PROJECT REPORT

Intelligent solar generator for Cubesat

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ACKNOWLEDGMENTS

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Finally, thanks to M. JACOB and M. LANGELLA for their help and educational support.

SUMMARY

INTRODUCTION

NiceCube is a nanosatellite project that will allow the Lab Lagrange to do technological demonstrations by performing optical communications between earth and the satellite.

A satellite can be powered by different types of generators. First, solar energy is often the most exploited, by putting solar panels. This is how NiceCube will power energy, but we could also use nuclear energy or batteries, which would create different problems such as security problems for RTG (Radioisotope Thermoelectric Generator), or lifetime ones for the batteries.

Our mission is to conceive from scratch a solar panel that will be able to power the whole satellite. It will be used as a solar generator, but also will be able to give us useful real-time information about the satellite. Indeed, we will need to measure the current and voltage output of the solar panel but also it’s temperature, the sun location, and the earth horizon orientation, to know the satellite orientation. Moreover, the solar cells will need to be electrically protected and individually deactivated if damaged.

SPECIFICATIONS

OBJECTIVES

This project is about developing and testing a functional solution for a solar panel. The solar panel will be integrated into the surface of the NICE^{cube}.

The panel needs to know in real-time the state of the solar cells and should be able to locate the satellite relative to the earth and the sun.

To do that, the panel needs to embed an ultra-low-power microcontroller connected to a bunch of sensors.

The panel will be separated into two main parts: the solar generator encompassing the solar cells and power electronics, and the control part encompassing the microcontroller and sensor environment.

SOLUTIONS

SENSORS

SOLAR SENSOR

We need to sense the satellite's orientation compared to the sun. Knowing the required angle precision between the satellite and the antenna are 10°, the sensor needs a 3° precision in the worst case. The technology used is a masked one-dimensional PSD (depth of the mask is 1.5mm), so the corresponding length precision of the diode is 78um maximum.

The S3274-05 model gets a 35um maximum precision, which is under the specification. This PSD needs an under 300um wide light ray. The R1DS3N mask got a 10um wide strip line.

MAGNETOMETER

We need to measure the satellite's inclination compared to the earth's surface. We will use a magnetometer to sense the earth's magnetic field.

As the solar sensor, we need a 3° precision in the worst case.

Knowing the earth's magnetic field of 05Gauss, we found a maximum error of 26mGauss.

The LSM9DS1’s precision is 0.14mGauss for 4Gauss magnetic fields and under. This corresponds to a 0.02° error. We are well under the specifications.

HORIZON SENSOR

We need another vector to angle the satellite compared to the earth, so we need to use a horizon sensor. Just like the other sensor, this one needs a 3° precision in the worst case.

The MLX90641 is a 16x12 pixel thermal camera with a field of view of 110°, giving us a 9°/pixel precision. It means we have a 2.6° precision in the camera.

Although we can use this camera, a further test needs to be done to see if we are not under the 3° error. If that’s the case, we will use the more power costly 32x24 pixels camera.

TEMPERATURE SENSOR

This is needed to control the panel’s temperature. We can put a sensor in the center of the panel and another sensor opposite to the microcontroller to check if there is no overheating. There is no need for a big precision, as we want to measure big temperature variation. A 1°C precision is enough for us. The PCT2075 got a 1°C precision.

VOLTMETER

We need to measure the volt variation (drop and pic) to check the state of our solar cells. We will use the analog pin of our micro-controller, with a max voltage input of 3.3V. To get maximum precision over the measurement, we take the voltage reference at 1.15V.

To make a voltage reference, we need to use a Zener Diode. As there is no Diode with a Zener voltage under 1.8V, we take 1.8V as a reference. With this, we can detect a voltage drop under 2V, which is enough to detect one solar cell’s failure.

AMPEREMETER

To complement the voltage measurement, we need a current variation measurement. We will use resistors in series with the solar cells and measure the resulting voltage. As the solar cells current is around 14mA, the analog pin of our microcontroller will be enough to detect a current drop.

MICROCONTROLLER

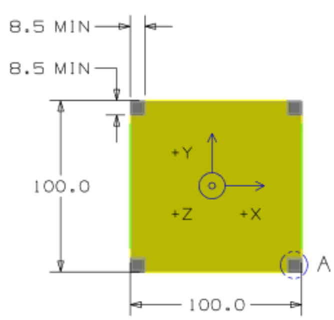
The microcontroller needs to manage the sensor network and control the well-being of the solar cells. It needs to embed the I²C protocol because each sensor uses this communication protocol. It must have at least 6 analog pins for current and voltage measurements. It also needs to be optimized for calculations.

There are some non-quantitative requirements on energy consumption, reliability, and magnetism protection.

The MSP430FR59XX family responds to all the requirements.

SOLAR CELLS

The system needs to be compatible with the CubeSat, meaning a 10x10cm² surface with truncated angles.



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The yellow plane above is the available space for our system.

We will use TrisolX solar cells.

Each one is approximately 2.6cm². We use a 5mm margin around each cell. Considering the cells will be using 60% of the total panel surface, we can place a total of 12 cells onto our panel.

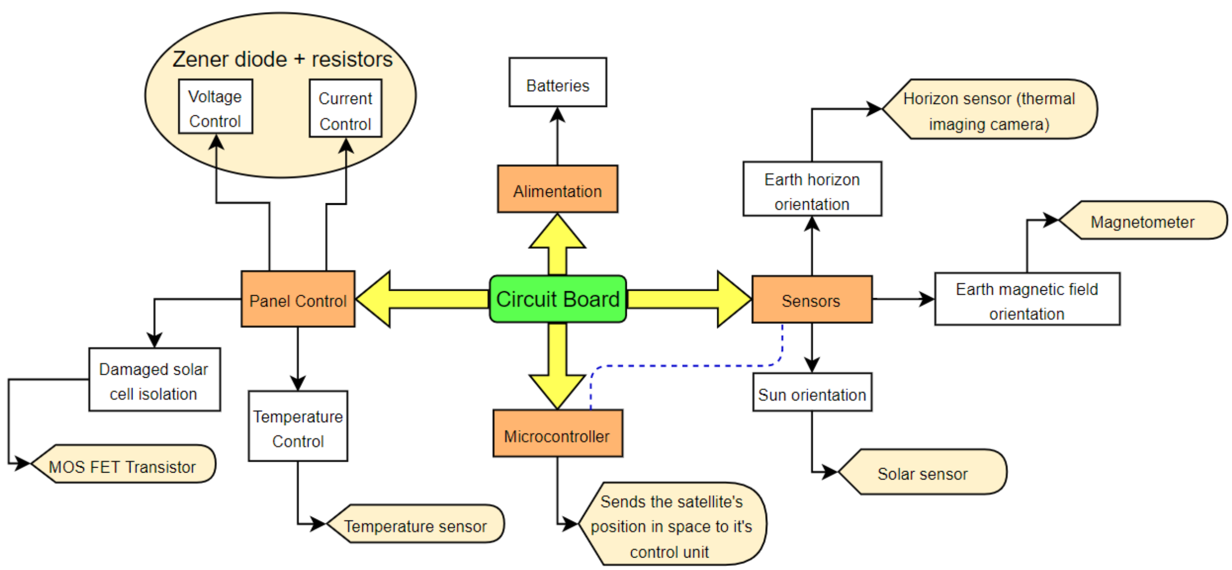
After testing, the ratio will be adjusted and more panels will be added, but for the prototype, this ratio will be enough.

The batteries' control system is GOMSpace, nanopower p31u. As stated in the datasheet, we need to deliver between 4.2V and 8.5V. Knowing the cells are 2.33V max each, we will put 4 cells in series to deliver the correct voltage. As we can use 12 cells, we will make a 4x3 cell matrix.

To protect each line, we put a Schottky diode in series with the 4 cells.

ARCHITECTURE

BLOCK DIAGRAM



DESCRIPTION

The circuit board will be organized into four different parts. Every part has its own purpose and they are all interacting with each other.

THE SOLAR PANEL

The first and most important part of our project is the solar panel. Indeed, it is the heart of our mission. The panel will be “intelligent”, meaning it will be able to self-maintain itself. In fact, we will do voltage and current measures to check if the cells are furnishing what we need to power the whole satellite for example, or if one or several cells need to be disconnected if they are no longer working so that the circuit isn’t damaged. Moreover, we will monitor the temperature of the cells with temperature sensors.

THE SENSORS

This is the second most important part of our project. It includes three different captors. They will be able to calculate the satellite’s orientation in space, thanks to three vectors calculated with the orientation to the sun, to the earth’s horizon, and to the earth’s magnetic field. As mentioned previously, there will also be a temperature sensor and a multimeter.

THE MICROCONTROLLER

The microcontroller’s duty is to process all the data sent by the sensors and send them to the central unit of the nanosatellite.

THE ALIMENTATION

This part would be the batteries, charged by our solar panel. However, we are not in charge of the batteries part. We just need to supply enough power to be able to charge them.

SOFTWARE

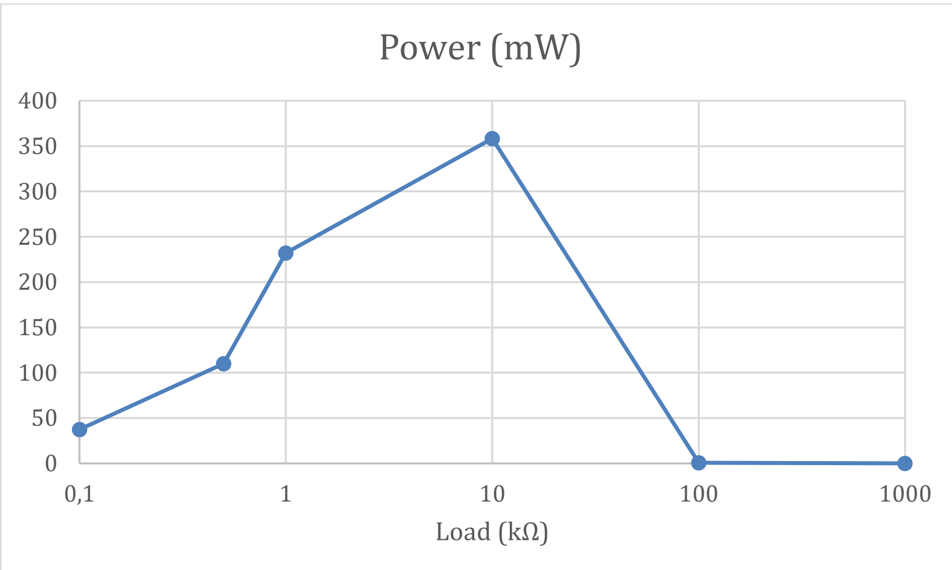
Expliquer la sequence d’opérations faite par le microcontrôleur : dans quel ordre il reveille les differents capteurs, combien de temps entre chaque acquisition, combien de temps il reste en mode « ultra-low power », comment il traite les données, etc…

DEVELOPMENT

SOLAR CELLS

POWER CHARACTERISTIC

We need to know the best load to put in input off the solar bank to maximize the power output. To do that, we try different load and measure voltage and current output. We computed the results into the following curve.



We can see the optimum load of 10k can provide us with 350mW.

VOLTAGE REFERENCE

At first, we tried to use a Zener diode to provide constant output voltage, but as explained in Prototype 1 category, the result was not satisfactory.

We chose the **MCP1501**. It provides a constant **1.25V** as reference, with 0.08% of precision. It is possible to shut down the device using the SHDN pin, so we can power consumption.

MICROCONTROLLER AND SENSORS INTERFACING

The MSP430G2553 must gather and analyze data from the satellite's environment. All the sensors we are using communicate their data through I2C busses. The

MSP430G2553 has a built-in I2C hardware module that we can use. To develop, calibrate, and prototype our system, we used the MSP430 LaunchPad from Texas Instruments. The Launch pad is a development board that allows us to easily program our MSP430G2553 microcontroller.

CODE DEVELOPMENT

To program the MSP430G2553 and use its hardware modules we used the Energia IDE. Energia is a modified version of the Arduino IDE that comes with custom libraries for specific use with development boards from Texas Instruments, such as our MSP430 Launchpad. This is useful for prototyping because we have access to the standard Arduino libraries that we are used to using. The program is written in a simplified C++ language, very similar to the Arduino syntax.

To establish the I2C communication we use the Wire library from the standard Arduino libraries. We first developed one code per sensor for independent testing and calibration. (We then merged the code… à remplir quand on l'aura fait)

We also need to use the ultra-low power capabilities of the MSP430G2553. This requires a lower level of access than what Energia provides us. We used the Code Composer Studio (CCS) IDE developed by Texas Instruments for their LaunchPad. With CCS we program the microcontroller at Register-Transfer Level using C code. We can also import code made with Energia into CCS. This allowed us to first develop a prototype using a higher-level language, and then modify it at a lower level for fine-tuning.

CALIBRATION

Each of our sensor might suffer from a bias, or a distortion, in the measurements. This can happen due to an imprecision during the manufacturing, or a physical phenomenon. This bias is generally small, but we need to take it into account nonetheless, which means we need to be able to measure it. In this section we explain the protocols used to calibrate our sensors.

Ajouter des schemas dans cette partie

LM75A – TEMPERATURE SENSOR

To calibrate the LM75A, we need to measure the temperature of an object whose temperature is known to us. We can then compare the theoretical value to the measured value. The easiest example of such an object is water that is changing phase. We know that the temperature of water stays constant during the transition between two states. We also know the temperatures at which water changes phases. So if we measure the temperature of water during a phase transition we should get a consistent result. We decide to measure the temperature of ice cubes that are melting.

We assume the atmospheric pressure during the measurements is equal to 1 bar, which means the temperature of water is 0°C when melting.

Measured temperature of the ice-water mixture: 0.25°C with 0.125°C precision

We determined that our LM75A sensor has a static offset of +0.25°C

LSM9DS1 – MAGNETOMETER

The magnetometer measures the intensity of the magnetic field along 3 directional axes. We can assume that the axes are aligned as they should be, meaning that they form an orthogonal 3D base. With that assumption, we only need to measure the static offset on each axis.

To measure the offset on one axis, a simple test consists of finding the minimum and maximum values on the axis. The offset is the mean value of those extrema. In order to calibrate the LSM9DS1, we need to measure the extrema on each axis.

The code used to calibrate the sensor performs continuous measurements of the magnetic field on each axis and displays the maximum and minimum values on each axis so far. It also displays the resulting offset of those measurements. While this code runs we rotate the sensor in every direction until the offset readings are stable.

We got the following values:

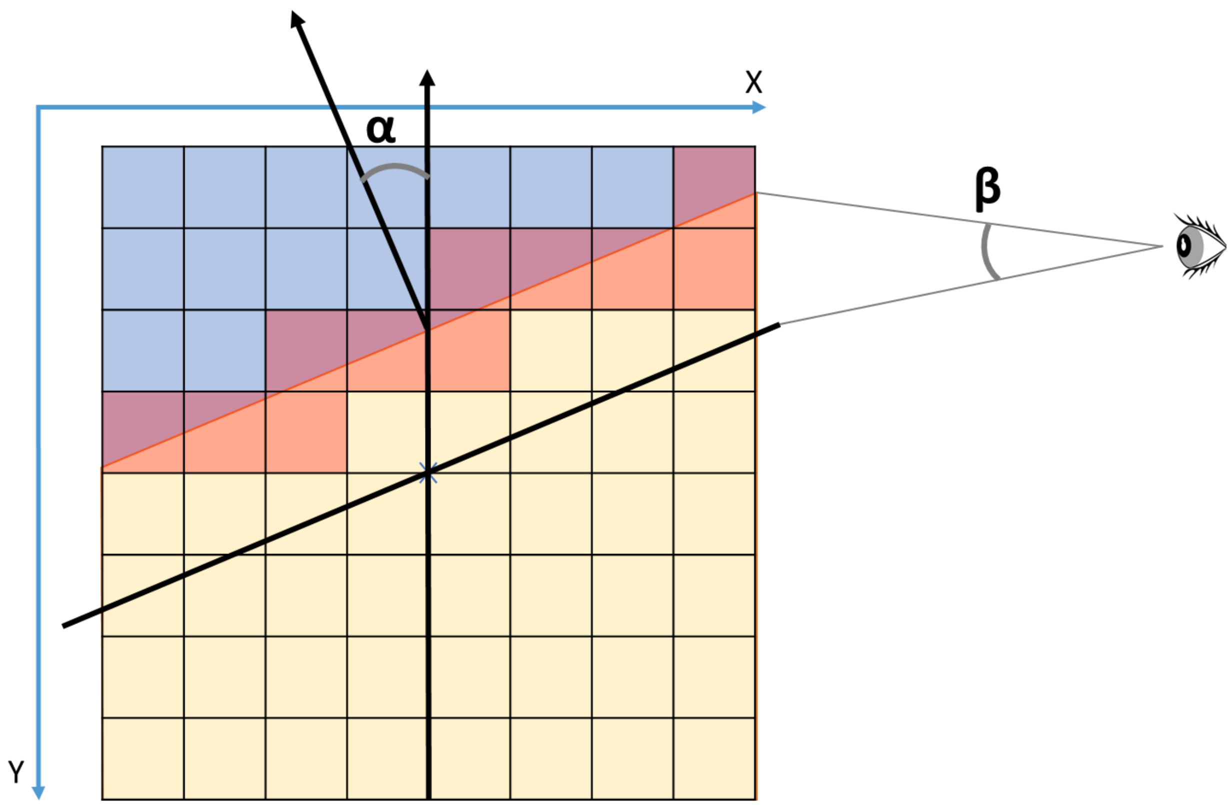
X offset: +122.5 mGauss
Y offset: +143.36 mGauss
Z offset: +56.35 mGauss

AMG88XX THERMAL CAMERA

We need to extrapolate the position of the satellite with the output of the camera, which is an 8x8 pixel array. To get the horizon, we made a linear regression using the matrix formula $(INDEX^T * INDEX)^{-1} * INDEX^T * V$, with $V = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \end{pmatrix}$, the matrix filled with the pixel position of detected horizon, and $INDEX = \begin{pmatrix} 1 & 1 \\ 2 & 1 \\ \vdots & \vdots \end{pmatrix}$ with the same length of V.

We get the matrix $C = \binom{a}{b}$, with a, b the coefficients of the linear expression of the horizon $y = a * x + b$.

We then need to calculate corresponding angles of the satellite position compared to the horizon. We choose the angles α and β as described in the following schematic.



From our linear expression, we can deduce α and β with the following formula in the XY plane (3.5 corresponds to the center of the screen).

$$\alpha_{xy} = \tan^{-1}\left(\frac{-1}{a}\right)$$

$$\beta_{xy} = \frac{\pi}{6} * \frac{1}{3.5} * \frac{|3.5(1-a) - b|}{\sqrt{a^2+1}}$$

And in the YX plane.

$$\alpha_{yx} = \frac{\pi}{2} - \tan^{-1}\left(\frac{-1}{a}\right)$$

$$\beta_{yx} = \frac{\pi}{6} * \frac{1}{3.5} * \frac{|3.5(1-a) - b|}{\sqrt{a^2+1}}$$

We did the operation in both planes as, depending of the orientation of the satellite, one projection can be more precise than the other (we have more points in the matrix). We then need to compute the average value.

$$\alpha = \frac{\alpha_{yx} * nbpoints_{yx} + \alpha_{xy} * nbpoints_{xy}}{nbpoints_{yx} + nbpoints_{xy}}$$

$$\beta = \frac{\beta_{yx} * nbpoints_{yx} + \beta_{xy} * nbpoints_{xy}}{nbpoints_{yx} + nbpoints_{xy}}$$

As you can see, we need to guard against limits values, such as a=0. We can explicitly calculate those values when we do the code implementation.

MLX90641 THERMAL CAMERA

MERGE INTO PROTOTYPE

PROTOTYPE 1

The first prototype aims at testing only some functionalities of the solar panel.

We want to use this prototype to establish f(I) = V of one solar bank, check if the cut-of circuit of the bank works and if V_{ref} is stable enough.

See Annex, Protype 1 to check out the schematics and layout.

This prototype highlighted that the polarity of our cells was inverted, so the tension was negative.

The reference voltage was not stable enough with wide variation of input voltage, with around 30% of deviation. We revised the schematic in Prototype 2 to integrate a dedicated reference circuit, explained in the Voltage Reference part.

The footprint of the solar cells was not well adapted and causes some cells to break, so we revised the footprint as seen in the layout of prototype 2.

PROTOTYPE 2

We want to test the I2C bus and the working of our sensors.

PROTOTYPING WITH ALL THE SENSORS

ANNEXE

ESTIMATED BUDGET

We were able to estimate the budget by taking into account all of the factors as if we really started this project from scratch. First, we estimated our salaries as engineers and our tutor's salary. It gave us a total of 6 007€.

Salaire équipe ingénieur débutant	
Salaire moyen ingénieur (brut) / mois	3,200€
Charges patronales	42%
Total/mois	4,544€
Total/heure	34€
Total sur année (pour projet) par personne	2,045€
Total sur année (pour projet)	4,090€

Salaire encadrant chercheur	
Salaire brut /mois	3,000€
Charges patronales	42%
Total /mois	4,260€
Total/heure	32€
Total sur année (pour projet)	1,917€
Total des totaux	6,007€

			nb de journées
Nombre de séances	Semestre 1	8	4
	Semestre 2	6	3
total des jours de travail			7

Then, we estimated the travel costs for us and our project tutor, which led us to a total of 1 299.96€.

Chevaux fiscaux 2019	Prix /km
5	0.543
6	0.568
7	0.595

	Barème fiscal		
	Etudiants		Encadrant
	Camille	Romain	
Aller/Retour	18.6304	57.12€	32.58€
Total (12 séances)	223.5648	685.44€	390.96€
Total des totaux	1,299.96€		

After that, we had to calculate the costs of the material that we are going to buy and rent, for a total of 2207.56+117 = 2324.56€.

Matériel	Prix
PCB	600€
Composants	677.56€
Ordinateurs	930
TOTAL	2207.5556

TVA
0.2
Taux de change USD-EUR
0.91

Panneaux solaires

	Prix de vente (cf trisolx)	
Quantité	Prix ($)	Prix (€)
25	115	104.65
100	400	364
650	2500	2275
2000	7600	6916

Componant	Quantity	Cost (euros)	Total (euros)	Frais de port
Solar cells	25		€104.65	59.15€
PSD (position sensitiv diode)	4	3.76€	15.02€	€8.34
Masque optique (solar sensor)	2	62.22€	124.44€	€0.00
Senseur d'horizon (carte)	2	47.88€	95.76€	€18.00
Senseur d'horizon (senseur)	2	34.93€	69.86€	€20.00
Magnetomètre (carte)	2	13.59€	27.18€	€0.00
Magnetomètre (senseur)	2	6.49€	12.98€	€0.00
Température (carte)	2	4.50€	9.00€	€27.92
Température (senseur)	10	0.45€	4.46€	€0.00
Lampe halogene	1	10.00€	10.00€	€6.36
Mircocontroller	2	5.87€	11.74€	€6.36
Carte de test	2	15.44€	30.88€	€0.00
Diodes de protections	20	0.29€	5.74€	€0.00
Diode zener	5	0.29€	1.43€	€8.28
Total	81			677.56€

	Matériel de tests	Prix
	Oscilloscopes	4€
TESTS SUR UN ECHANTILLON	Simulateur de vide	
	Simulateur de T° extrèmes	
	Simulateur de vibration	
	Gbf	4€
	total	7€

Matériel de production	Prix
Fer à souder	100€
Etain	10€
total	110€

total	117€

Finally, we arrived at a total of:

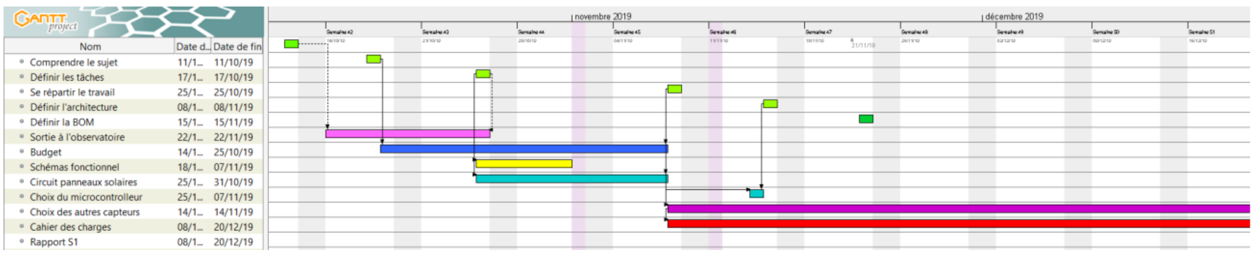
total	9,631€

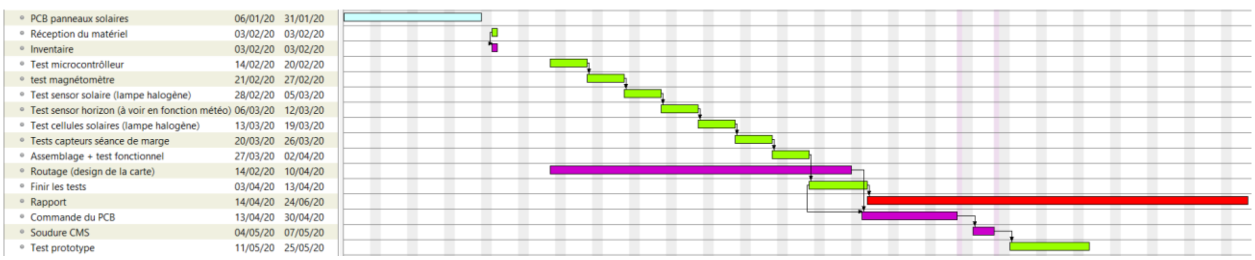
ORGANIZATION

To organize our project, we used a software named Gantt. It assigns a “Resources” (student) to every task.

A- TASKS DESCRIPTION

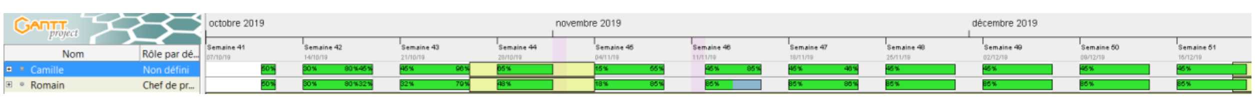
The first semester is made of six weekly courses of 3 hours and 6 hours for the second semester, but we assumed we would also work during our free time. We created thirteen different tasks to execute in the first semester, and sixteen in the second. All these tasks are described in the Gantt diagram below.

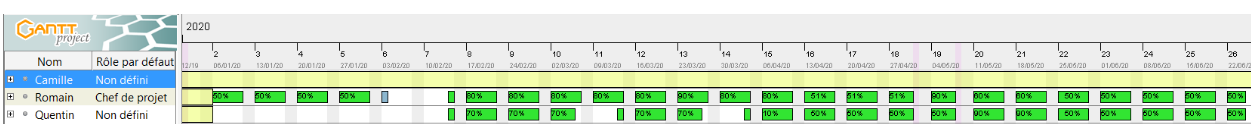




B- TASKS REPARTITION

We estimated the tasks repartition following, for the second semester, but it is likely to change.





BOM

Finally, after having fully analyzed our project’s specifications, we made a Bill Of Material (BOM), including all the material that we will need to realize the project.

Name	Quantity	Cost (euros)	Total (euros)	Frais de port	Pointer	
Solar cells	25		€104.65	59.15€	https://www.trisolx.com/	
PSD (position sensitiv diode)	4	3.76€	15.02€	€8.34	https://fr.rs-online.com/web/p/photodiodes/1247164/	
Masque optique (solar sensor)	2	62.22€	124.44€		https://www.thorlabs.com/thorproduct.cfm?partnumber=R1DS3N	
Senseur d'horizon (carte)	2	47.88€	95.76€	€18.00	https://www.digikey.fr/product-detail/fr/PIM366/1778-1232-ND/9606192/?itemSeq=302225100	
Senseur d'horizon (senseur)	2	34.93€	69.86€	€20.00	https://www.mouser.fr/ProductDetail/Melexis/MLX90641ESF-BCA-000-SP?qs=sGAEpiMZZMve4%2FbfQkoj%252BFqHfmNssTqNVeDnbDMeWbs%3D	
Magnetomètre (carte)	2	13.59€	27.18€		https://www.adafruit.com/product/3387	
Magnetomètre (senseur)	2	6.49€	12.98€	€8.34	https://fr.rs-online.com/web/p/accelerometres/1106555/	
Température (carte)	2	4.50€	9.00€	€27.92	https://www.adafruit.com/product/4369	
Température (senseur)	10	0.45€	4.46€	€20.00	https://www.mouser.fr/ProductDetail/NXP-Semiconductors/PCT2075GV-P110X?qs=sGAEpiMZZMve4%2FbfQkoj%252BPyhPk0PUDBbnknVZO4cVYA%3D	
Lampe halogene	1	10.00€	10.00€	€6.36	https://www.harborfreight.com/250-watt-halogen-work-light-63972.html	
Mircocontroller	2	5.87€	11.74€	€6.36	https://www.ti.com/store/ti/en/p/product/?p=MSP430FR5964IPNR	
Carte de test	2	15.44€	30.88€	€6.36	http://www.ti.com/tool/MSP-EXP430FR5994#buy	
Diodes de protections	20	0.29€	5.74€	€20.00	https://www.mouser.fr/ProductDetail/Infineon-Technologies/BAT60AE6327HTSA1?qs=sGAEpiMZZMtQ8nqTKtFS%2FAU2i4P1o9FIDMoexexoQ%2F8%3D	
Diode zener	5	0.29€	1.43€	€8.28	https://fr.farnell.com/diodes-inc/ddz9678-7/diode-zener-1-8v-0-5w-sod-123/dp/1858631	
TOTAL	81		€523.15	154.41€		
TVA						
0.2		TOTAL	€677.56			Legend = same website so just one shipping for all of the components ordered on the same website
Taux de change USD-EUR						
0.91						