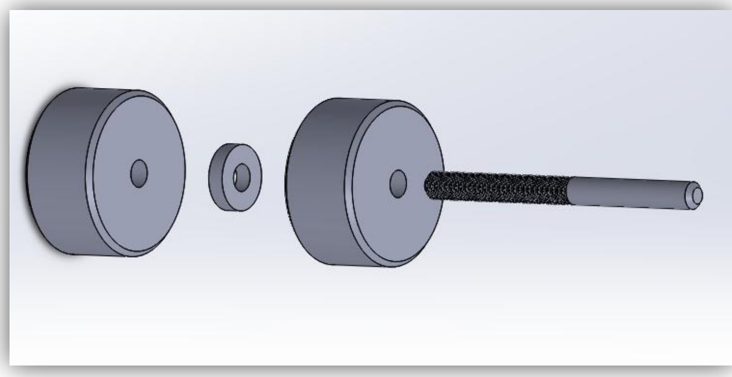


Figure 31 – Coil winding tool

Figure 30 – Winded coil

wet with transparent acrylic lacquer. This gives the necessary mechanical resistance to the coil. Once all the spires were winded and after the lacquer has hardened enough (about 5 minutes) the left most cylinder is unscrewed and the coil extracted. This operation is facilitated by the presence of the silicon oil which doesn't allow to the lacquer to attach to the elements walls. After these operations the coils are left to complete the hardening for one week and then immerged in the same lacquer for one second and left again to harden.

As seen in the previous mechanical description inside the coils are inserted the iron cores and together will be attached to the PCB. There

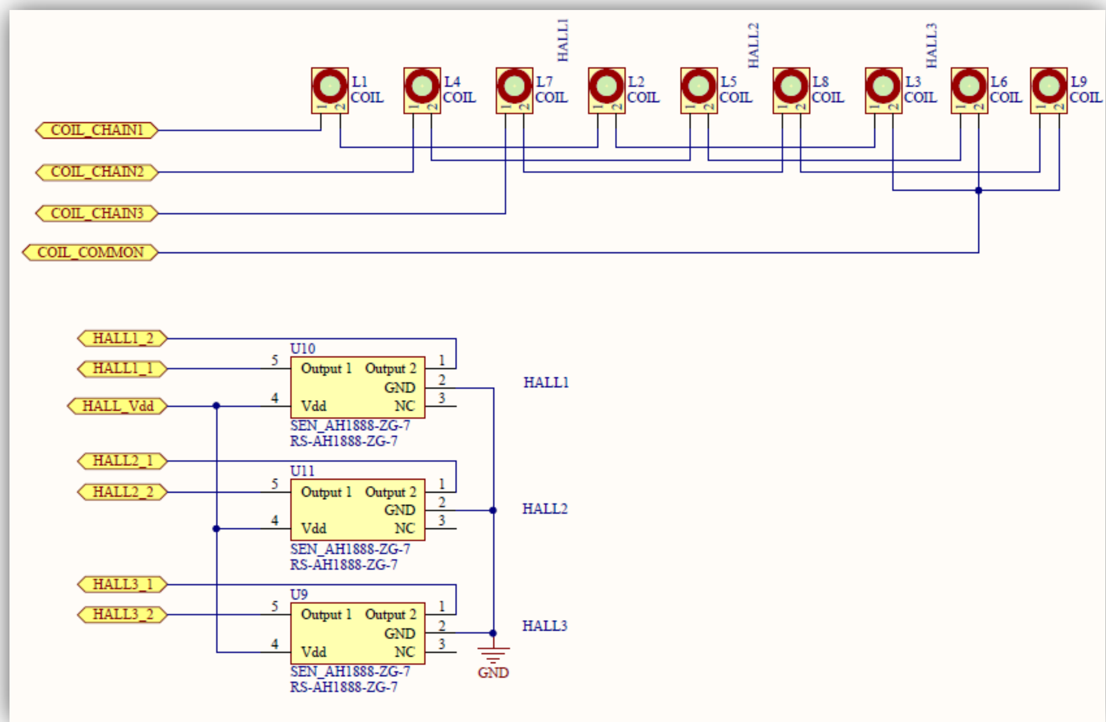


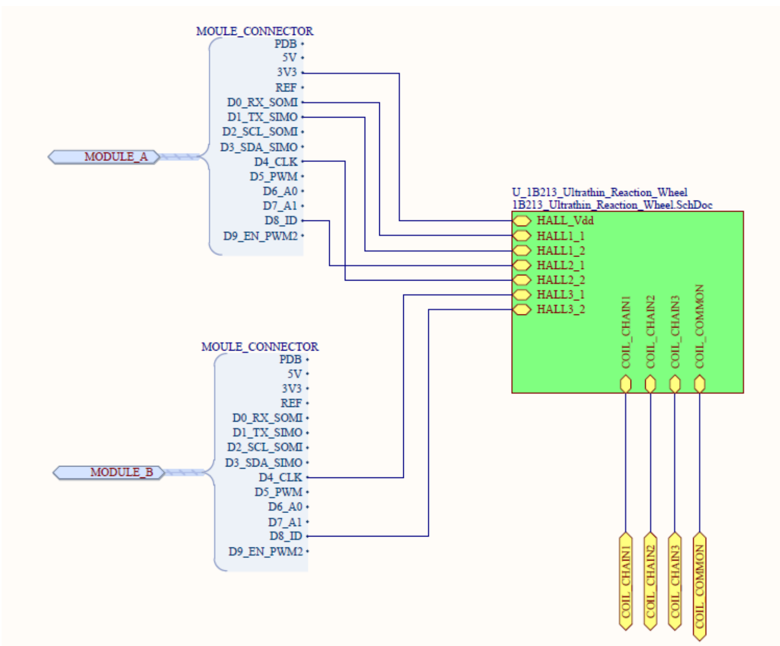
Figure 32 – Ultra thin reaction wheel schematic

are a number of 96 spires and a wire of 0.2mm diameter enamelled copper (0.25mm insulation included) in order to achieve a 2.8ohm. The coils are connected in series to limit the current, in case of continuous conduction of the output, to a maximum of about two Amps for 15 volts supply.

Another important element is the star connections of the coils group with an forth point in the centre of the star. This kind of connection allow, first the rotation of the plate rotor by rotation the magnetic field as normally did into a three phases brushless motor and presented in previous figures. Second, when desired, allows to fill all the coils with the constant current to generate a perpendicular magnetic field, as already mentioned, for the passive control of the asset. As the coils are driven with a PWM signal of course, these two different modes are practically run together more or less powerfully according with the received instructions.

The ultrathin reaction wheel schematic is presented in the Figure 32. To be noted the positions of the HALL sensors in the upper side between coils, as mentioned earlier in this chapter. In the lower side are the electrical connections of the same sensors.

6.3.Harness Connection Diagram



The harness connection diagram is shown in the Figure 33.

Figure 33 – Ultrathin reaction whell Harness connections

7. 1B4222_Tile_processor_4M_V2 Module

This module controls all the other modules on the Inertial Attitude Subsystem. It has an MSP430F5437AIPNR Texas Instruments microcontroller. It is part of TI MSP430 family of ultralow-power microcontrollers. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximize code efficiency. The MSP430F5437AIPNR is configured with three 16-bit timers, a high performance 12-bit analog-to-digital converter, two universal serial communication interfaces, a hardware multiplier, DMA, a real-time clock module with alarm capabilities and 67 pins.

7.1. Communication organisation

The communication on the subsystem is organized in modules. Modules are kind of harness that allow any kind of circuit to be connected. This is possible because was thought to hold various kind of communication types the microcontroller can offer. There are power signals that allows the power supply to be brought to the peripheral modules. The PDB bring the unregulated battery voltage to the Reaction Wheel Actuator Module on this Tile. The regulated 5V and 3.3V are general power supply. Also, every module has two serial communication ports, one I2C and a SPI, two analogical inputs and two PWM outputs.

All the supply voltages are generated externally by the Power Management Tile through Power Supply Connector. The signals are:

- PDB – is the battery unregulated power
- 5V – is 5V stabilized power supply
- 3V3 – is 3.3V stabilized power supply
- REF – is a 3V reference voltage
- D0_RX_SOMI – is SPI Slave Out Master In
- D1_TX_SIMO – is SPI Slave In Master Out
- D2_SCL_SOMI – is I2C clock
- D3_SDA_SIMO – is I2C data
- D4_CLK – is SPI clock input/output
- D5_PWM – is the first PWM microcontroller output
- D6_A0 – is the first analog input
- D7_A1 – is the second analog input
- D8_ID – is one wire communication signal
- D9_EN_PWM2 – is the second PWM microcontroller output

To be noted that every signal correspond to o microcontroller pin which has, in addition of the function just described, an I/O function and, in case the main function is not used, the signal can be used as an I/O. The MSP430F5437 microcontroller allows four modules to be connected. The only resource shared between two modules is the I2C engine. S1, S2, S3, S4 are jumpers that put together the shared signals as the schematic shows. As the microcontroller has only two SPI engines

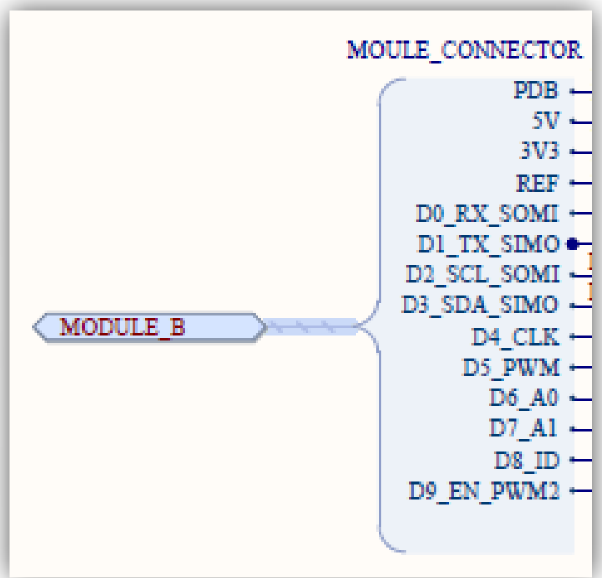


Figure 34 – Harness signals

the other two needed are handled in software, so the relative pins are connected to generic I/O pins.

The JTAG module is used to program on the field the microcontroller. The MSP430 family supports the standard JTAG interface which requires four signals for sending and receiving data. The JTAG signals are shared with general-purpose I/O. The TEST pin is used to enable the JTAG signals. In addition to these signals, the RST/NMI/SBWTDIO is required to interface with MSP430 development tools and device programmers.

The microcontroller clock runs at 4MHz, and the oscillator is driven by the X1 crystal.

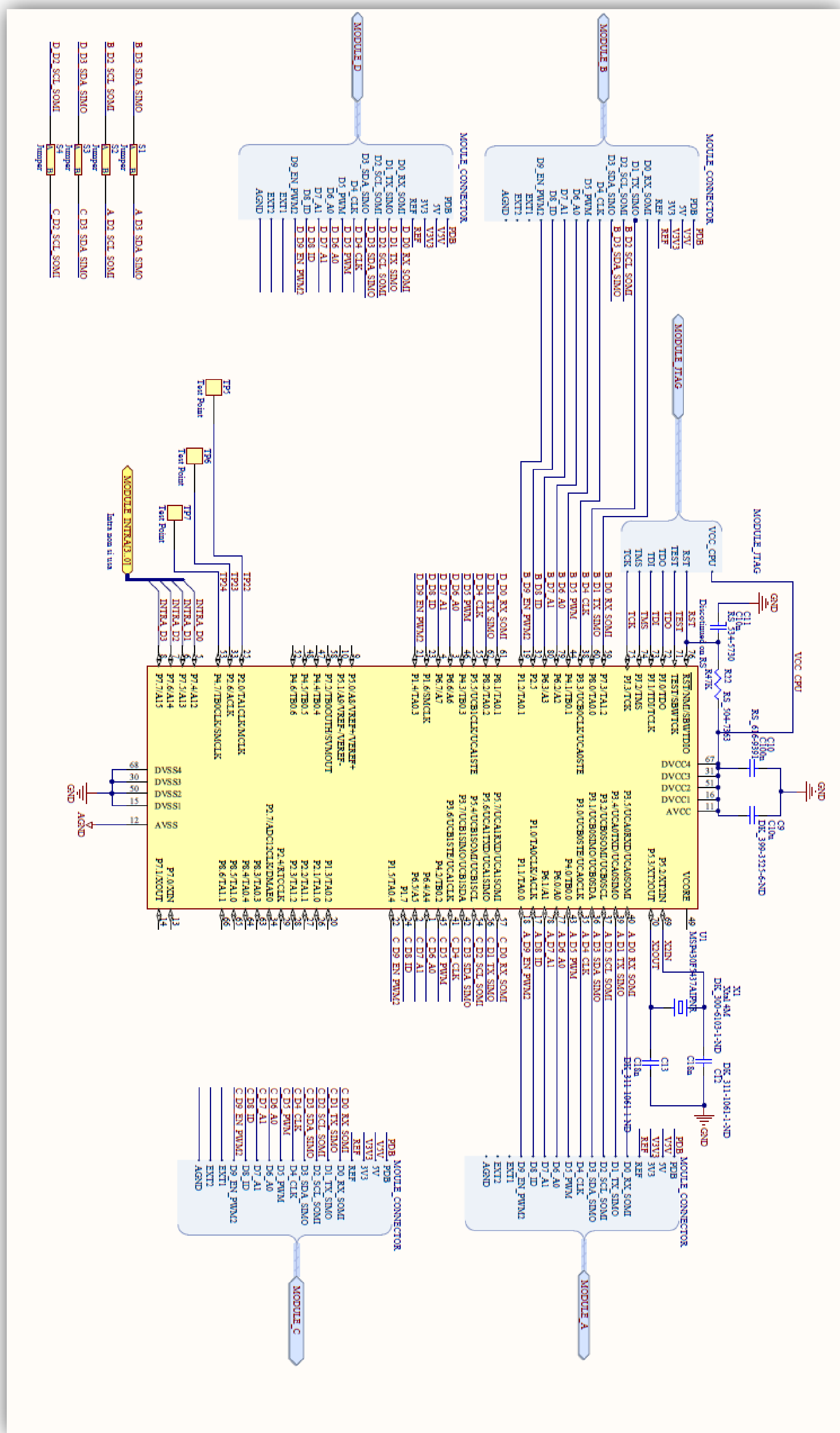


Figure 35 – Tile processor 4M V2 schematic

8. Schematic Design

For this Thesis Altium Designer CAD was chosen. In the Electronic department of Politecnico di Torino the Mentor DX Designer is currently used but it was interesting to test the capabilities of another CAD system, to compare them and evaluate the state of art of these systems. I have chosen Altium Designer as I had already some experience on it and because the supervisor of this thesis was interested in too.

8.1.Altium Design

Is an EDA (electronic design automation) software package for printed circuit board, FPGA and embedded software design. It is developed by Altium Limited of Australia. It was first launched in 1985 as a design tool named Protel and later Autotrax. In 1987 Altium launched the circuit diagram editor named Protel Schematic. In 1998 was launched Protel98 including the Protel Advanced PCB and Protel Advanced Schematic into the same package. Protel99 had introduced the first 3D visualization of the PCB assembly. In 2011 Altium moved to Shanghai in China.

The package is quite complete and have a huge quantity of Schematic and PCB design instruments. Moreover has the possibility to run Delphi, Visual Basic, Java and other scripts which enlarge enormously the number of functions. Due to its 3D capabilities allows to interact with other CAD systems. In this project we used to exchange mechanical data between Altium and SolidWorks. All of them were made by means of step files and done in both direction, to import shapes into Altium from SolidWorks or other STEP files, or to export them from Altium and import into the mechanical project.

Another important skill of Altium is the library management. It allow to design components into a very complete way, create and add 3D shapes, create custom pads, component footprins and maybe the most important it offer a very advanced tool for documentation management. All the documentation can be stored and linked from the component schematic and added into the documentation files (pdf.) . One main difference I observed is that Altium Designer unlike Menthor Graphics doesn't allow bus wire to be casually named. The names of the wire bus are given by adding a number at the name of the bus. As we needed to create connection modules which contains different type of signals, I used a different type of signal called harness. Harness models the real harness cable and allows to incorporate different types of signals and/or busses.

It must be said that Altium has a huge mass of documentation and hundreds of tutorial which made it very easy to understand, even for the most complex functions.

8.2.Schematic organization

The schematic was made into hierarchical manner, using blocks connected through port and harness types. As it's known hierarchical designs allows the reusability of the blocks or substitution of the block without the need to rebuild the entire design as long as the signals between blocks remains the same, saving time. The hierarchical design lets you organize into functional levels of abstraction and detail. This can be useful to hide the lower levels to protect them from being copied, showing only the higher levels as an interconnection between functional blocks. Of course allows the team work as every member of the team can

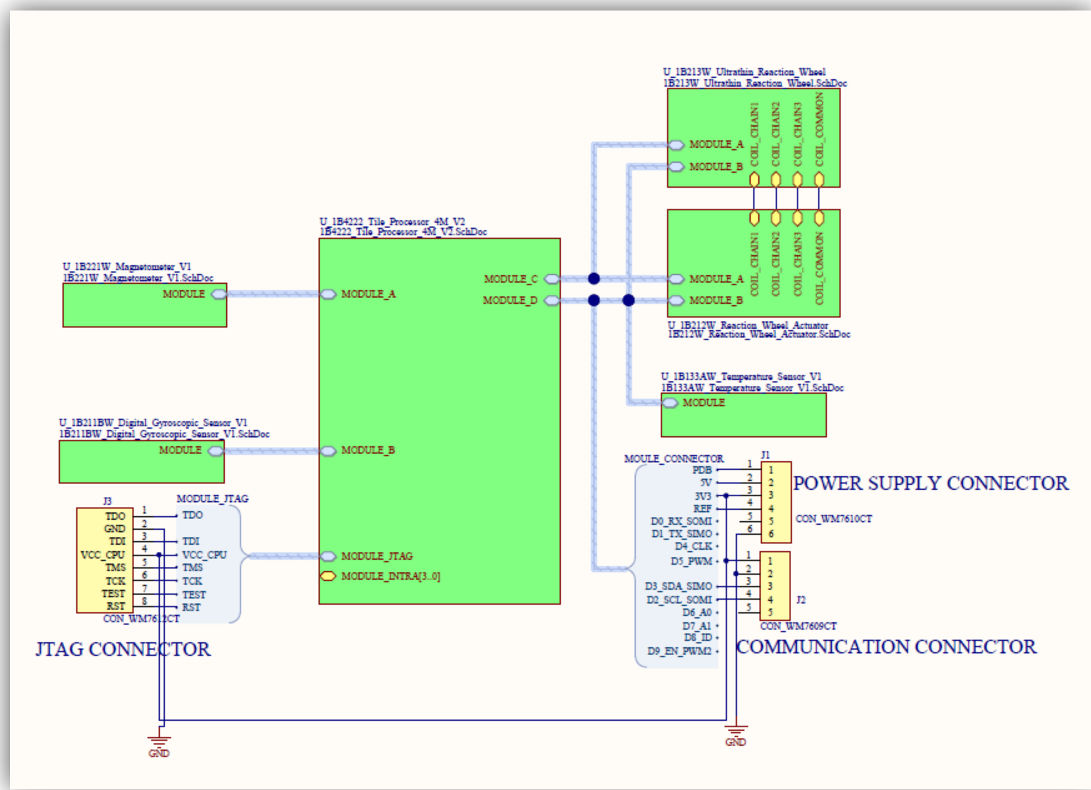


Figure 36 – Inertial Attitude Subsystem highest level

work separately and then, once the design was end, add it as a block to the main design.

In the Figure 36 the highest level of the schematic project is presented. There can be seen the functional blocks connected though the harness connectors. The blocks were presented one by one in the previous chapters. As we already saw between the schematic modules and the highest level there are connection blocks. They were created to increase the readability of the design.

9. PCB design

Altium is a powerful tool for PCB design too. It’s very versatile, can be used for simple to huge complexity designs. It has some important utilities to work in 3D too. This offer a good compatibility with the other CAD software, in our case with SolidWorks.

9.1.ISO10303

The STEP (**ST**andard for the **E**xchange of **P**roduct model data) is an ISO 10303 standard which had some rules for the integration, presentation and exchange of data (through computer). It can be used to transfer data between the following systems: CAD(**C**omputer-**A**ided **D**esign), CAM (**C**omputer-**A**ided **M**anufacturing), CAE (**C**omputer-**A**ided **E**ngineering). Its goal is to clear description, which can be adapted to all informatics systems. Also it allows the storage of the data and the creation of centralized data bases.

Globally there are many systems for design and production used to handle technical data. Every system has its own data system, to the information must be input several times in many system. This results in a increase of the error. Also the American National Institute of Standards and Technology has esteemed that the cost of the incompatibility in the industry have a cost of 90 billion dollars. That’s why engineers around the world had search to converge to a standard. There was many solutions proposed. The most successfully were the data exchange regulations. The first ones, as always happened with all other standards, were national. They were focusing on geometrical data interchange.

Almost all of major CAD/CAM systems have a way to read and write data defined by one of the Application Protocols of STEP. Altium Designer is one of them. It has powerful function to import, convert, generate and export STEP files.

9.2. Board data import

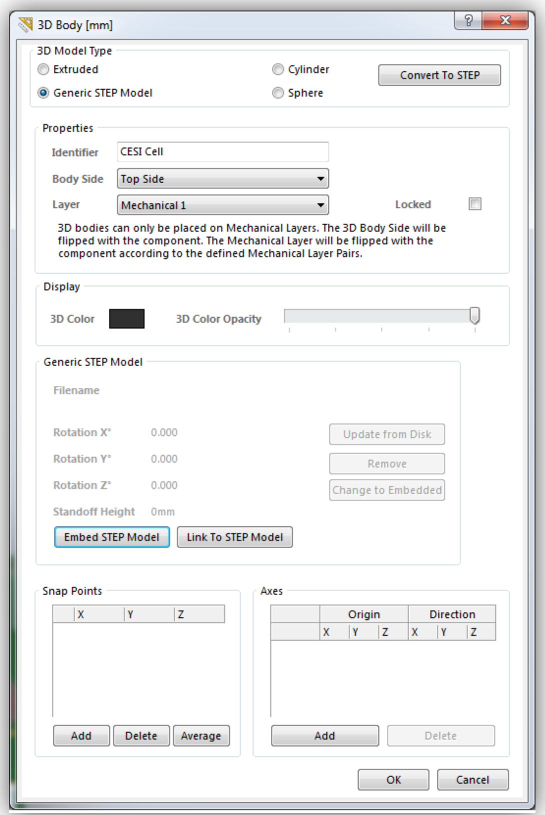


Figure 37 – 3D body insert window

The PCB dimensions and other mechanical elements were given by another colleague which cure the mechanical part of the global project. Thanks to the importing function of the Altium CAD the PCB shape could be imported directly into the PCB project. There are a series of steps to complete the import process.

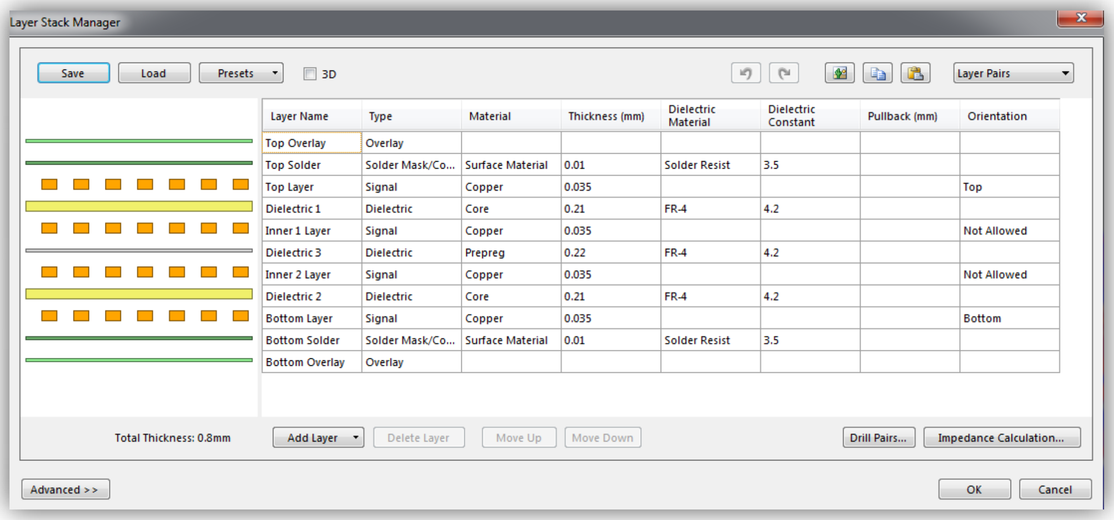
First step is to import STEP object into the PCB design to 3D and then execute command place 3D Body from the Place menu. In the 3D Body window choose Generic STEP Model and then selecting Embed STEP Model browse to were the file in stored and select it. By selecting OK the shape is imported and ready to be placed were is wanted to be.

Second one is to execute the Design/Board/Define from 3D Body command which allows to select the just imported object and which face of this one to be used to copy into the PCB shape. At the end of this process the board shape can be seen in the design.

Finally the imported 3D shape must be deleted.

9.3.Board data export

The step data are useful for the exportation the finite PCB design data to the mechanical design tools. This tools are very evolved and can give the exact dimension of the PCB with the components on and the resulting files to be used to assemble virtually the product in this case the



Layer Name	Type	Material	Thickness (mm)	Dielectric Material	Dielectric Constant	Pullback (mm)	Orientation
Top Overlay	Overlay						
Top Solder	Solder Mask/Co...	Surface Material	0.01	Solder Resist	3.5		
Top Layer	Signal	Copper	0.035				Top
Dielectric 1	Dielectric	Core	0.21	FR-4	4.2		
Inner 1 Layer	Signal	Copper	0.035				Not Allowed
Dielectric 3	Dielectric	Prepreg	0.22	FR-4	4.2		
Inner 2 Layer	Signal	Copper	0.035				Not Allowed
Dielectric 2	Dielectric	Core	0.21	FR-4	4.2		
Bottom Layer	Signal	Copper	0.035				Bottom
Bottom Solder	Solder Mask/Co...	Surface Material	0.01	Solder Resist	3.5		
Bottom Overlay	Overlay						

Figure 38 – Layer stack management window

nanosatellite. In order to do that the environment and the board parameters must be properly set.

First the layer stack must be set. Of course this operation must be done at the start of the design when the board material, number of layers and cooper thickness are defined. The Layer Stack Manager is part of the Design menu in the PCB view and it's shown in the Figure 38. In this window more parameters can be set and impedance calculation formulae modification, but in this project only the base settings are of interest, as we don't have particular signaling condition. There was defined four conductive layers with three FR-4 insulation material.

Once defined these elements, all the component placed and all the tracks routed the PCB can be exported as mechanical object through a STEP file. To do that it occurs only to save the board with name and choose, from the dropdown menu the Export STEP. The next window would ask for exporting parameters. In this case, as we are interested to export all the elements, the default settings can be used. The resulting file can be easily imported in SolidWorks and used as assembling component.

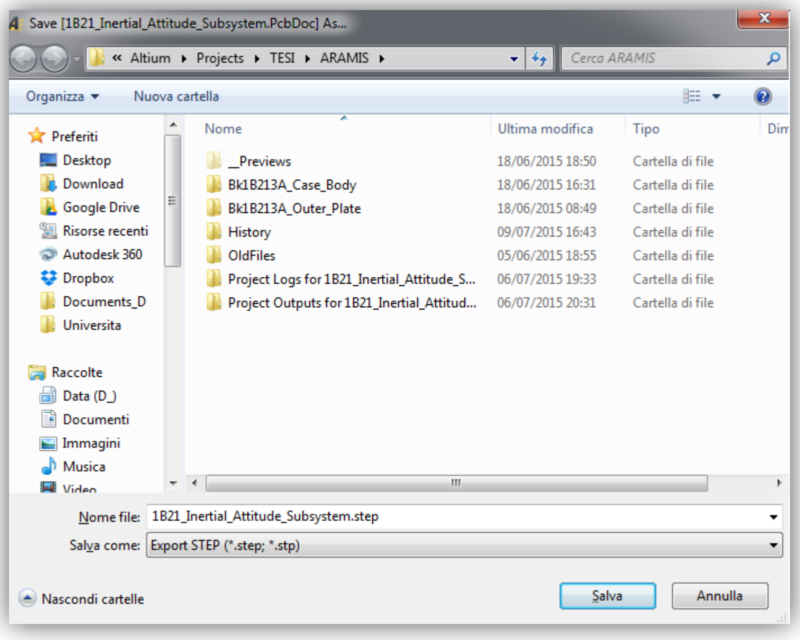


Figure 39 – Step file save window dialog

This file has inside all the components as independent objects mechanically placed on the PCB and for that freely editable. The next figure shows the imported board in SolidWorks.

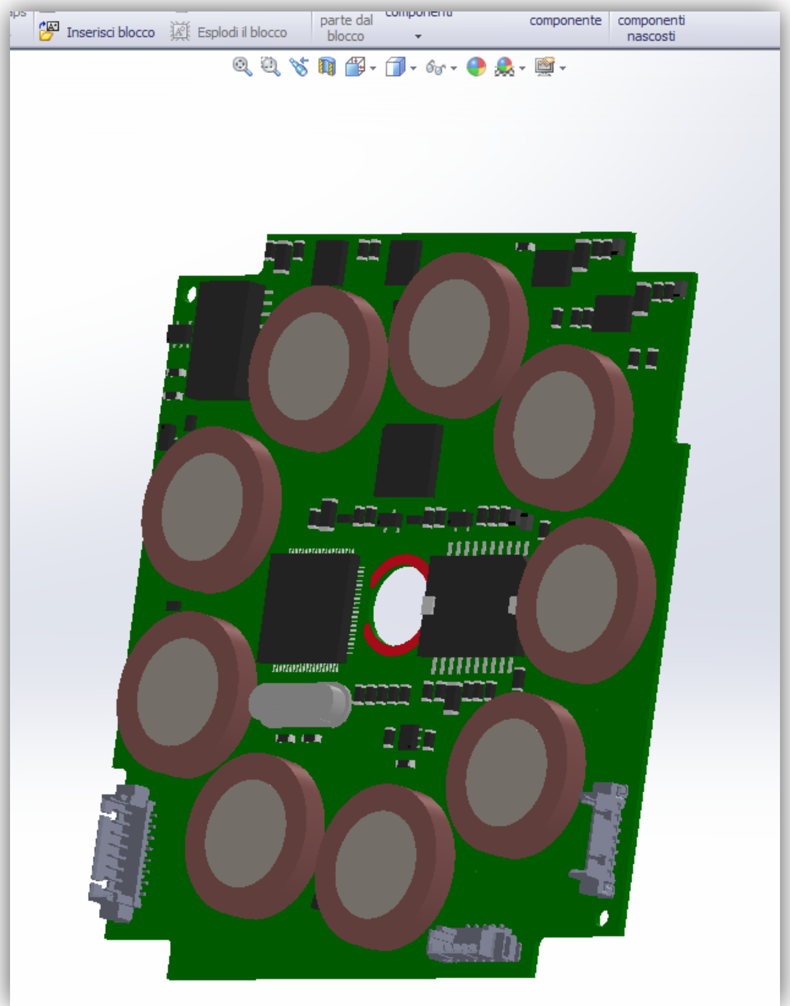


Figure 40 – Expoted PCB from Altium

9.4.Library design

Even if a large part of the schematics of this project was already designed, as there wasn’t found a tool to convert the Menthor DX Designer libraries into Altium, all the components had to be redesigned. To be mentioned that all the conversion tools met so far gives an partial solution of the problem. This because often they are limited to converting shapes and footprints, but not accessories elements as documentation links, 3D bodies and other tool based elements.

The library was designed following the main ideas of components annotation in use in the electronic lab. All the components have own schematic drawings and footprints were created for every type of component according with the datasheet specification. The additional data were added following the Electronic Department Warehouse organization, including the supplier link and component code and the datasheet link.

9.5.PCB Design

The PCB was designed using four layers, due to the high amount of the components and the high dimension of the coils with respect of the reduced space available, in FR-4 (Flame Retardant), an self-extinguishing epoxy-resin bound fiberglass. An particular attention was given to create a ground plain not only for electrical considerations but to allow a continuous metalized surface, as already mentioned, in order obtain an cooling surface for the Reaction Wheel Actuator driver as large as possible. Another reason which determinate the GND plane creation was to avoid accidental shortcuts between the rotating mechanical wheel and one of the tracks, during the experimental phases. plane creation was to avoid accidental shortcuts between the rotating mechanical wheel and one of the tracks, during the experimental phases. In fact, the not GND tracks on the GND plane were reduced to minimum, to only those which could not be eliminated. The GND plane is shown in the figure 41.

Under the coils I didn't placed any track in order to avoid self induced currents and compromise the wheel rotating forces and, on the

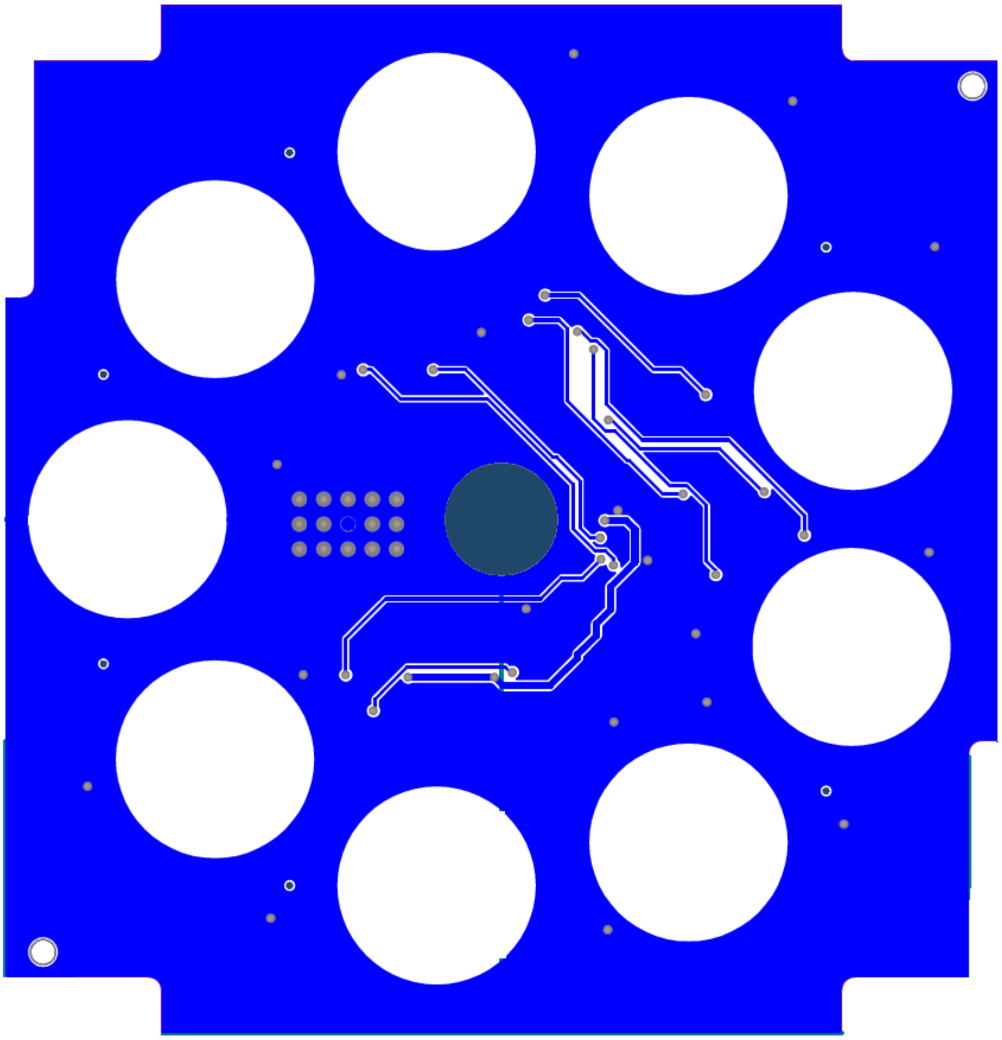


Figure 41 – PCB Bottom Layer view

other hand, to induce false signals into the other components tracks. This can be seen clearly on the bottom layer. In the next figures top layer and all layers prints are shown.

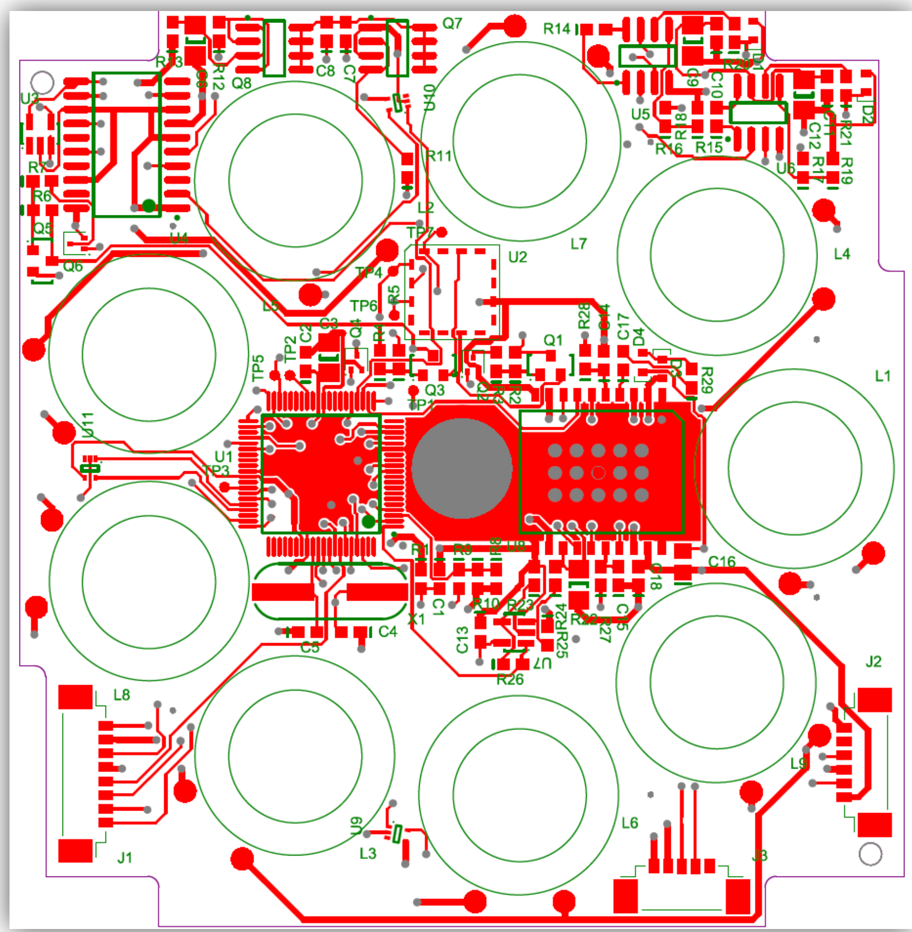


Figure 42- PCB Top Layer view

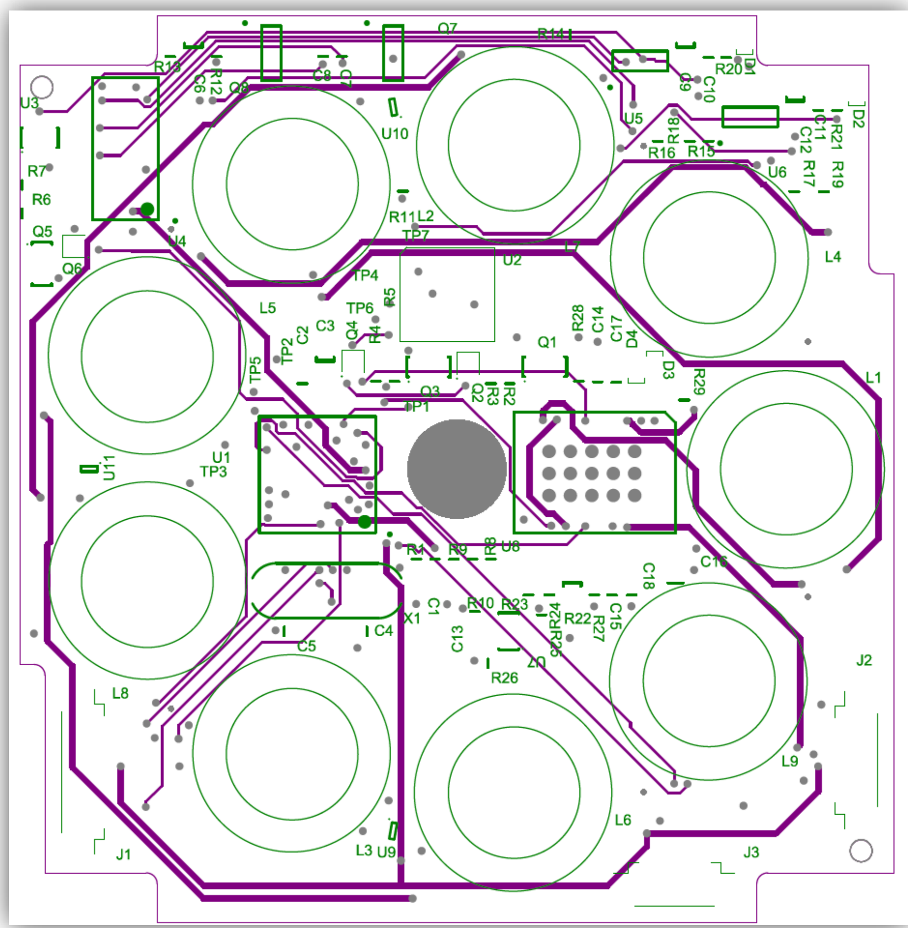


Figure 43 – PCB Inner 1 Layer view

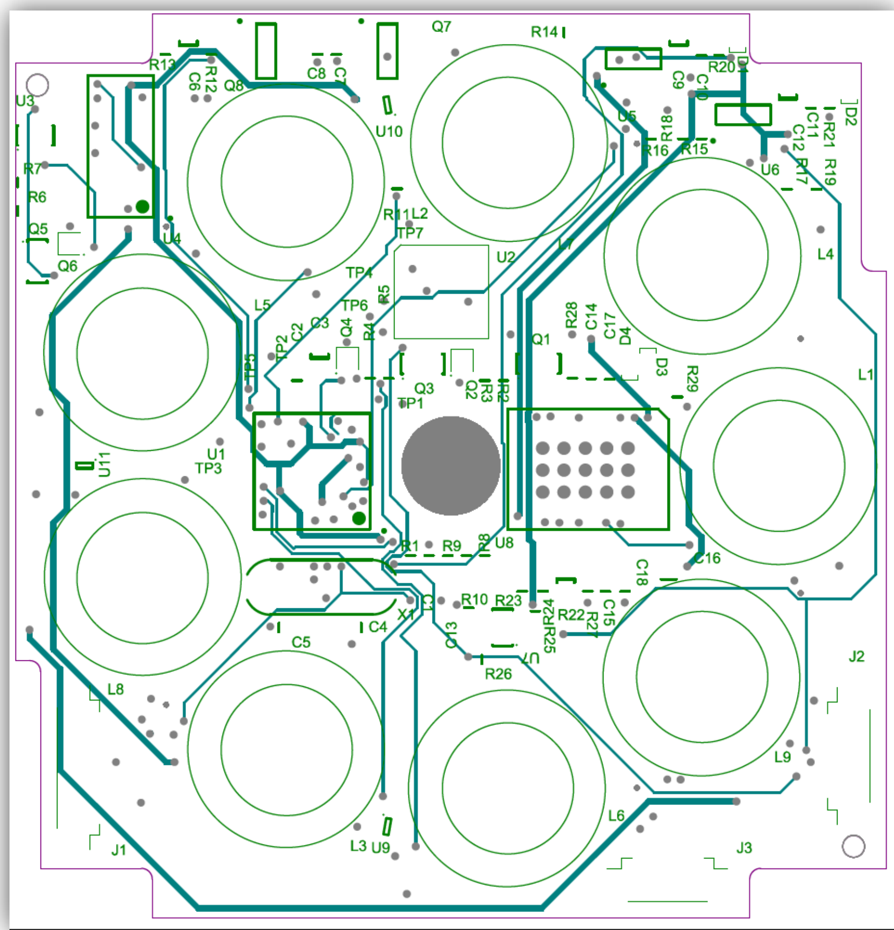


Figure 44 – PCB Inner 2 Layer View

10. Conclusions

The work on this thesis allowed me to practice the notions I had acquired during the course. It has given me the opportunity to face the practical side of the Electronic Engineer work. Moreover it let me enter into the space science, and learn about the nano-satellite today's technology. The interaction with the others students involved into the Aramis project had given me a real view about the criticality should be solved during an interdisciplinary project.

Most of the schematics were already present into this project as it is an successive version of an older project and made me adapt the added element to present ones. Also, redesigning them I had to study their specifications and understand how they are working in order to verify the schematic design correctness, the signals compatibility and the covered functions from the microcontroller.

All this work made me pass through all the steps necessary to develop a prototype, from the requirements analysis, schematic design, PCB design, to the supplier search and ordering procedure.

Another important profit in doing this thesis was learning the use of the Altium Designer, in very detailed manner, in what concern the hierarchical schematic design and the automatic and manual procedures of the PCB Design.

First the project requirements were studied, the physical phenomena involved and the elements already designed. Then remained modules have been designed, the components searched on the market and controlled if they meet the needs. This implied every component to be redesigned into all its aspects, graphical, documentation, footprint and 3D representation. Altium was able to give the instruments to do all the job for most of the elements but, in few cases, I needed to use SolidWorks for particular mechanical shape designs.

After this the PCB was designed following the indications of the mechanical designers. This was necessary to allow the PCB to be inserted into the dedicated space inside of the nano-satellite.

The successive steps should be the PCB ordering from the chosen manufacturer, order the components, mount them manually on the board and create the prototype. The very next last step should be microcontroller firmware design for the peripheral and data bus communication and data processing. This last steps haven't been possible to follow due to the missing order of the PCB to the manufacturer.

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