Escola Politècnica Superior
de Castelldefels
UNIVERSITAT POLITÈCNICA DE CATALUNYA

TREBALL DE FI DE CARRERA

TÍTOL DEL TFC: Study of a low cost inertial platform for a femto-satellite deployed by a mini-launcher

TITULACIÓ: Enginyeria Tècnica Aeronàutica, especialitat Aeronavegació

AUTOR: Esteve Bardolet Santacreu

DIRECTOR: Joshua Tristancho Martínez

DATA: 28 de Juliol de 2010

Título: Study of a low cost inertial platform for a femto-satellite deployed by a mini-launcher
Autor: Esteve Bardolet Santacreu
Director: Joshua Tristancho Martínez
Fecha: 28 de Julio de 2010

Resumen

Durante este TFC, el estudiante trabaja de forma intensa en el modelado y validación para el espacio de una plataforma inercial así como de un estudio del impacto en la trayectoria derivado del error de la plataforma inercial.

En una primera fase se define lo que es un femto-satélite y una mini-lanzadera. Se presenta la tecnología de bajo coste para el espacio y el paradigma '*Space Payload*', es decir, realizar un diseño de ingeniería en función de la carga de pago y no en función de la industria.

Se describe el programa de espacio *WikiSat* donde se define un femto-satélite en concreto que cumple con los requisitos del concurso *N-Prize* y de su mini-lanzadera. También se genera una lista de subsistemas que forman el binomio satélite-lanzadera.

La parte importante de este TFC gira alrededor de la caracterización de la plataforma inercial que va a llevar el femto-satélite y que va a dirigir la trayectoria de la misma mini-lanzadera a fin de obtener sus actuaciones, asegurando que la fiabilidad de dicho componente se corresponde con los requerimientos de sistemas *Single-Fault-Tolerant* sin redundancia. Se define una librería para gestionar los datos inerciales de los acelerómetros, giróscopos y datos atmosféricos / eléctricos que nos permite corregir los errores que se producen en diferentes condiciones de trabajo.

Por último se valida la plataforma inercial en cuanto a calificarla para el espacio (Radiación, vacío, cambios térmicos, etc.) apoyado con alguna simulación en SPENVIS y ensayo real. También se realiza un estudio de la trayectoria usada en el programa de espacio *WikiSat*, a fin de modelizar las condiciones en las que se va a encontrar dicha plataforma en el femto-satélite y la mini-lanzadera. Este estudio está basado en la presuposición de la alteración de la trayectoria debido a fallos de motor o errores introducidos en el control de navegación a fin de determinar una política de actuación de emergencia del sistema de autodestrucción.

Title: Study of a low cost inertial platform for a femto-satellite deployed by a mini-launcher
Author: Esteve Bardolet Santacreu
Director: Joshua Tristancho Martínez
Date: July, 28th 2010

Overview

While doing this TFC, the student works hard on modeling and validating for space an inertial platform. Moreover, he does a study of the rockets trajectory derived of the cumulative error of this inertial platform.

In a first stage the concept of femto-satellite and mini-launcher is defined. The low-cost technology for space use and the Space Payload paradigm are presented.

The Wikisat space program is described and a specific femto-satellite and its mini-launcher are defined to fulfill the N-Prize rules. A list of subsystems that compose the joint satellite-launcher is presented as well.

The important part of this TFC is focused on the description of the inertial platform, which will be carry the femto-satellite and will control the trajectory of the mini-launcher. The reliability of this last component must be guaranteed and must correspond to Single-Fault-Tolerant systems' requirements, without redundancy. A library is defined to process the sensors' inertial data and the atmospheric and electric data for being able to correct the possible errors.

Finally, the inertial platform is validated for space use. This is done by many tests (like radiation, vacuum, thermal changes, etc.) supported by a SPENVIS simulation. A study of the trajectory used for the space program WikiSat is also done for modeling the conditions that this platform may experience in the femto-satellite and the mini-launcher. This study is based on the assumption that trajectory can change due to engine failure or mistakes from the navigation control system in order to determine an actuation plan and a policy to activate an auto-destruction system.

INDEX

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

We define the space payload paradigm as the engineering process of designing a space mission around its payload and not around space industry [5]

Nowadays, putting a satellite on orbit is really difficult. The use of a big reusable launcher makes the cost of the “renting” very expensive.

Following the space payload paradigm, in this paper we present the idea of using a launcher specially designed for the satellite. This launcher is controlled by the satellite and it has a scalable design. Because of this, the reduction in size makes the weight and the complexity of the subsystems very significant. A Single-Fault-Tolerant system is used for this kind of approaches. No redundancies are allowed and the same inertial platform is used for the satellite and the launcher as a basic synergy between both. In this sense, this paper pays special attention to the implementation of the inertial platform.

Of course, for large and medium satellites, this approach is too expensive and inefficient in terms of cost per mass in orbit. To put mini-satellites or smaller the piggyback is used, but up to now there is not a significant market that justifies the existence of small launchers. Moreover, the main client doesn’t want to assume risks and can oblige to have the satellites switched off until the deployment. These satellites must also pass very restrictive tests to prove they will not be a threat to the main mission.

The so called cube-sats are popular but no one uses a launcher to put less than one kilogram single cube-sat in orbit. Our approach tries to allow a mission based on small satellites without depending on the piggyback or the current launchers market that are not prepared for so small satellites.

In recent years, the satellites have started to be classified by mass. This is useful because it has a direct connection to launch cost. There are three main categories:

Table 0.1 Categories for mass classification

Category	**Mass range (kg)**
Large satellites	> 1,000
Medium-sized satellites	500 – 1,000
Small satellites	< 500

Inside the small satellites category, we can find subcategories:

Table 0.2 Subcategories for mass classification

Category	**Mass range (kg)**
Mini-satellite	100 – 500
Micro-satellite	10 – 100
Nano-satellite	1 – 10
Pico-satellite	0.1 – 1

Femto-satellite	< 0.1

Small satellites are called “Lightsats” by the U.S. Defence Advanced Research Projects Agency, “SPINSat’s” (Single Purpose Inexpensive Satellite Systems) by the U.S. Naval Space Command and “TACSat’s” (Tactical Satellites) by the U.S. Airforce

A mini-launcher is a small launcher that can put femto and pico satellites on orbit. The main idea is to reduce the costs and avoid the space monopoly established.

In chapter 1 the Wikisat space program is presented: the relation between Wikisat and the N-prize, the presentation of our femto-satellite and mini-launcher and the subsystems of the satellite to introduce the use of an inertial platform. There is also a description of the prototypes to explain what we had and what we can do after the research.

In chapter 2 the inertial platform and its components are introduced. There is also a mention of the technologies used (Printed Circuit Boards or PCBs and Micro Electro-Mechanical Systems or MEMS) and an explanation of the market research that has been done to find the best components for our requirements.

In chapter 3 there is a research of the technologies used in order to know their origins, how they work and other relevant information. The bus I²C is also introduced because of its important role in our inertial platform.

In chapter 4 the inertial platform manufacture process is explained, from design (and presentation of the CAD tool we have used: EAGLE PCB) to implementation. At the end, a comparison between the old and the new inertial platforms is done.

In chapter 5 there is an explanation of the processes which must be done to validate the inertial platform, not only in the ground (EMC and maybe vibrations) but also in the space (radiation and thermal changes).

In chapter 6 there is a study and action plan that has to be done when using the inertial platform to control our launcher. It also studies the impact it may have over environment.

Acknowledgements

I am grateful for the collaboration to the WikiSat members: Joshua Tristancho, Victor Kravchenko, Juan Martinez, Roger Jové, Sonia Pérez, etc.

I am grateful to Jordi Gutiérrez for introducing me to the WikiSat group.

I am grateful to my friends and family for encouraging me.

I am grateful to Rosa Gadea from *ST* sale office for giving us free accelerometer samples.

I am grateful to EPSC teachers who motivated me throughout the degree.

I am grateful to Joshua Tristancho for the help during these three months and the recommendations and advices that he has given to me.

Finally I want to thank our sponsors and collaborators:

Fig. 0.1 WikiSat partners

Trade Marks

In this work there are references to trade marks that have copyright:

- Analog Devices
- Arduino
- Atmel AVR
- Bosch Sensortec
- CadSoft
- EAGLE PCB
- Hewlett-Packard
- InvenSense
- LabVIEW
- Matlab
- National Instruments
- Nintendo

- Nintendo Wii
- Nintendo 3Ds
- Philips
- Robert Bosch
- SparkFun
- STMicroelectronics
- Texas Instrument
- Yole Développement

GLOSSARY

ADC	Analog-to-Digital Converter
APCP	Ammonium Perchlorate Composite Propellant
CAD	Computer Aided Design
CC	Creative Commons
CMOS	Complementary Metal Oxide Semiconductor
CNC	Computer Numerical Control
CVD	Chemical Vapour Depositionç
DOF	Degrees Of Freedom
EMC	Electromagnetic Compatibility
ESA	European Space Agency
GPS	Global Positioning System
IC	Integrated Ciruit
I^2C	Inter-Integrated Circuit
IMU	Inertial Measurement Unit
ISA	Inertial Sensor Assembly
HMDS	Hexamethyldisilazane
LED	Light-Emitting Diode
LEO	Low Earth Orbit
LPCVD	Low Pressure Chemical Vapour Deposition
MCU	Main Control Unit
MEMS	Micro Electro-Mechanical Systems
MIPS	Million Instructions Per Second
PCB	Printed Circuit Board
PECVD	Plasma Enhanced Chemical Vapour Deposition
PVD	Physical Vapour Deposition
RF	Radio Frequency
RIE	Reactive Ion Etching
SAA	South Atlantic Anomaly
SAD	Slave ADdress
SCL	Serial CLock line
SDA	Serial DAta line
SEU	Single Event Upset
SI	Système International d’unités (International System of Units)
SMD	Surface Mounted Devices
SMT	Surface Mounted Technology
THD	Through-Hole Devices
THT	Through-Hole Technology
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus
UV	Ultraviolet
VPE	Vapour Phase Epitaxy

CHAPTER 1. TECHNOLOGIES FOR THE INERTIAL PLATFORM

In this chapter few technologies for the inertial platform are presented such as:

- PCB. Printed Circuit Boards
- MEMS. Micro-Electro-Mechanical Systems
- I²C. Inter-Integrated Circuit bus

1.1 PCB. Printed Circuit Boards

Printed Circuit Boards (or PCB) is the name of a technique in inter-component wiring and assembly. The main components of a PCB are the base (a thin board of insulating material, rigid or flexible, which provides mechanical support to the conductors and all components attached to them) and the conductors (thin strips of high purity cooper with the appropriated shape that provide not only the electrical connections between components but also solderable attachment points).

1.1.1 *PCB history*

Although the original idea could date at the early 20th century, the major contribution to modern PCB was made by Paul Eisler (an Austrian engineer) circa 1936 and lately used for military applications during the World War II (because of the greater robustness). After the war (when USA released the technology for commercial use), great developments in the field of electronics resulted in a high demand for consumer products such as radio or television. Nowadays, any electronic product can contain one or more PCBs.

1.1.2 *PCB advantages*

In comparison with other electronic circuits methods, the advantages of the PCB technologies are:

- Smaller and lighter
- Less noise sensitivity
- Greater Electromagnetic Compatibility
- Greater mechanical robustness
- Possibility of serial production

1.1.2.1 Smaller and lighter

The size of component assembly is reduced with the corresponding decrease in weight.

1.1.2.2 Less noise sensitivity

PCBs do not need wires to connect the components because they use printed tracks. This means a noise sensitivity reduction because tracks are shorter than wires and they are all at the same plane.

1.1.2.3 Greater Electromagnetic Compatibility

Electro-Magnetic Compatibility (EMC) is defined as the capability of systems or equipment to be tested in the intended environment at designed levels of efficiency without degradation due to electromagnetic interactions. It is possible that electromagnetic emissions from some devices affect other components of the same circuit. This is really important when working with wireless communications with digital and analogical devices.

1.1.2.4 Greater mechanical robustness

Since they have the components soldered directly to the board, PCBs can withstand greater mechanical vibrations.

1.1.2.5 Possibility of serial production

Component wiring and assembly can be mechanized. Quantitative production can be achieved at a lower cost unit. PCBs ensure a high level of repeatability and offer uniformity of electrical characteristics from assembly to assembly.

Easy to manufacture and repair: printed wiring personnel require minimal technical skills and training. Chances of miss-wiring or short-circuited are minimized. Inspection time is reduced because printed circuitry eliminates the probability of error. The location of parts is fixed, which simplifies identification and maintenance of electronic equipment and systems. Circuit characteristics can be maintained without introducing variation in inter-circuit capacitance.

1.1.3 *PCB classification*

Traditionally, PCBs were classified according to their use and applications. Nowadays, there are no such differences and they can be classified according to the materials, the assembly type or the number of layers.

1.1.3.1 Use and applications

In accordance with their use and their applications, PCBs were classified into consumer, professional or higher reliability types:

Consumer PCBs: They used less expensive base materials, allowed greater tolerances for manufacture and were used in consumer products (such as radio or television). It was more important to keep the price low than giving good electrical properties.

Professional PCBs: They were made with higher quality materials to achieve greater electrical and environmental specifications.

Higher reliability PCBs: They used high quality base materials and tightly controlled manufacturing process to provide the best of electrical properties. They were normally used in strategic operations.

1.1.3.2 Materials

PCBs can be classified on the basis of the type of insulating material. Rigid boards normally use fibreglass or phenol formaldehyde resin as base materials. Flexible boards use flexible substrate material like polyester or polyamide. Other materials can be used, usually characterized among others because of different dielectric and thermal constants and behavior against moisture and fire.

1.1.3.3 Assembly type

According to assembly type, the PCB classification is through-hole and surface mounted devices:

Through-Hole Devices (THD): Normally used in single-side boards, this technology (THT) uses devices with large pins (with a distance of 0,1” between them) that are inserted through holes in the board and soldered in one or both sides.

Surface Mounted Devices (SMD): The components are soldered over pads on the board’s surface. Surface mounted technology (SMT) has several advantages over THT.

Table 1.1 PCB assembly type comparisons

	Through hole	**Surface mount**	**% Reduction**
Board size	11” x 14”	6.5” x 9.6 “	59
Number of layers	6	4	33
Board cost	150 $	75 $	50

As we can see, SMD has an important size reduction that involves a significant price reduction in mass production. This size reduction happens mainly because it allows a higher placement density. So traces between components are shorter and this lowers parasitic inductance and capacitance. Furthermore, SMD components are generally smaller and cheaper than THD.

THT is easier to work for manually developing prototypes and can be also used on breadboards. These kinds of devices are very suitable for amateur constructions and for fast prototyping.

1.1.3.4 Number of layers

According to the number of layers, the PCB classification is single-sided, double-sided and multilayer PCBs:

Single-sided PCBs: They have cooper conductor in only one side called ‘solder side’. The other side is called ‘component side’ because THD usually have the components in this side and circuit in the other.

Double-sided PCBs: They have a cooper layer in both sides. They also can contain more complex circuits and their components can be soldered in one or both sides. Holes can be metalized in order to connect upper and lower layouts.

Multilayer PCBs: Using chemical processes, they can achieve a great number of inner layers apart from the two outer layers (such as the double-sided). This process is more complicated and cannot be done manually.

1.1.4 *PCB design*

It is hard to explain how to design a PCB and practice is always highly recommended to improve your design’s performance. There are some free CAD programs (like EAGLE) which make this process easier. However, experience can be even more important.

Being aware of the possible problems when manufacturing can be very helpful when it comes to acknowledge our limits. For example: working with digital components is not the same as mixing analogical and digital with wireless together (there are some rules to avoid EMC problems or malfunctions when doing these designs). Nevertheless, an order of procedures may be followed to any circuit design:

- First of all, we have to place the connectors and the LEDs in a specific position due to casing restrictions. If there are shape or size restrictions, they must be specified in the design from the beginning.

- Second of all, we must arrange the MEMS or Integrated Circuits (IC), trying to minimize the space between them.

- The next step regards the capacitors, resistors and other electronic components. We have to remember that we may have some positioning restrictions specified on the MEMS and IC datasheets.

- The supply track and ground track or plane come next. They are very important particularly in analogical circuits (where we need a big ground plane). A good design of supply and ground tracks helps to reduce noise and improve the EMC of the circuit.

- Finally, we only have the remaining tracks left.

There are also some rules that have to be taken into account especially when designing RF circuits and using analogical and digital devices:

- With digital devices that require high frequency supply lines, decoupling capacitors between ground and power supply must be used (as close as possible to the pins that must be decoupled). One decoupling high quality ceramic capacitor must be used for each node that is going to be decoupled.

- The magnitude difference between digital and RF signal can be as large as 120dB. If these signals are not separated or shielded properly, the RF signal can be corrupted. Some RF device lines should be handled with special caution and be kept as far as possible from the digital lines.

- Analog circuits are extremely sensitive to power supply noise. It is mandatory to separate power lines (and ground) from the analog and digital domains of the circuit.

- Two long parallel lines have a capacitive effect between them.

- Long lines and 90º angles act as antennas and should be avoided.

- RF circuits should always be laid out with a ground plane. Even short lines will work as inductors so it is important to reduce the length as much as possible. This also reduces noise and improves EMC.

- Radiation from antenna can affect other analog parts from PCB (such as MCU’s ADCs).

- Star-routing is a layout trick in analog design. It is the separation of the power lines for each module (digital, RF and other analog), each one decoupled separately. This process helps to isolate power noise from digital part.

1.1.5 *PCB manufacture*

Commercial PCB manufacture can have more or less steps depending on the company or customer requisites. The following example presents the processes done by one of these companies according to their website (see Fig. 1.1) but also used in most of the companies we have found. It is a double-sided PCB to compare with our processes.

Step 1: Cutting panels: they buy big panels and cut them to use as much as possible for the same manufacturing series. They do not separate them until the end of the process.

By now, the process explained affects a single board but they do it for all the boards of the panel, resulting in a lot of boards at the same time.

Step 2: Drilling: using the computer numerical control (CNC) drilling machine they can do high-precision holes quickly.

Step 3: Metalization: the holes are plated with various metal options.

Step 4: Laminating: a thin layer is set over the board.

Step 5: Exposure: a pattern is placed over the layer and exposed to a radiation source (normally UV).

Step 6: Photoresist developing: the non-exposed part from the material is removed.

Step 7: Second metalization: when filling the removed parts of the layer, another metalization is done involving tin, solder or nickel.

Step 8: Photoresist striping: the photoresist layer is completely removed.

Step 9: Alkaline etching: the non-covered metal (normally cooper) of the board is removed and metal of second metalization acts as a shield.

Step 10: Tin striping: the second metalization is removed.

Step 11: Solder mask: a polymer solder resistant coating that protects the circuit from soldering is used. It prevents bridges between connectors, short circuits and it also provides environmental protection.

Step 12: Surface finish: the last metalization is done over the holes.

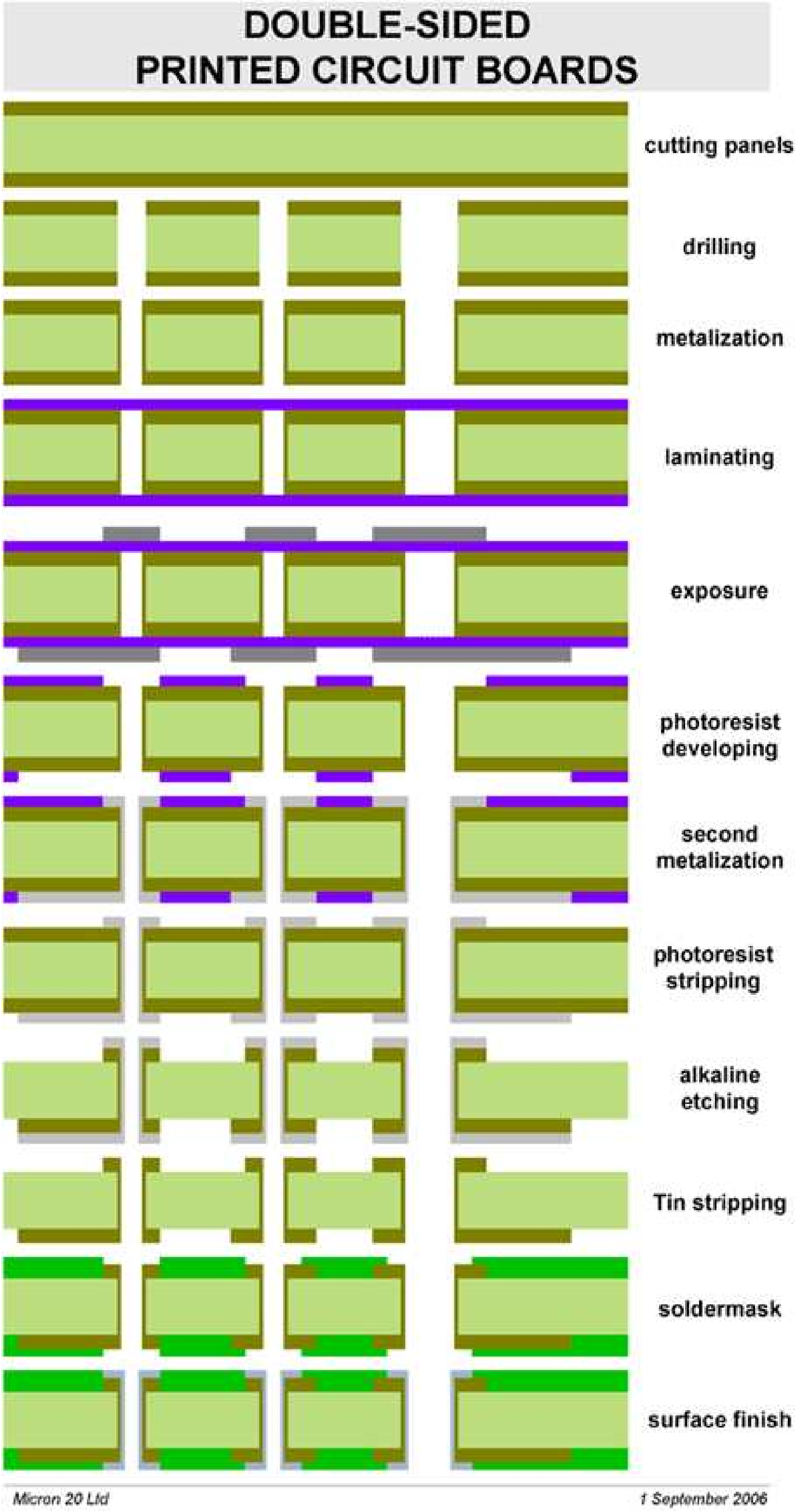


Fig. 1.1 PCB manufacture process

1.2 MEMS. Micro-Electro-Mechanical Systems

Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate through micro-fabrication technology.

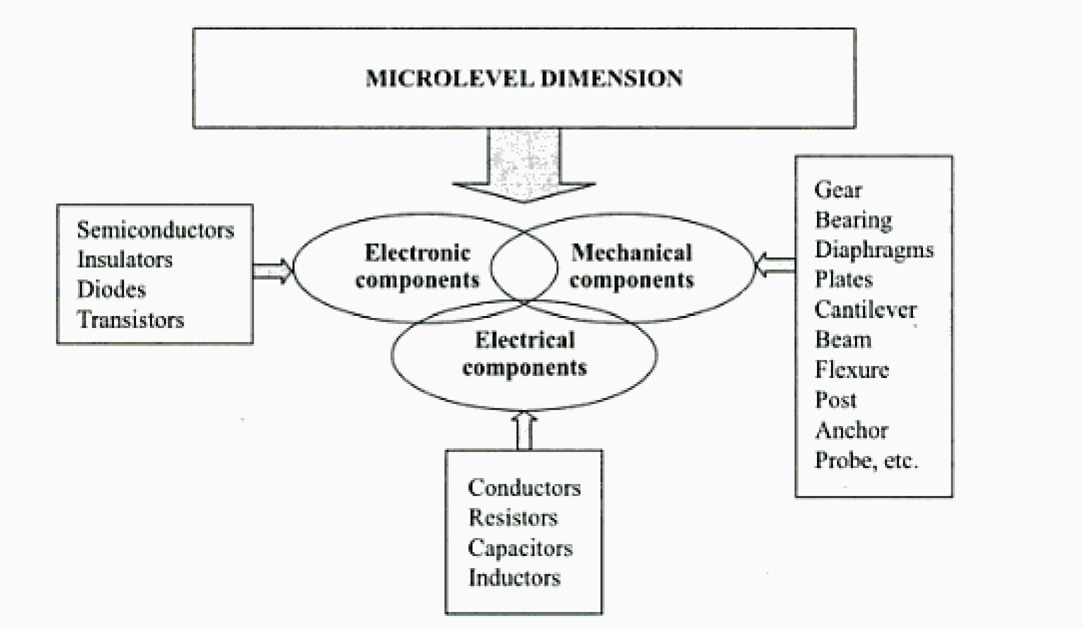


Fig. 1.2 Integration of electronic, mechanical and electrical components with microlevel dimensions

MEMS is an extended form of traditional microelectronic IC technology. While IC technology only allows us to fabricate conductors, insulators and junctions; with MEMS technology we can also create mechanical elements such as springs, gears or diaphragms.

1.2.1 MEMS history

In the 50's, Richard Feynman proposed the possibility of manufacturing ultraminiaturize systems by explaining the potential of this technology. However, his visionary idea was not possible at that time and it was not until more than twenty years later that first MEMS appeared.

Jack Kilby, from *Texas Instrument,* built the first Integrated Circuit (IC) in 1958. As explained, MEMS are like an IC improvement.

The first high-volume pressure sensor was marketed by *National Semiconductor* in 1974.

Around 1982, the name 'micromachining' came into use to designate the fabrication of micromechanical parts for silicon micro-sensors.

Between 1987 and 1988, techniques for integrated fabrication of mechanisms on silicon were demonstrated. The term MEMS was coined in 1987. It is also usual to use the term ‘Microsystems’ in Europe and ‘Micro-machines’ in Japan.

1.2.2 *MEMS accelerometers*

Nowadays, the most widespread MEMS accelerometers rely either on piezo-resistive or capacitive detection principles.

1.2.2.1 Piezo-resistive Accelerometer

They have been in the market since early eighties but they have some disadvantage. They need an extensive calibration and require additional actuators for self-test (very important for safety critical operations). This can be solved but increases the cost.

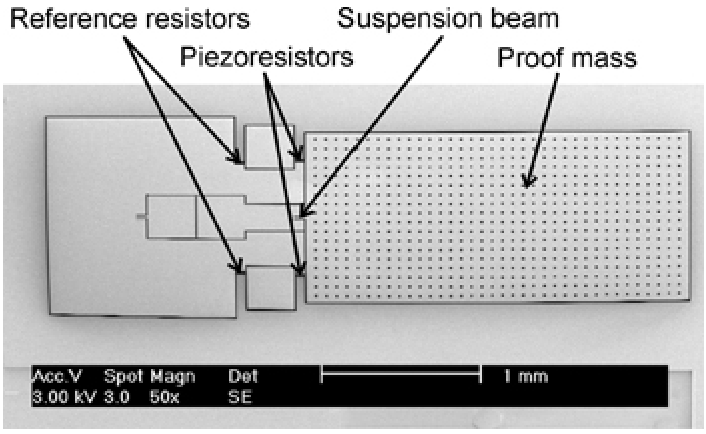


Fig. 1.3 Piezo-resistive accelerometer

The working principle is: one or more tether beams (with at least one of this tether beams containing piezo-resistors) carry a seismic mass. When external forces deflect the seismic mass, the piezo-resistors are strained and change their resistance values. If fed by an electrical current, a bridge voltage appears. This is called the piezo-resistive effect and is commonly described by:

$$\frac{\Delta R}{R} = \Pi_l \sigma_l + \Pi_t \sigma_t \qquad \textbf{(1.1.)}$$

Where Π_l and Π_t denote the longitudinal and transversal piezo-resistive elements, σ_l and σ_t the corresponding stress values caused by mechanical strain of the structure and $\Delta R/R$ denotes the relative resistance change.

1.2.2.2 *Capacitive Accelerometer*

They appeared in the late eighties and they rapidly established themselves as preferred devices due to the increased precision, linearity and temperature stability apart from a reduction on calibrating effort (normally the only factor that has to be calibrated is the full-range adjustment).

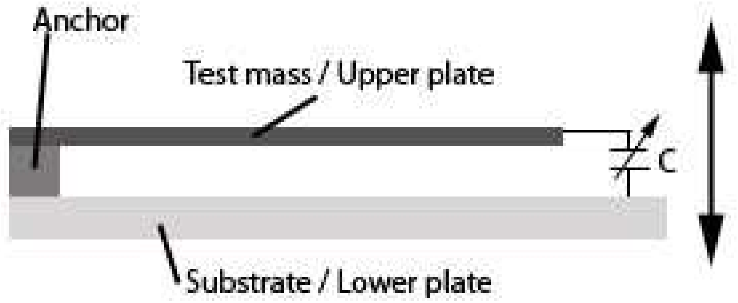


Fig. 1.4 Capacitive accelerometer

The working principle is: deflection of the seismic mass is usually transformed into corresponding capacitance changes in a differential capacitor arrangement. When seismic mass approaches to a detecting surface, it increases the corresponding capacitance. At the same time, it moves away from another detecting surface, reducing its capacitance. There are a lot of C/V converters but in most cases the electrical output voltage is proportional to:

$$\frac{C_1 - C_2}{C_1 + C_2} = \frac{\Delta x}{x_0} \qquad \textbf{(1.2.)}$$

Where Δx is the deflection of the seismic mass, x_0 is the distance between capacitor plates in the undeflected state ($C_1 = C_2$) and C_1 and C_2 are the individual capacitance values in the differential capacitor arrangement.

1.2.3 *MEMS gyroscopes*

Mechanical gyroscopes contain at least one moving element that responds to Coriolis forces if its motion is distributed by a forced rotation around a sensitive axis. In classical mechanized gyroscopes, Coriolis forces are measured and compensated in the bearings of a spinning rotator. The fabrication of high-quality bearings is not possible in micromechanics so MEMS gyroscopes are mostly based on a periodic vibratory motion, not a unidirectional rotation of mass. Bearings are replaced by a spring-mass system.

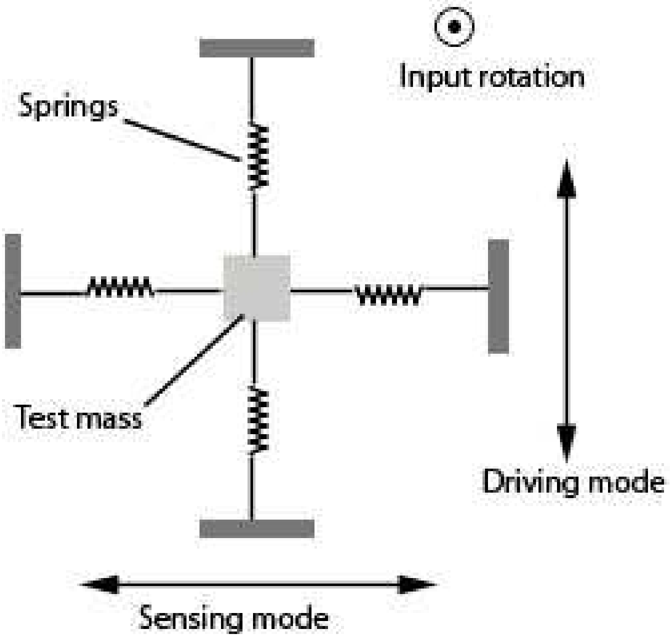


Fig. 1.5 Vibrational gyroscope

The action can be understood regarding a forced change of an angular momentum, which induces a corresponding reaction of the mechanical element.

The working principle is: the generation of Coriolis forces in response to external rate of vibrations. Considering a test mass vibrating in plane, the Coriolis effect induces an acceleration on the mass known as Coriolis acceleration:

$$a_c = -2(v \times \Omega) \qquad \textbf{(1.3.)}$$

Where v is the velocity vector and Ω is the angular velocity vector.
The in-plane position of the test mass is given by:

$$x_{ip} = x_0 \sin\left(\omega_r . t\right) \qquad \textbf{(1.4.)}$$

Where ω_r is the vibration frequency.

So, the in-plane velocity of the test mass is given by:

$$v_{ip} = x_0 \omega_r . \cos\left(\omega_r . t\right) \qquad \textbf{(1.5.)}$$

The out-plane motion is given by:

$$y_{op} = \frac{F_c}{k_{op}} = \frac{2m\Omega x_0 \omega_r \cos\left(\omega_r . t\right)}{k_{op}} \qquad \textbf{(1.6.)}$$

Where m is the mass of the test mass and k_{op} is the spring constant in the out-plane direction.

1.2.4 *MEMS manufacture*

There are three basic blocks when manufacturing MEMS devices: deposition, lithography and etching.

1.2.4.1 Deposition process

Deposition process is the ability to deposit thin films of material on a substrate (with a thickness between a few nanometers to about 100 micrometers). MEMS deposition technology can be classified in two groups depending on the reason why deposition may happen:

Chemical reactions: Creation of solid materials directly from chemical reactions in gas or liquid compositions or with a substrate material. There are four types of chemical reaction deposition processes:

- Chemical Vapor Deposition (CVD), where the substrate is placed inside a reactor where gases are supplied. It can be Low Pressure CVD (LPCVD) or Plasma Enhanced CVD (PECVD). LPCVD processes produce high quality layers but need high temperatures (higher than 600 ºC). PECVD processes can operate at lower temperatures (down to 300 ºC) but their quality is also lower.

- Electrodeposition is restricted to electrically conductive materials. These can be Electroplating and Elecroless Plating. In Electroplating processes, the substrate is placed in a liquid solution (electrolyte) and an electrical potential is applied resulting in the formation of a layer of material on the substrate. In Electroless Plating processes, a more complex chemical solution is used, in which deposition happens spontaneously without requiring external electrical potential.

- Epytaxy is similar to CVD but with some particularities when using specific substrate materials (like semiconductor crystal). The most important is Vapor Phase Epitaxy (VPE) where gases are introduced in an induction heated reactor and only the substrate is heated. This technology is primarily used for depositions of silicon.

- Thermal oxidation is the most basic deposition technology. It is based on the oxidation of the substrate in an oxygen rich atmosphere, with high temperatures that speed up the process.

Physical reactions: The material deposited is moved to the substrate. There are two types:

- Physical Vapor Deposition (PVD) covers deposition technologies in which material is released from the source and transferred to the substrate. Generally, the quality is worse than CVD. The process may happen because of Evaporation or Sputtering. In Evaporation the substrate and the source material are placed in a vacuum chamber and the source is heated (using an electron beam or electrically) until it starts to boil and evaporates, then condensing on all surfaces. In Sputtering the substrate and the source material are placed in a vacuum chamber. Then, an inert gas is introduced and ionized, causing atoms from the source to break off in vapor form and condensing on all the surfaces.

- Casting is the process in which the material is dissolved in a solvent liquid form and applied to the substrate by spraying or spinning. When the solvent evaporates, a thin film remains on the substrate. It is the most common method in photolithography.

1.2.4.2 Lithography

Lithography is the transfer of a pattern to a photosensitive material by selective exposure to a radiation source. A photosensitive material is a material that experiences change in its physical properties when exposed to a radiation source. Depending on the source, we have different types of lithography: Photolithography, Electron beam lithography, Ion beam lithography, X-ray lithography, Extreme Ultraviolet lithography.

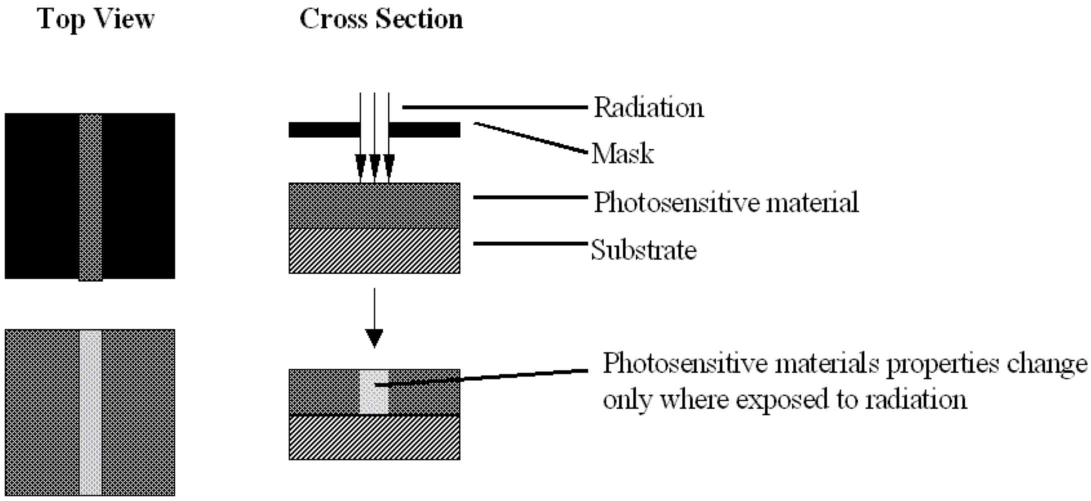


Fig. 1.6 Lithography process

Exposing selectively a photosensitive material to radiation, different properties among exposed and unexposed regions may appear.

The standard steps in a lithography process are:

Dehydration bake: dehydrate the wafer to aid resist adhesion.

HMDS prime: coating of wafer surface with adhesion promoter. Not necessary for all surfaces.

Resist spin/spray: coating of the wafer with resist either by spinning or spraying. Typically desire a uniform coat.

Soft bake: drive off some of the solvent in the resist, may result in a significant loss of mass of resist (and thickness). Makes resist more viscous.

Alignment: align pattern on mask to features on wafers.

Exposure: projection of mask image on resist to cause selective chemical property change.

Post exposure bake: baking of resist to drive off further solvent content. Makes resist more resistant to etchants (other than developer).

Develop: selective removal of resist after exposure (exposed resist if resist is positive, unexposed resist if resist is positive).

Hard bake: drive off most of the remaining solvent from the resist.

Descum: removal of thin layer of resist scum that may occlude open regions in pattern, helps to open up corners.

1.2.4.3 Etching process

Etching process consists of etching the film to the mask. There are two types of etching processes: Wet etching (the material is dissolved when immersed in chemical solution) and Dry etching (the material is sputtered or dissolved using reactive ions or a vapor phase etchant).

Wet etching: is the simplest etching technology. It requires a container with a liquid solution that will dissolve the material. It also requires a mask (to selectively remove parts from this material) that will not dissolve or will dissolve slower than the material. The depth of the cavity can be controlled using the etching time and the known etch rate. There are two main types: the isotropic and the anisotropic.

In the isotropic type, etch progresses at the same speed and all directions. In the anisotropic type, there are different etch rates in different directions. The result is a pyramid shaped hole in anisotropic etching but rounded sidewalls in isotropic etching.

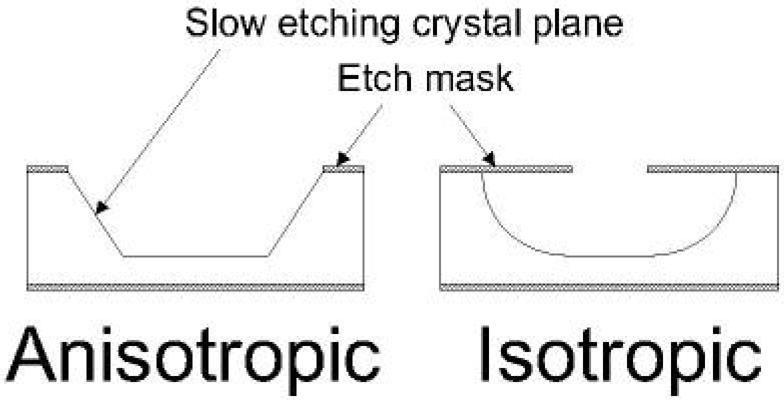


Fig. 1.7 Wet etching processes

Wet etching holes cannot be vertical to the surface. It has less resolution than dry etching but the cost is 1-2 orders of magnitude lower than them.

Dry etching: can be divided in three types: Vapor phase etching, Sputter etching and Reactive ion etching (RIE).

- Vapor phase etching: The wafer to be etched is placed inside a chamber, in which one or more gases are introduced. The material is dissolved at the surface in a chemical reaction with the gas molecules.

- Sputter etching: It is very similar to sputtering deposition systems. The main difference is that the substrate is subjected to the ion bombardment instead of the source material.

- Reactive ion etching: The substrate is placed inside a reactor in which gases are introduced. The plasma is generated at low pressure (vacuum) by a strong RF electromagnetic field. The ions are accelerated and collide with the surface of the material being etched, forming another gaseous material. Moreover, if the ions have high enough energy, they can also knock atoms out of the material being etched.

Deep-RIE is a highly anisotropic etching process that is growing in popularity. It allows the fabrication of truly vertical walls (90º) but they are often slightly tapered. There are two main technologies: Cryogenic and Bosch processes but only Bosch is a recognized production technique. The “Bosch process” was patented by the German company *Robert Bosch* and alternates repeatedly between two modes: a first gas that creates a polymer over the surface (deposition) and a second gas (nearly isotropic plasma) that etches the substrate from a nearly vertical direction. The polymer is sputtered away on the horizontal surfaces by the physical parts of the etching. Since it dissolves slowly by chemical etching, it builds up on the sidewalls. Short etch cycles yield smoother walls and long cycles yield a higher etch rate.

These are not the only MEMS manufacture techniques. Since this technology is constantly developing, it is really difficult to give an exact list of types for each block. There are a lot of patents related to MEMS manufacture. For instance, *InvenSense* has patented his Nasiri-Fabrication process (showed in figure Fig. 1.7) which permits the combination of MEMS and a complementary metal oxide semiconductor (CMOS) at the wafer level.

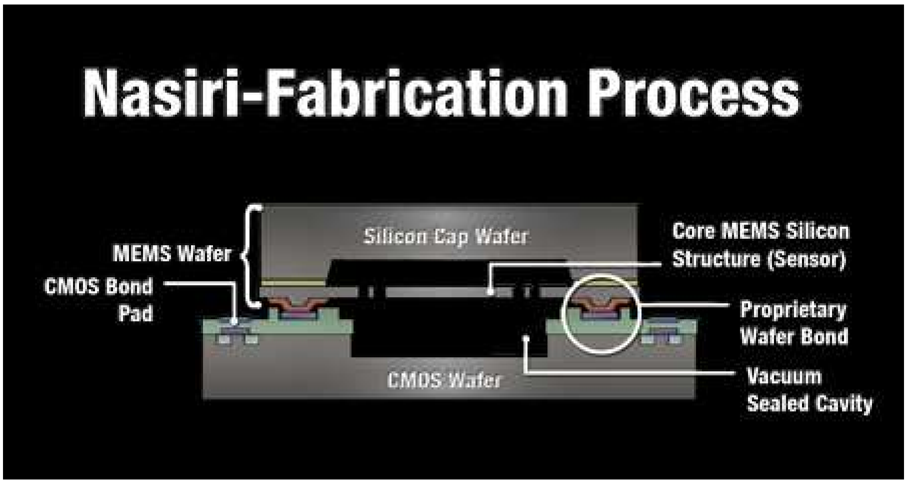


Fig. 1.8 Nasiri-fabrication process

1.3 I²C. Inter-Integrated Circuit bus

1.3.1 I²C history

I²C (Inter-Integrated circuit) is a multi-master serial bus widely used in electronics industry, particularly in printed circuits technology (like IC or MEMS). Version 1.0 was invented by *Philips* in 1993 and version 2.1 was launched in 2000.

1.3.2 I²C specifications

The I²C bus uses only two lines: Serial CLock line (SCL) and Serial DAta line (SDA).

The addresses have a length of 7-bits but 16 are reserved so there is a maximum of 112 nodes that can communicate on the same bus. Each sensor we have used allows us to choose between two different addresses, so two of them can be connected on the same line. Some devices allow us to select more addresses.

Common speed is 100 kbit/s but it can run faster (400 kbit/s, 1 Mbit/s, 3.4 Mbit/s) or slower (10 kbits/s) depending on the mode.

1.3.3 I²C modes

There are two roles for modes: Master and Slave. Since there is a multi-master bus, any number of masters can be connected at the same bus. It also allows some devices to change its role between messages. Sensors, for example, can only be slave but MCUs may change their role.

While the bus is free, the lines are in HIGH state. Then a Master sends a START condition (a transition to LOW on the SDA line while SCL remains HIGH) and the bus is considered busy. After that, the Master sends the address from the Slave and shows if it will transmit or receive data. After the Slave acknowledgement, the communication starts. After each data transfer, the master sends a STOP condition (a transition to HIGH on the SDA line while SCL remains HIGH).

CHAPTER 2. WIKISAT SPACE PROGRAM

2.1 Wikisat Project

2.1.1 N-Prize contest

It is a competition to stimulate innovation towards obtaining cheap access to space. According to the rules, the objective is to put a satellite with a mass of between 9.99 and 19.99 grams into orbit around the Earth, and to prove that it has completed at least 9 orbits. No orbit part may be lower than 99.99 km above the surface of the earth.

The cost of the launch must fall within a budget of £999.99.

A prize of £9,999.99 will be awarded to the first group that achieves this objective.

The Wikisat group is formed by teachers, students and collaborators. We are developing a femto-satellite called WikiSat and a mini-launcher for this satellite called WikiLauncher to participate in the N-prize.

2.1.2 WikiSat: The femto-satellite

The satellite WikiSat will be the brain of our mission. The idea is that the payload has the control of the launcher and takes predefined decisions when needed. This is one of the group statements related to the satellite. To avoid further problems, the satellite will not have a receiver. The WikiSat is designed to fit N-Prize rules.

One of the most restrictive parameters in the satellite will be the weight. A non redundancy policy has been applied and the system must be Single Fault Tolerant.

2.1.3 WikiLauncher: The mini-launcher

The WikiLauncher will be controlled by the WikiSat. There is no available prototype yet but the design has been already decided. It will use multinozzles approach and it will not have fins. A GPS will be used in the mini-launcher but not in the satellite.

Current simulations have shown that it will be able to carry a 20 g payload to an altitude of 250 km for 8 days with a launcher of 1.5 m of length and 34.52 kg of weight, using APCP (ammonium perchlorate composite propellant) as a combustible.

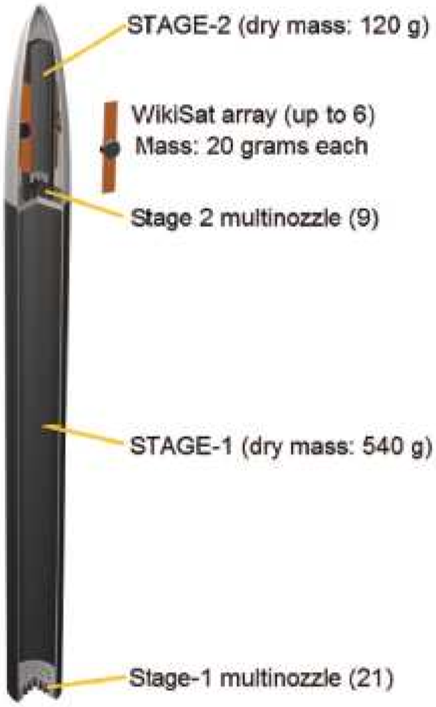


Fig. 2.1 WikiLauncher and the WikiSat

2.2 WikiSat Satellite

2.2.1 Performances

Orbit: LEO 250 km
Communications range: 200 to 1,000 km
Time in orbit: 8 days
Mass: 20 grams
MIPS: 20

2.2.2 Subsystems

Actually, because of weight restrictions, we cannot equip our satellite with lots of subsystems. So it only has the minimum required subsystems to accomplish its mission. These subsystems are:

- MCU: The Main Control Unit subsystem shall process the acquired data.
- Communications: Communications subsystem shall transmit information using the 2.4 GHz amateur band. It is composed by the antenna, the transceiver and the amplifier.
- Structure: The structure subsystem shall protect the components and gives robustness to the satellite. The same board that contains the antenna and the printed circuit will be the structure subsystem of the satellite.
- Power supply: The power supply subsystem shall provide electrical power to the MCU, the inertial platform and the transceiver.

- Attitude control: The attitude control subsystem shall point the high antenna to Earth. It is composed of magnetorquers.
- Position determination: The position determination subsystem shall give to the MCU the position of the satellite. It is composed by 3-axis accelerometers and 3-axis gyros.
- Thermal control: The thermal control subsystem shall control the satellite temperature. This subsystem is designed to be a passive control.
- Radiation shield: The radiation shield subsystem shall protect the satellite from radiation. It is composed of layers of foils from different materials.

2.3 Prototypes

2.3.1 Prototype 1

The WikiSat *Prototype 1* was launched in a high altitude balloon on Monday, October 19th, 2009 at 04:00 am. The balloon was never recovered [27]. This version was used to validate the coin battery, the initial IMU and the MCU.

Fig. 2.2 First WikiSat prototype

2.3.2 Prototype 2

The prototype is based on commercial boards. It uses:

- 6 DOF (Degrees Of Freedom) Razor – Ultra -Thin IMU from *SparkFun*.
- Arduino Pro Mini 168 from *SparkFun*.
- Transceiver nRF2401A with Chip Antenna from *Sparkfun.*
- Coin Lithium battery

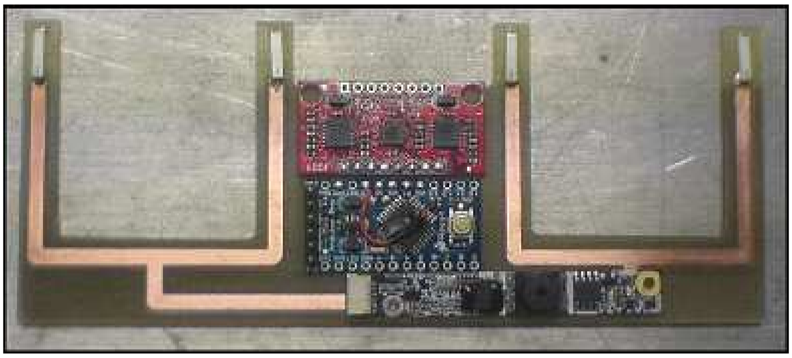


Fig. 2.3 Second WikiSat protoype

2.3.3 *Prototype 3*

This is the current design where our inertial platform is installed to control the launcher and the satellite. This design includes the High Gain Antenna, the Coin battery, the IMU and MCU.

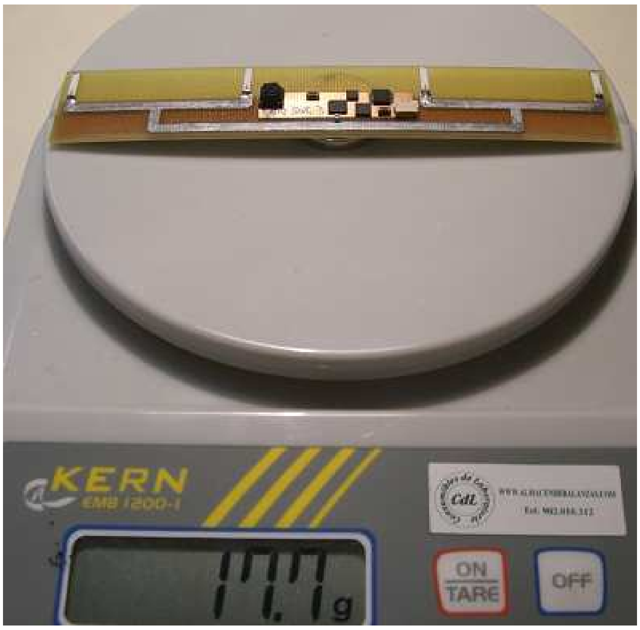


Fig. 2.4 Third WikiSat prototype

CHAPTER 3. INERTIAL PLATFORM STUDY

3.1 Inertial platform aspects

The inertial platform is composed by sensors that measure mainly inertial accelerations and rotations. These sensors are the accelerometers and the gyroscopes. As we will explain later, for additional corrections of the integration drift errors, other magnitudes like magnetic field and sensor temperature are taken.

The same happens with the other components (explained in the previous chapter) but it may be interesting to explain why we are using these technologies.

- Low cost and reduced size are the main aims for our inertial platform.
- Printed Circuit Boards is a technology that can achieve really reduced sizes depending on the type of used devices. It is also inexpensive; a good evidence of this is the great amount of information, communities, forums and websites of home-made PCBs.
- MEMS is a technology of very small devices that allows us to do high quality sensors and actuators. It is also very cheap, especially when it is bought in big amounts. MEMS accelerometers and gyros improve every day and we can work with new low cost technology.

3.1.1 Accelerometer

They are sensors that measure inertial acceleration. Inertial or proper acceleration is the acceleration relative to free-fall. Such accelerations are measured in terms of G-forces. The **g** unit is the one normally used and it is equivalent to 9.80665 m/s^2 (SI units), the gravity over Earth's surface. When the sensor is over a table, the sensor feels the gravity field.

3.1.2 Gyroscope

They are sensors for measuring rotation. Rate gyros measure rotation rate and displacement gyros measures accumulated rotation angle. They provide with orientation.

3.1.3 ISA. Inertial Sensor Assembly

An Inertial Sensor Assembly (ISA) is an ensemble of inertial sensors rigidly mounted to maintain the same relative orientations. It is normally composed by accelerometers in 3 axes and gyros in 3 axes. An Inertial Measurement Unit (IMU) includes an ISA and its associated support electronics for calibration as well as a control of the ISA. There is usually no difference between them and the term IMU is used to define both.

Using the inertial platform, an Inertial Navigation System can determine the position. Gyros are used to determine the changes in orientation. They can determine the changes by acceleration or either doing a double integral position. The main problem is the accumulated error or integration drift.

$$v = \int a \, dt + v(0) \tag{3.1.}$$

$$r = \int \int a \, dt^2 + v(0)t + r(0) \tag{3.2.}$$

$$\theta = \int \omega \, dt + \theta(0) \tag{3.3.}$$

Where:

a: Inertial acceleration vector [m/s²]
v: Inertial speed vector [m/s]
r: Inertial position vector [m]
θ: Attitude vector [rad]
ω: Rate of turn vector [rad/s]
t: Time [s]
v(0): Initial speed vector [m/s]
r(0): Initial position vector [m]
θ(0): Initial attitude vector [rad]

3.1.4 *Inertial platform errors*

There are two types of errors introduced by this method: Random error and the integration drift.

3.1.4.1 Random error

The random error is due to fluctuations in the sensor and the temperature of the sensor that is called noise in the signal. This error can be reduced taking an average value. In addition, the random error can be corrected if sensor temperature and calibration behavior are known.

3.1.4.2 Integration drift

The integration drift is subjected to little error in each integration process; the faster the sampling frequency, the smaller the drift. The integration drift is something that cannot be determined without an external input like GPS for accelerometers and magnetic field (compass) for gyros. There are other parameters that increase the error in the integration process like the accuracy of the acceleration value and also the accuracy of the increment of time between each integration.

3.1.4.3 Corrections of the errors

The use of Kalman filters can reduce these errors assuming that the inertial platform changes its acceleration slowly. Other techniques were proposed before, such as the average value for random error or external corrections for the integration drift, but a Kalman filter can improve the inertial platform performances [28].

3.2 Market study

In this section, a market study on the state of the art regarding accelerometers and gyroscopes is presented. A good market study is the key factor to reach the high quality inertial platform at a low cost. For this reason, we have dedicated large quantity of time and effort in order to develop a good job in this part.

In this study, we are assuming that we shall produce an inertial platform for space applications after its validation and qualification for the space but at a low cost and having components from the consumer market. We try to have providers from Barcelona, in the best case, or at least the European providers so that we can avoid import taxes.

3.2.1 Accelerometers in the market

We carry it in a rocket so we have decided to take accelerometers with a range bigger than ±10 **g**. This has been the first restriction.

Weight is one of the most critical restrictions of the N-prize, so if we want to succeed we need a satellite as small and light as possible.

The second restriction to select the components has been the number of axis. If we can have good devices in a single package, it is better than having two or three accelerometers. That way, we can save weight not only directly, but also indirectly: the occupied space means more weight because of the amount of board we need for drawing the circuit.

In order to save weight, I have also looked for the smallest packages (3x3x1 mm or less), this kind of package is only available for digital accelerometers.

Table 3.1 Accelerometers in the market

Provider	**Component**	**Output**	**#Axis**	**Range [g]**	**Bandwidth**	**Resolution**	**Sensitivity**	**Size mm**
Analog Devices	ADXL326	Analog	3	±16	1.6 kHz		57mV/g	4x4x1.45
Analog Devices	ADXL346	Digital	3	±2/4/8/16	1.6 kHz	10/11/12/13 bit	4 mg/digit	3x3x0.95
Kionix	KXD94-2802	Analog	3	±15	800 Hz		200mV/g	5x5x1.2
ST	LIS331HH	Digital	3	±6/12/24	500 Hz	12 bit	3/6/12 mg/digit	3x3x1
ST	LIS3DH	Digital	3	±2/4/8/16	2,500 Hz		1/2/4/12 mg/digit	3x3x1
Bosch	BMA120	Digital	3	±2/4/8/16	1kHz ...32Hz	6 bit (62.5mg)	16/8/4/2 LSB/g	3x3x0.98
Bosch	BMA220	Digital	3	±2/4/8/16	1kHz ...32Hz	6 bit (62.5mg)	16/8/4/2 LSB/g	2x2x0.98

As we can see on the table, there are three main interesting manufacturers for our requirements: *Analog Devices*, *STMicroelectronics* and *Bosch Sensortec*.

The most interesting accelerometer from *Analog Devices* is ADXL346.

ST has two interesting accelerometers: LIS331HH and LIS3DH. The main differences are that the first one has a bigger range and the second one has lower power consumption. LIS3DH model is very new (21/05/2010) and it is not available yet.

Bosch Sensortec has the BMA120 and BMA220 models. The second one has the same characteristics than the first one but it is smaller.

Right now, we are at the point of explaining the Wikisat team's policy to justify the final choice:

We want to have at least an alternative for every component. They have to have more than one European distributor and, if possible, one in Spain. It would be still better if the provider were local.

ST and *Bosch* are European companies (*ST* Italian-French and *Bosch* German), *Analog Devices* is American. *ST* has a sale office and a distributor in Barcelona, other distributors around Spain and the headquarters in Switzerland. *Bosch Sensortec* has a distributor in Spain and the Headquarters in Germany. *Analog Devices* has distributors in Spain (one in Barcelona).

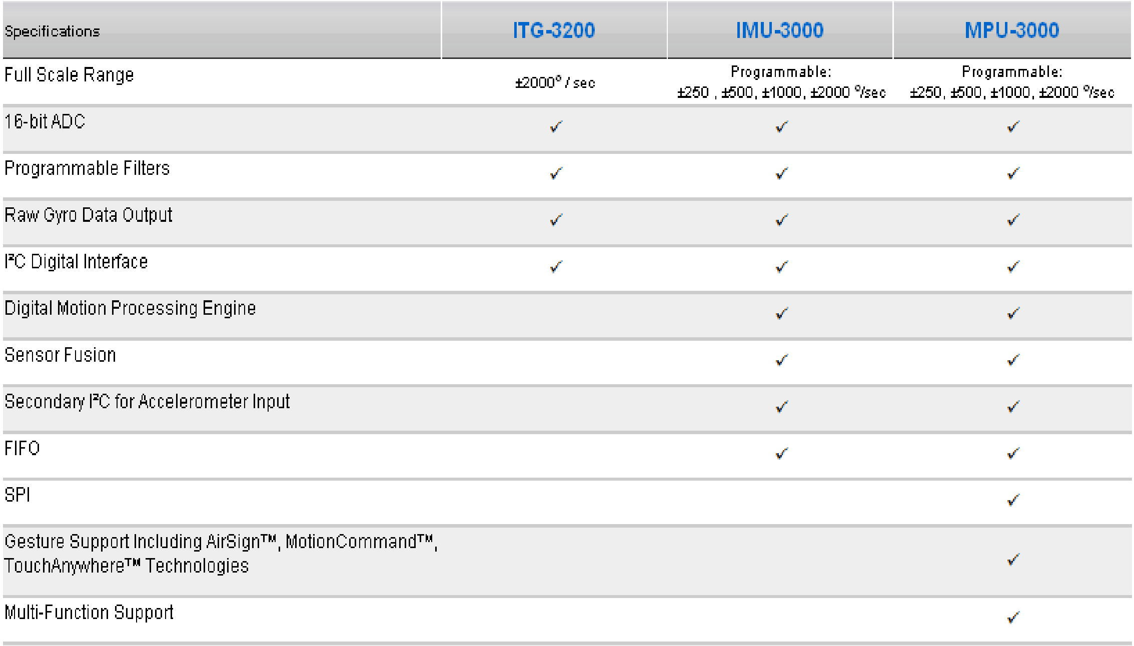
3.2.2 *Gyroscopes in the market*

For the gyroscopes, we had the same restrictions of weight. Looking for small-package three-axial gyros, we realized that only two manufacturers met our requirements:

Table 3.2 Gyroscopes in the market

Provider	**Component**	**Output**	**#Axis**	**Range**	**Sensitivity**	**Size**
ST	L3G4200D	Digital	3	250 500 2,000 º/s	8.75 17.5 70 mdps/digit	4x4x1 mm
InvenSense	ITG-3200	Digital	3	2,000	14.375 LSB/dps	4x4x0.9 mm
InvenSense	IMU-3000	Digital	3	250 500 1,000 2,000 º/s	115 57.5 28.75 14.375 mdps/digit	4x4x0.9 mm

These gyros are really similar (in size and specifications). The *ST* model is programmable but it seems to be unavailable. ITG-3200 does not have a programmable range and *InvenSense* has two more interesting models but they are not available yet (even the datasheets). There is a comparison between these models:



Specifications	ITG-3200	IMU-3000	MPU-3000
Full Scale Range	±2000° / sec	Programmable: ±250 , ±500, ±1000, ±2000 °/sec	Programmable: ±250, ±500, ±1000, ±2000 °/sec
16-bit ADC	✓	✓	✓
Programmable Filters	✓	✓	✓
Raw Gyro Data Output	✓	✓	✓
I^2C Digital Interface	✓	✓	✓
Digital Motion Processing Engine		✓	✓
Sensor Fusion		✓	✓
Secondary I^2C for Accelerometer Input		✓	✓
FIFO		✓	✓
SPI			✓
Gesture Support Including AirSign™, MotionCommand™, TouchAnywhere™ Technologies			✓
Multi-Function Support			✓

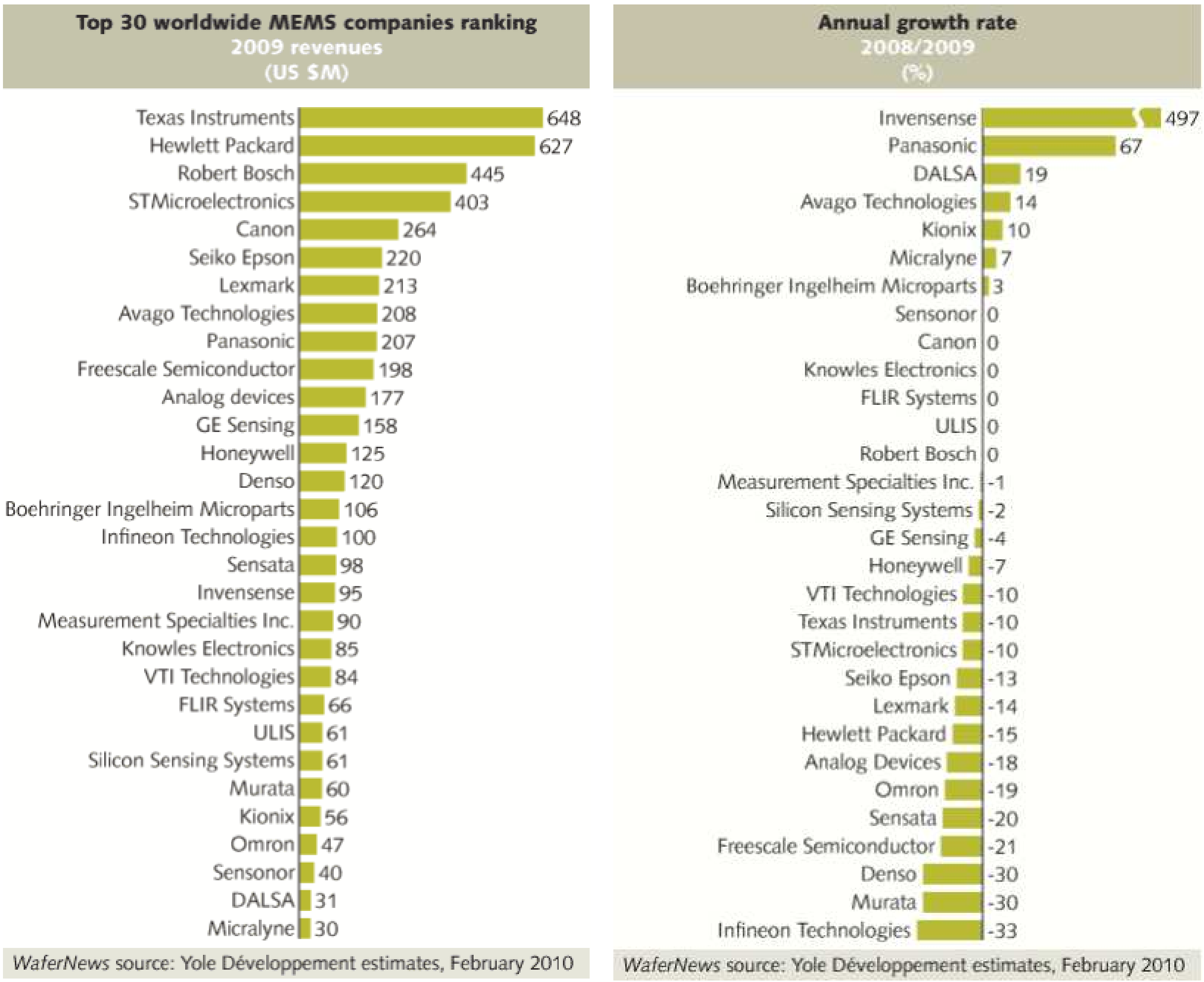
Fig. 3.1 Comparison between *InvenSense*'s gyros

As we have seen before, *ST* has local providers and distributors (more than one). *InvenSense* is an American company and has some distributors in Germany and the United Kingdom.

3.2.3 *Market analysis*

We can analyse the MEMS market to know a little more about these companies:

Yole Développement is a market research and strategy consulting company, founded in 1998 and involved (among others) in the MEMS field. In order to obtain this information, I have used the documents that refer to their reports because the price of each report is between 1,790€ (the old ones) and 3,990€.



WaferNews source: Yole Développement estimates, February 2010

WaferNews source: Yole Développement estimates, February 2010

Fig. 3.2 2008 top 30 and annual grow rate

We are going to start with some graphics of the Top MEMS companies ranking (2009) and annual growth rate (2008/2009):

First, I have to emphasise the fact that the overall growth rate of MEMS market between 2008 and 2009 is -5%. They have sold $7B this year, $5.1B from the top 30 companies (out of 250 tracked by *Yole*).

We can look at the market leaders: *Texas Instruments* and *Hewlet Packard*. In 2009, they accounted 25% of the top 30 revenues. However, it was the 29% two years earlier. In 2008, both dropped around 13% and in 2009 we can see that *TI* dropped by 10% and *HP by* 15% (losing the first place).

The next two from the list (*STM* and *Bosch*) are interesting for us because they manufacture sensors that satisfy our requirements. In 2008, *ST* grew by 37% but in 2009 dropped by 10% (losing the third place that it had won one year before). *Bosch* grew by 5% in 2008 and remained constant in 2009, partly thanks to the *Sensortec* unit that reached a 125% growth.

Analog Devices grew by 2% in 2008 but dropped by 18% in 2009.

Finally, we have to talk about *InvenSense*: although in 2008 it did not appear on the top 30 list, in 2009, it reached the 18th place with an incredible growth of 497%.

Taking into account that they are only selling gyroscopes, it is a really good result.

Talking about MEMS accelerometer, we can see in the next graph that *STM* led the market in 2008. Nevertheless, bearing in mind that *Bosch Sensortec* has grown a lot in 2009, the *Bosch* group may have gained the first position.

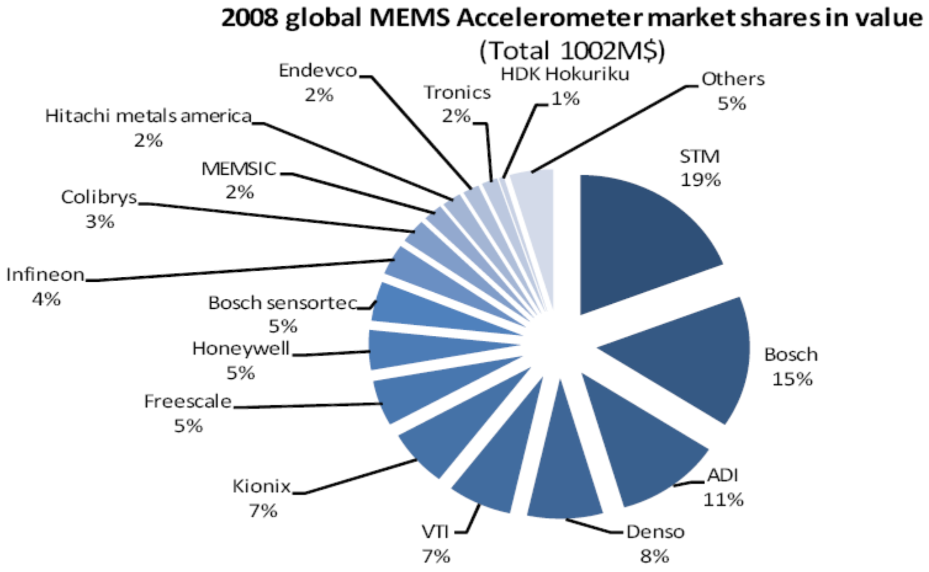
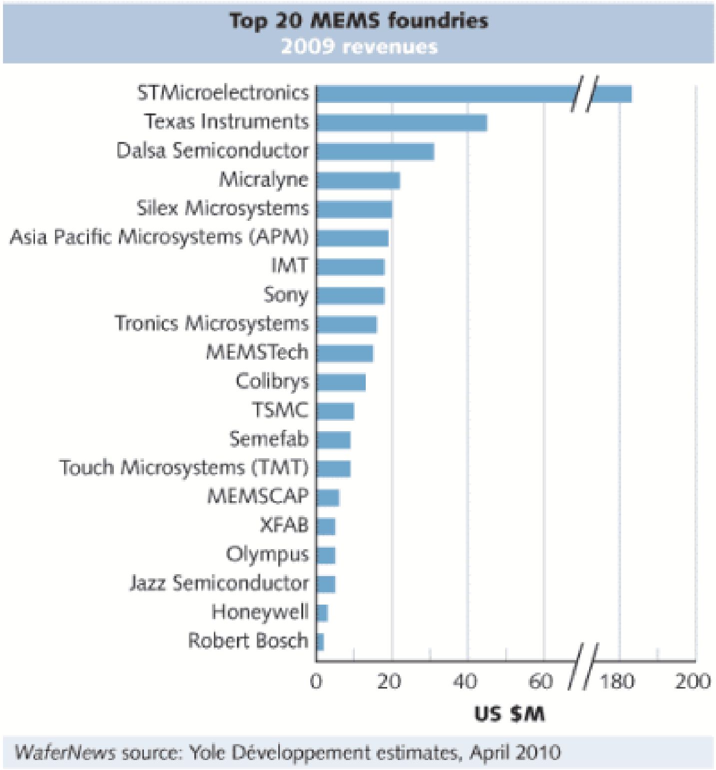


Fig. 3.3 2008 MEMS accelerometers sales (Source: Yole Développement)

In the MEMS gyroscope market, it is known that *STM* and *InvenSense* are leading the race of the 3-axis gyros. The ITG-3200 from *InvenSense* is used in the expansion of the *Wii-mote* (of *Nintendo Wii*). Moreover, it has been announced that it will also be used in the new *Nintendo* portable console: *Nintendo 3Ds*.



WaferNews source: Yole Développement estimates, April 2010

Fig. 3.4 Top 20 MEMS foundries

We can also take a look at the top 20 MEMS foundries:

ST is the leader in MEMS foundry business with 40% share (a little less than the previous year). *Hewlet Packard* is now the largest consumer for MEMS foundry services, followed by *InvenSense*. So, some of the MEMS producers are using external foundries but some of them (like *Sony*) are also offering their own foundry services.

3.2.4 *Final choice of components*

In the choice of the components, we are taking a main choice and a backup choice in order to feed the independent dual design we have to do.

3.2.4.1 Accelerometer component

As our first choice, we will use *ST* LIS331HH mainly because of his bigger range. Moreover, *STMicroelctronics* seems a company that fits the profile we were looking for. The second one will be *Bosch* BMA220, although the last *ST* accelerometer is also interesting. This is principally not to give the monopoly to a company.

3.2.4.2 Gyroscope component

We have used *InvenSense* ITG-3200 because it is the only one available in the market. An *InvenSense* representative has told us that the other two will be available in November. A *ST* representative has told us that their gyro will be available in January 2011 (despite being announced as available now).

CHAPTER 4. INERTIAL PLATFORM CONSTRUCTION

4.1 EAGLE, a PCB CAD

EAGLE (Easy Applicable Graphical Layout Editor) is a CadSoft program for designing printed circuit boards (PCB). EAGLE works with Windows, Linux and Mac. The EAGLE Light Edition can be downloaded for free in the *CadSoft* website and be used for non-profit projects (such as educational projects). The EAGLE Light Edition has some limitations: useable board area limited to 100 x 80 mm, only two layers (Top and Bottom) can be used and Schematic can only create one sheet.

EAGLE 5.9.0 Light version has been used in this project

When opening the EAGLE program, the first window that opens is the Control Panel. Here we can find the default libraries, design rules, projects and user interface. If we want to design a PCB board, we can either start a New Project or a New Schematic or Board (each Board has a Schematic linked).

The Schematic window is used for designing the circuit diagram. The Board window is used to draw the circuit board based on the schematics connections. There is also a window called library to create or edit the library files (components).

4.1.1 *How to start?*

The first thing we need is to know HOW the board will be. For this, we have to know which components we need. As soon as we find it out, we can run EAGLE and start.

The first step is to assure that we have all the components in the libraries and if not, download, edit or create them.

4.1.2 *Library window*

Each library is divided in three sections: Device, Package and Symbol.

The package section is the land pattern of our component. The symbol section is the schematic representation of the component. The device section is used to define the object with a package and a symbol and link them.

4.1.2.1 Package

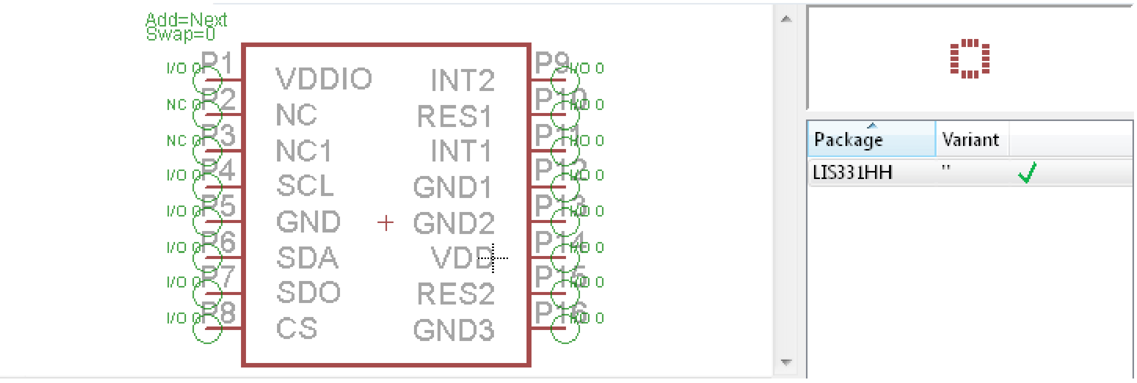
Basically, we use Wires (in the tPlace layer) and Smd (in Top and Bottom layers). Wires show the shape and size of our component and Smd show the contact surface.

4.1.2.2 *Symbol*

We use Wires to draw a schematic (box) of our component, Pins to determine the pin out and Names to rename the pins.

4.1.2.3 *Device*

We utilize Add, to add a Symbol of the device and New to add a package for the device. Finally, we have to connect the pins with the equivalent pads.



Package	Variant	
LIS331HH	''	✓

Fig. 4.1 Device section of a library

4.1.3 *Schematic window*

Once we have all the components we need in library files, we can put them on a Schematic file and determine how they will be connected.

In order to do so, we will ADD the parts. We will use WIRE to determine the connections between them, JUNCTION to determine the junctions and LABEL to name the nets (and also to connect separate ones).

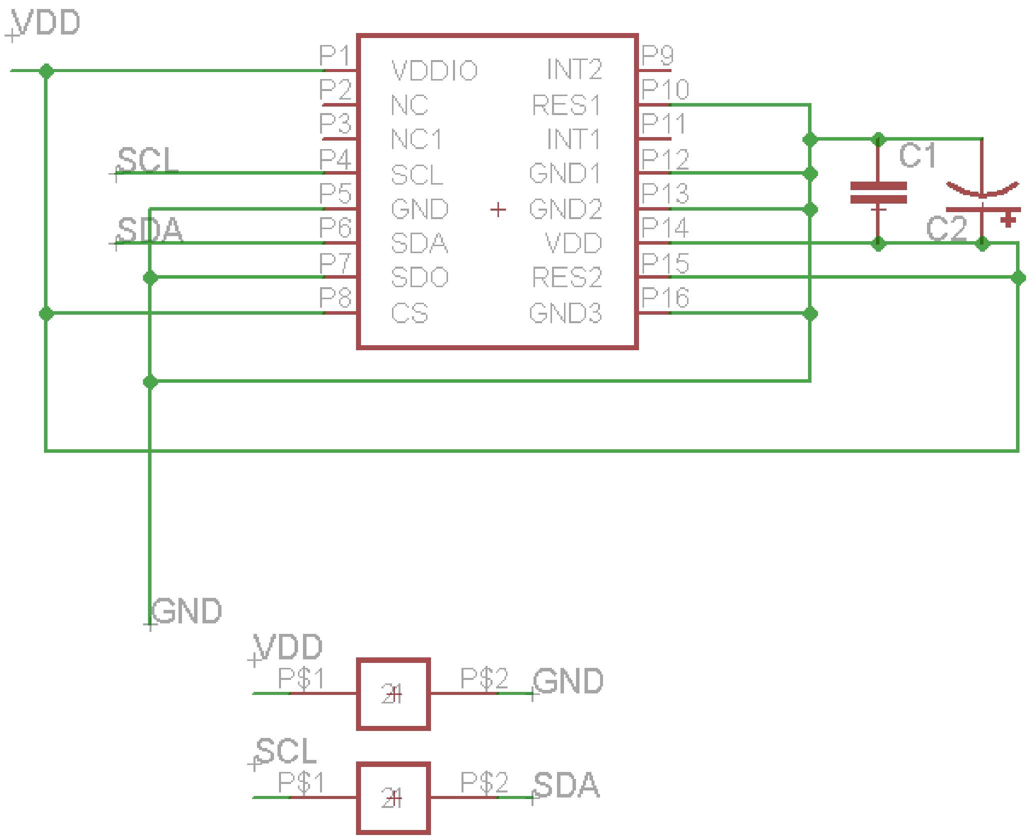


Fig. 4.2 Schematic Window

4.1.4 *Board window*

Once the Schematic is finished, we can switch to the board and the program will create all the packages indicating the connections we must do (based on the Schematic) with lines in the Unrouted layer.

So it is time to set each component on its place, using Move and Rotate commands. When all of them are in the desired place, we use the Ratnest command to optimize the “unrouted” lines.

Now we can connect them using the Route command (and delete using Ripup). We can choose between different types of Wire Bend and Width on the Parameters bar. If we use the route command, switching the layer between top and bottom will create vias automatically (we can also change the characteristics in the Parameters bar).

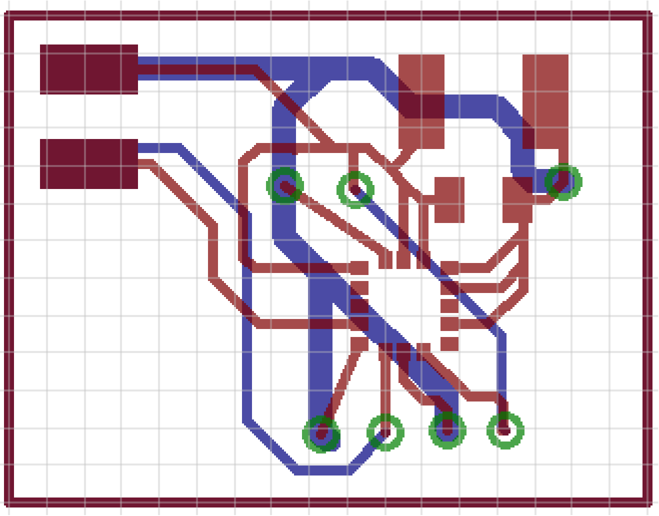


Fig. 4.3 Board Window

4.1.5 Printing the board

When the board design is finished, it is time to print it. It is highly recommended to follow the next indications when printing the boards:

EAGLE prints the layers that are shown at that moment so we have to hide all the layers that contain things we do not need in the board (normally we are going to let only Top or Bottom, Pads and Vias). When printing double-side boards, we will have to print both sides separately: one with Top and the other one with Bottom.

In the Print window:

- We have to make sure that the Scale factor is set to 1, and the Options Black and Solid are activated.

- When printing the Top side, we have to remember to select the Mirror option and unselect it when printing the Bottom.

- The first time we print, it will be necessary to check Printer properties to be sure that we are printing with the highest resolution (at least 1,200 dpi if we are working with small sizes).

4.2 Inertial platform design

To do the low cost inertial platform, we have decided to make separate boards for the accelerometer and the gyroscope to test them separately. One of the reasons is that we have few samples and, by doing separate boards, we reduce the probability of error. Besides, in case of error it is easy to detect it if we know in which sensor occurred.

To test them as one (like an inertial platform) we have done an I²C hub and used an Arduino Board (also designed and manufactured by us).

As we will see on the next section, we have built a drilling machine. It is important to mention that now because we have used an approach to place the Vias aligned for our inertial platform designs. For our first Arduino boards designs, this was not really important because it did not suppose a manufacture time reduction.

4.2.1 *Accelerometer board*

As we can see, we have a four pin connector: VCC and SCL on top and GND and SDA on bottom. Connecting the SDO/SA0 pad to ground means the accelerometer will have the Slave ADdress (SAD): 0011000b. Power supply decoupling capacitors are placed as close as possible to the device pin 14 for datasheet specification and one of them must be 10µF aluminium capacitor. We did not have aluminium capacitors so we had to use the only 10µF polarized capacitor we had, a big tantalum one. Interrupt pads are disconnected.

4.2.2 *Gyroscope board*

It has a similar approach to the accelerometer board: the same 4 pins connector. This time, we have connected the SA0 pad to VDD, which gives the gyro the SAD: 1101001b. In the next figure, we can see the evolution from the first design to the final one. The main differences are: an optimization of space (size reduction) and holes alignment. There is also a shape delimitation to make the transfer easier.

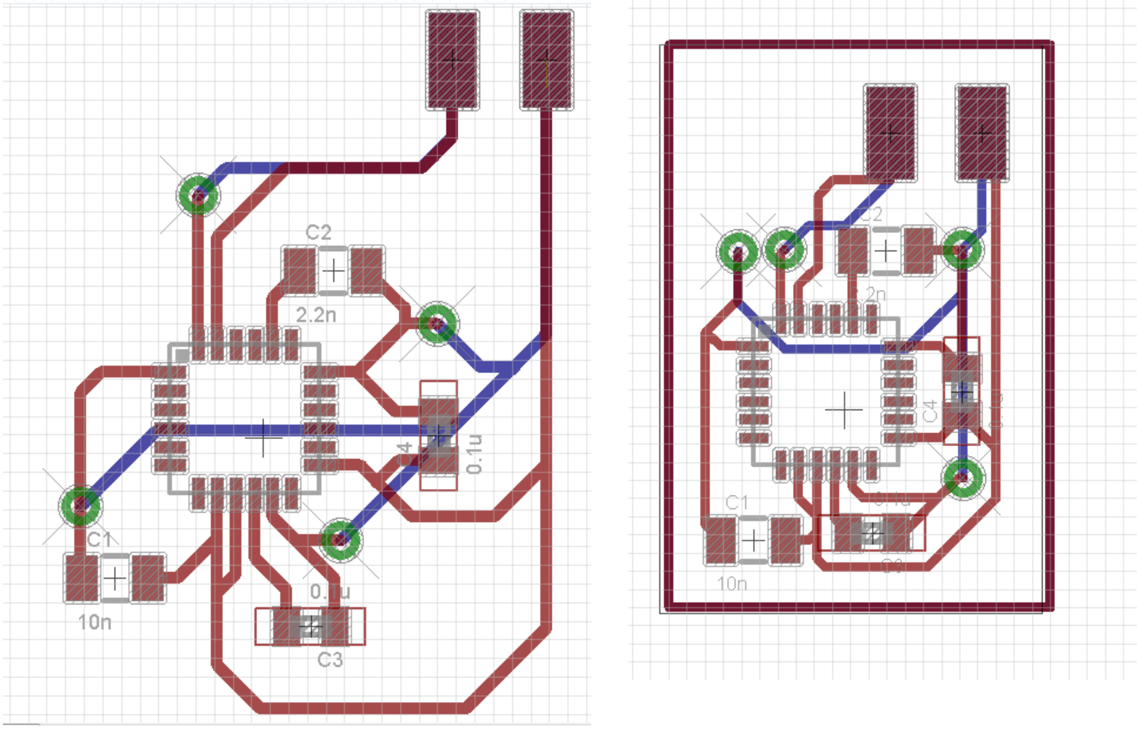


Fig. 4.4 First and final design of the gyroscope board

4.2.3 *I^{2}C hub board*

We tested the two boards separately and they worked, so it was time to test them together. We have made a “hub” to be able to plug both boards to the same I^{2}C bus and also the same power supply and ground. We have done two possible approaches. The first one, with the three boards on the same plane, rotated 90º respect the Arduino board. The second one is also perpendicular to the Arduino board but the accelerometer and gyro boards are in different parallel planes. We have used the second one because the Arduino and sensor boards are parallel in this approach, the size is smaller and the holes are aligned.

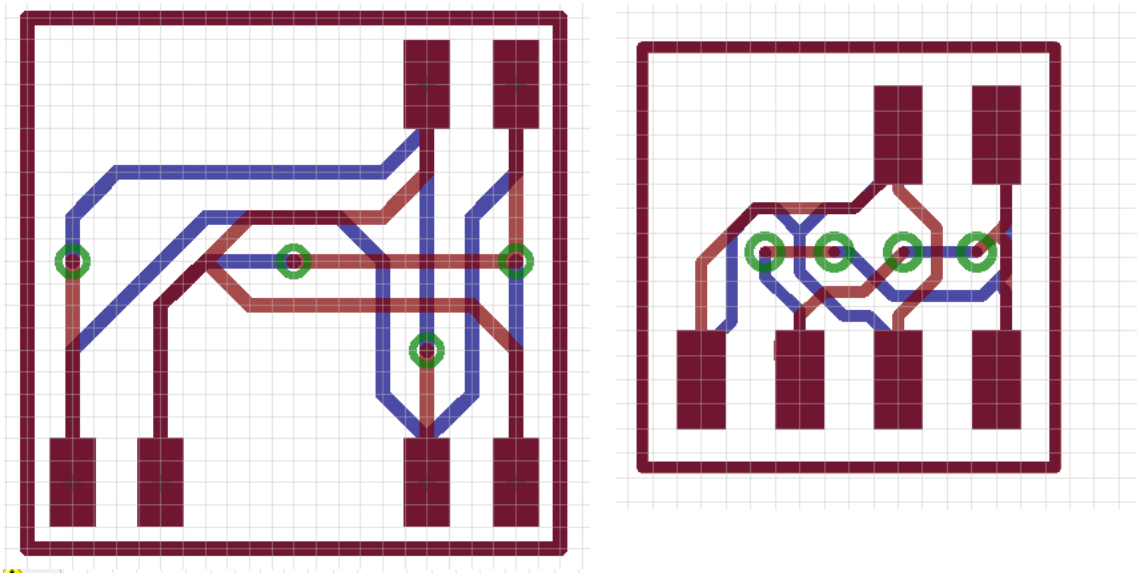


Fig. 4.5 Two versions of I^{2}C hub board

4.2.4 *Inertial platform board*

This is basically an assembly of the other three boards. But there are also some changes. We have decided to try a 10µF ceramic capacitor in the accelerometer (instead of the polarized one) because we found that the ST evaluation board used this kind of capacitors. We have also used the smallest capacitors we have (0201).Therefore, there is an optimization of space.

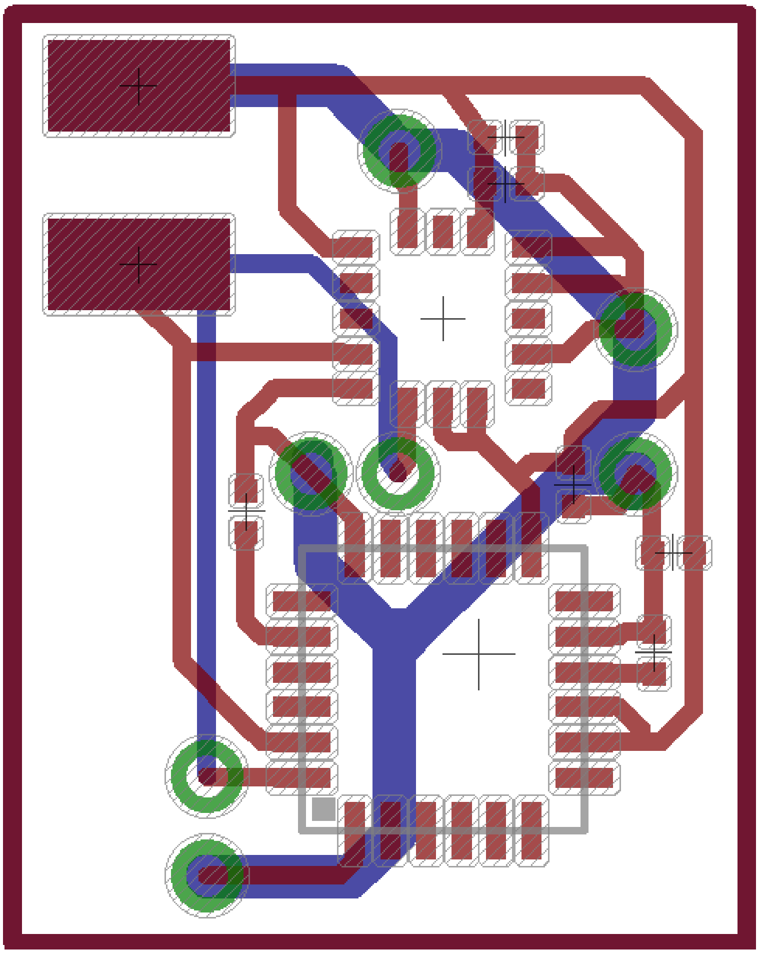


Fig. 4.6 Inertial platform board

4.3 Inertial platform manufacture

A lot of time has been spent improving our own PCB manufacture process. This is because, when doing it manually, you can have a lot of constants and trial. The result method for each particular process is often the most efficient way to find the optimum results.

Now we are going to explain the different things we have tried and the results we have obtained, a guide of optimum PCB manufacture with our equipment that may not be used for other equipments (since we could not simply use the instructions or guides we found on books and websites). Nonetheless, it can be taken as a reference.

4.3.1 Printing the design

One of the most important things in printing is to use a laser printer. Depending on the size that you are going to work, high-resolution will be necessary (at least 1,200 dpi).

We tried different papers: normal, recycled, photographic, transparency and magazine.

We had a lot of problems to transfer with transparency paper (acetate) because of heat (when printing and also when transferring). We didn’t obtain good results in tonner transfer with photographic paper. Normal and recycled paper had similar results, good transfer but difficult to remove. So our best option was magazine paper.

4.3.2 *Preparing the board*

The first thing to do was to select the cooper clad board thickness. We had 1/16” and 1/32” and we decided to use the first one because of the greater robustness.

One of our problems when doing the toner transfer was the alignment. The best solution we came up with was to delimitate the board size in EAGLE design and use this size also to cut the board.

Once we had the board with the appropriated shape and size it was time to clean the cooper plates. We used sandpaper to remove impurities and prepare the board for transfer. We tried two different grid sizes: P400 and P2000. We got better results with the second one. It is said that it works better if it is wet, but we did not have any remarkable improvement. If a wood and sandpaper are used, it is easy and faster to remove any spline or defect in the cooper surface in order to make a homogeneous surface. Then a random pattern is recommended in order to see if there are any de-lamination, bubble or bending in the board. It is important to ensure a correct toner transfer process.

After sanding, we cleaned the board with acetone avoiding to touch cooper surface with dirty or wet hands.

4.3.3 *Aligning top and bottom layers*

This is one of the weakest points of our method. The first process we tried to improve was to align the top and bottom papers using a light source, staple them together and put the board between them. The problem was that the thickness of the board introduced a chance of error greater than our margin allowed. We improved the alignment process by cutting the paper and the board with the same size and rolling up toilet paper to fix the alignment and also to help distributing pressure and heat. However, the magazine paper sometimes moves a bit when rolling up the toilet paper and the top and bottom layouts are not aligned.

4.3.4 *Transferring the printing*

In order to transfer the layouts from the paper to the board, we need heat and pressure. The first option was to use an iron but this only allowed single-side transfer at a time and when doing the other side we would deteriorate the first transfer.

The second option was to use a hair iron. This allowed us to do the dual-layer transfer at a time but, because of the open and close angle, there were some errors due to irregular pressure over the board.

The third option was to use the hair iron to make a device for our purpose. Modifying a little bit a drilling press and adding the hair iron plates, we built what we have called the “Masking Device”.

Experience has shown us that it is important to centre the board to obtain a regular pressure and to use a determinate weight to obtain the optimum one. Depending on the pressure, the results are different. If we use a very light weight to press the Masking Device, we will lose part of the layout when removing the paper. If we use a very heavy weight, the layout will be over transferred and we will lose quality of the layout (thicker tracks can touch and that will mean a short circuit). The irregular pressure involves an unbalanced transfer (while a part of the board is still not transferred, the other part is over transferred).

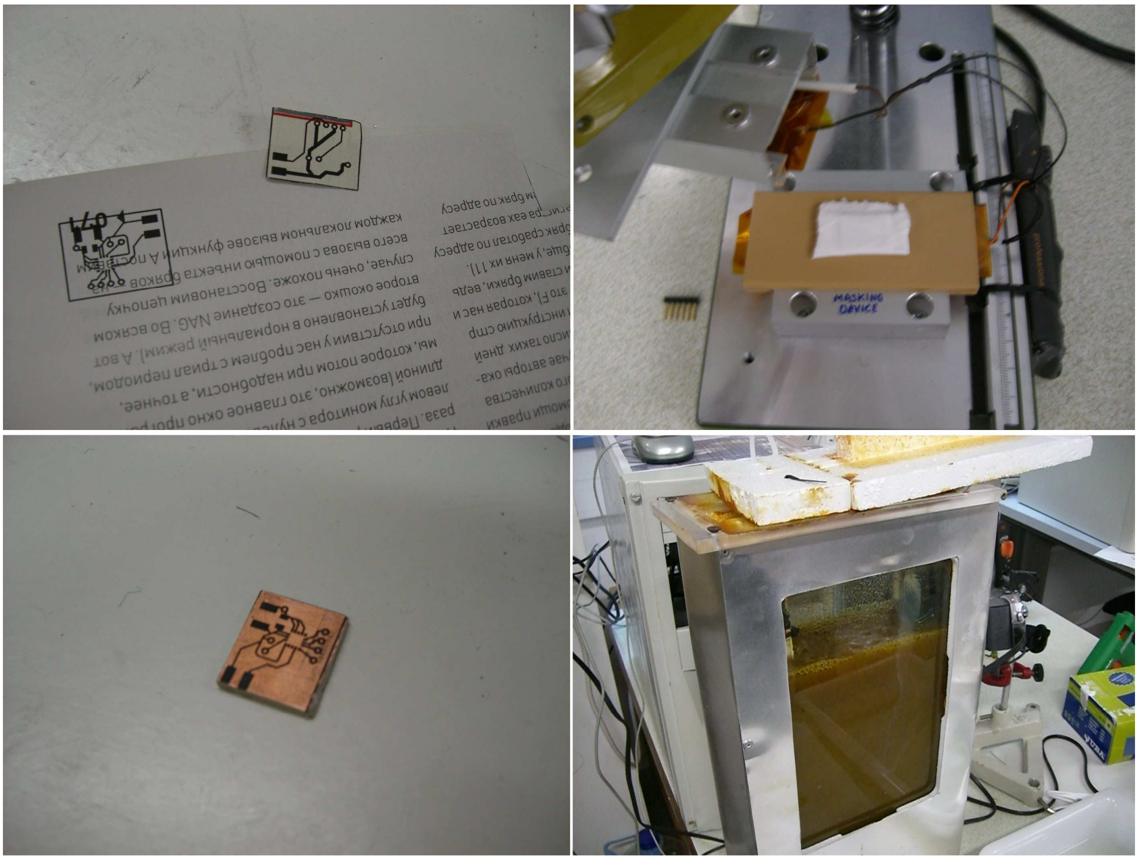


Fig. 4.7 Printed design, board before and after transfer and during the etch

Heat is also important so we decided to choose the maximum heat and always proceed the same way: first putting the board on place and next turning the Masking Device on. So the different results depend on heating time. Through trial and error method, we found that around four minutes was our optimum heating time. More time or less than those four minutes will produce similar results to over- or under-pressure.

After these four minutes, we turn the Masking Device off, remove the weight and throw the board to a water container. After few seconds, we can remove the paper.

4.3.5 *Removing the paper*

We tried several ways to remove the paper from the board after the transfer. The best option is to remove it rolling it carefully with the finger all along the board. After this, we can use a brush to remove the paper, cautious not to brush too hard. Using a cleaning brush is easy to remove the paper in order to reduce chemical contamination when etching.

4.3.6 *Checking the alignment*

This step is very important. After removing the paper from the board, we have to do an alignment check of top and bottom sides in two axes. This can be done placing carefully any connector over the pads and visually comparing both sides.

If there is a displacement of more than a millimeter in any of the axis, we have to consider if it is critical or not. In case of doubt, it is recommended to clean the board with acetone and restart the process from step 1 (the board can be reused).

4.3.7 *Etching*

We have a mix of water and ferric chloride inside an aquarium. Between step 1 and 2, it is recommended to connect it to start heating the etching machine.
The use of disposable gloves is indispensable for safety reasons.

We have to look for an empty space in any board border where it will be set inside the tank. We remove the lid that the plastic clothe-spin has attached and hold the board with the clothe-spin.

We close the tank in order to avoid hazard vapors and the board will be immersed in the mix.

After 5-7 minutes, we can remove the board of the etching machine. Lower time can leave metallic debris that can short-circuit the board. More time can start to eat away the printed part of the board and that can imply to lose some connections. The time is extended when chemicals are degraded with the use and extra time is required.

Now it can be cleaned using current water.

4.3.8 *Drilling*

We have a big drilling press platform but it is not very good for accuracy drilling because of the vibrations. So we decided to use a hand drill. It was very slow and still imprecise. So we decided to make a drilling platform for precision drilling.

It first moved upon an axis automatically and another manually so we decided to align the holes in our designs to speed up the process. Now the other axis is also automatic. It is somehow planned to automatize the third axis and to computerize all the drilling process in a completely automatic high-precision drilling machine. In the future, it will be upgraded to a numeric control CNC device commanded by a computer application.

Fig. 4.8 Board in the drilling platform, with solder paste, inside the oven and the final result

4.3.9 *Preparing the board (2)*

We have to prepare the board for the soldering process. We have to carefully press the board to a paper soaked with acetone. Once no more ink is transferred with only pressing, we can rub the board with the paper. This is not to get the board dirty.

It is time to test the circuit to search for short circuits. If we have any, we can repair it using the blade.

After this, we can sand lightly the board and clear the board one more time with acetone.

4.3.10 Applying solder mask and solder paste

We have to print again the Top layer (we can use normal paper). In this pattern, we have to cut all the pads that need solder paste, align them with the board and fix them together using tape.

We can take the soldering paste out off the fridge and put a bit over the solder mask, using a blade we can distribute the paste all over the board.

When finished, we can carefully separate the mask and the board and place all the components over the board on its place.

4.3.11 Soldering

We have an oven that has been programmed to follow a typical heat curve for the correct soldering of the components.

If needed, we can do some soldering corrections: if some component has not finished the soldering process, we can use the soldering iron to finish it manually. If we have any short circuit due to an excess of soldering paste, we can use Flux and a wire to clean it.

Finally, we connect the wires and connectors manually. Using flux, tin solder and the soldering iron, we can solder the wires inside the holes (vias) to connect top and bottom layouts and connectors over its corresponding pads.

4.3.12 Improvements study

We are studying some alternatives to Step 10. Doing a paper solder mask is an inefficient and slow process. We found the possibility of using a paint that can “print” our mask over the board with an exposure unit and transparency stencil.

As explained, the drilling process can also be improved (in terms of manufacturing time and accuracy).

4.4 Inertial platform implementation

We used several programs to do the implementation of the board. The use of each one is justified and explained.

4.4.1 Arduino

Arduino is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. The hardware is a single-board microcontroller with an Atmel AVR microcontroller. The connectors are exposed allowing the CPU board to be connected to interchangeable modules.

Some versions of original Arduino hardware have been commercially produced but the designs are distributed under Creative Commons license so if you have the components and the technology you can do your own Arduinos (although the name cannot be used for non-official products).

We have a commercial Arduino Pro Mini but, after learning a little about the processor, we decided to redesign a MCU that exploits all the capacities of the Atmel processor.

In the next figure, the evolution of our boards is shown. The last versions are able to control up to 6 servos.

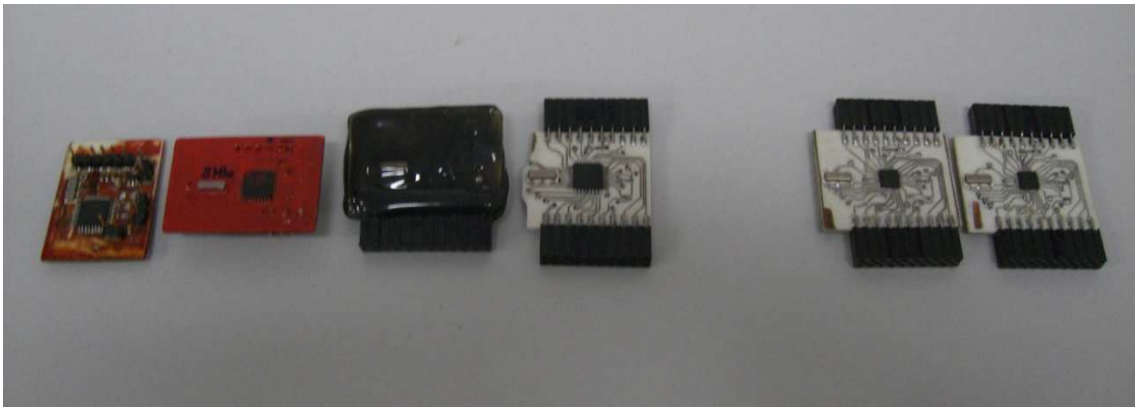


Fig. 4.9 Evolution of the Wikirduinos

The Arduino software can be downloaded for free in the Arduino's website. It is an application written in Java. It includes a code editor and it is easy to compile and upload.

We used the I²C ports of our called "Wikirduino" to communicate the gyro and the accelerometer (as slaves) with the Atmega processor. We used the UART ports and a UART to USB converter to connect the Wikirduino to the computer.

Using the software Arduino, we have programmed the MCU to ask the gyro and the accelerometer for the measurements.

The following libraries have been defined:

For the Gyroscope (ITG-3200)

```
#define "itg3200.h" // GYRO ITG-3200
#define GyroID B1101001
//Register 22 - FS_SEL, DLPF_CFG
#define R22 0x16
#define R22INIT B00011011
//Register 62 - Power Management
#define R62 0x3e
#define R62INIT B00000001
//Registers 27 to 34 - Sensor Registers
#define TempH 0x1b
#define TempL 0x1c
#define GyroXH 0x1d
```

```
#define GyroXL 0x1e
#define GyroYH 0x1f
#define GyroYL 0x20
#define GyroZH 0x21
#define GyroZL 0x22
```

For the Accelerometer (LIS331HH)

```
#define "lis331hh.h" //Accelerometer LIS331HH
#define AccID 0x18
//Register CTRL_REG0 - Power management and conf
#define RCTR0 0x20
#define RCTR0INIT B00100111
//Sensor Registers
#define AccXH 0x29
#define AccXL 0x28
#define AccYH 0x2B
#define AccYL 0x2A
#define AccZH 0x2D
#define AccZL 0x2C
#define AccStat 0x27
```

When the libraries are defined, we can name them.

With Arduino, we ask the MCU to give us the values in a specific format. We can see the output in the Serial Window.

4.4.2 LabVIEW

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a graphical programming environment to develop measurement, test, and control systems.

Using Arduino, we obtained the numerical values in rows and columns or the way we preferred. Using LabView (and also Matlab but with worst results) we put these values into graphs to see the behavior of the inertial platform. Moving the IMU, we appreciated changes in the different “axes” on the graph lines and also on the gauges.

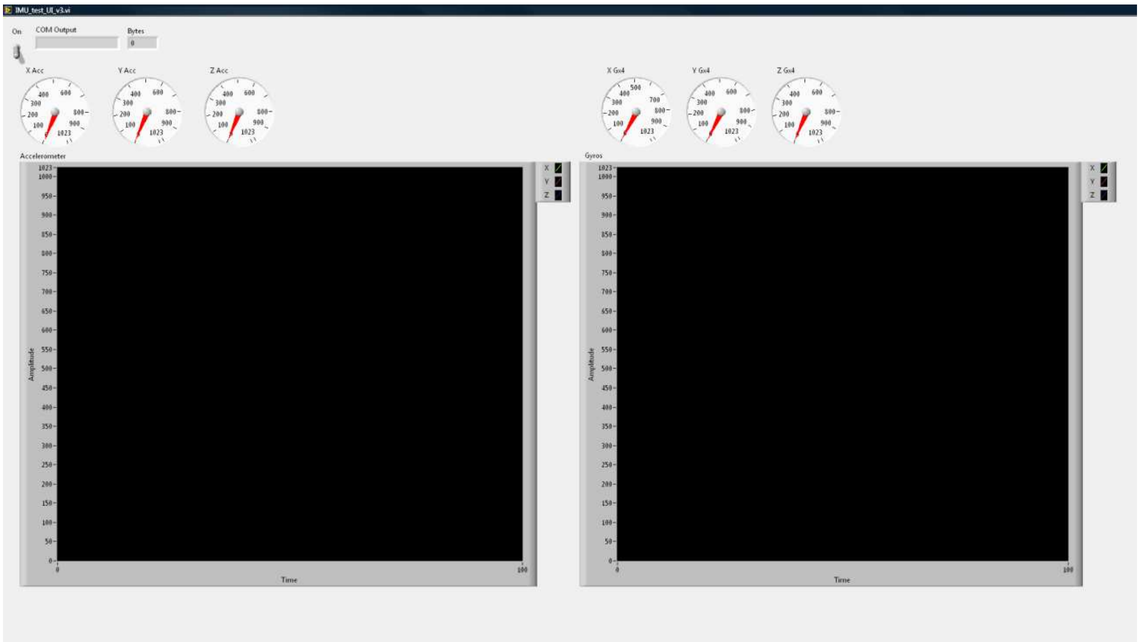


Fig. 4.10 LabVIEW interface

4.4.3 *C Sharp*

C# or C Sharp is an object-oriented and component-oriented programming language. We can move or rotate a 3D model in accordance with the parameters provided by the IMU. This is only an example of OpenGL based application connected to the IMU.

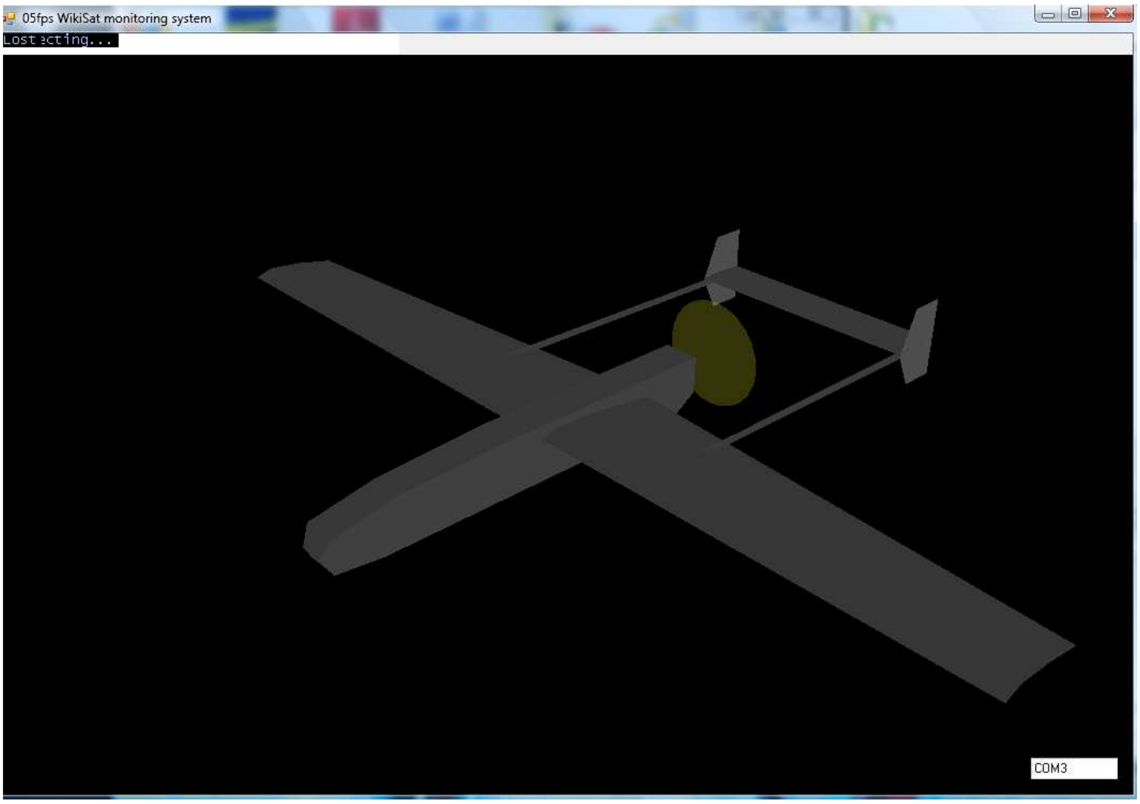
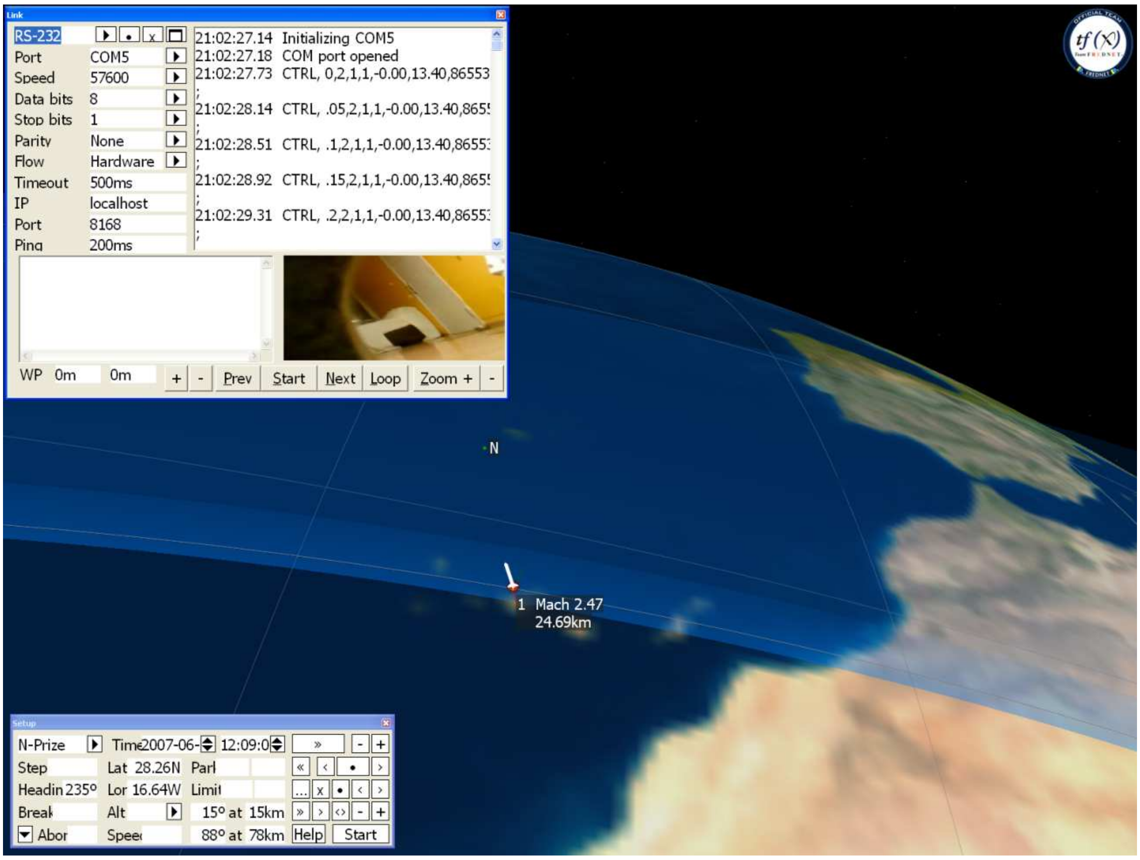


Fig. 4.11 C# interface

4.4.4 *Moon2.0*

Moon2.0 is an open source Windows based application. It is a launcher simulator first created to simulate trajectories for the team FREDNET's mini-launcher for the Google Lunar X PRIZE. Now it is also used to simulate the trajectories of the WikiLauncher for the N-prize.

Since the 2.0.100712.1007 version, the option to use an Inertial Platform to control the trajectory has been implemented by Laia Navarro. This is a simulation of how it will be used during the launch.



RS-232
Port COM5
Speed 57600
Data bits 8
Stop bits 1
Parity None
Flow Hardware
Timeout 500ms
IP localhost
Port 8168
Ping 200ms

```
21:02:27.14  Initializing COM5
21:02:27.18  COM port opened
21:02:27.73  CTRL, 0,2,1,1,-0.00,13.40,86553
;
21:02:28.14  CTRL, .05,2,1,1,-0.00,13.40,865
;
21:02:28.51  CTRL, .1,2,1,1,-0.00,13.40,8655
;
21:02:28.92  CTRL, .15,2,1,1,-0.00,13.40,865
;
21:02:29.31  CTRL, .2,2,1,1,-0.00,13.40,8655
;
```

WP 0m 0m

N-Prize
Time 2007-06- 12:09:0
Step
Lat 28.26N
Parl
Headin 235°
Lor 16.64W
Limit
Break
Alt
15° at 15km
Abor
Spee
88° at 78km

Fig. 4.12 Moon2.0 interface with the Link panel

4.5 Inertial platform comparison

We can compare size, weight, price and specifications between our own inertial platform and the commercial one that used the prototype (6 DOF Razor – Ultra-Thin IMU):

Table 4.1 Comparison table between commercial and our inertial platform

	Commercial IMU	**Our IMU**
Output	Analogical	Digital
Accelerometer range	±3 **g**	±24 **g**
Accelerometer sensitivity	18 mg /mV	12 mg /digit
Acc bandwidth	1.6 kHz	500 Hz
Acc noise density	300 µ**g**/rtHz	-
Gyroscope range	±300 º/s	±2,000 º/s
Gyroscope sensitivity	0.83 -3.33 mV/ (º/s)	14.37 LSB/ (º/s)
Size	30 x 12 mm = 18.97mm^2	7 x 4.5 mm = 5.61 mm^2
Weight	5.4 g	0.565 g
Price	$89.95 = 69.83€	18.78€

4.5.1 *Price bill*

Taking into account only the material and components prices (because we are using the equipment to do lots of PCBs) the final price is:

- Accelerometer: 5.72€
- Gyroscope: $15= 11.64€
- Board: £4.11 (266 mm^2) → £0.09 (5.61 mm^2) = 0.11€
- Solder paste: $15 (12 g) → $0.05 (4 mg) = 0.04€
- Capacitors: 0.87€ (10)

TOTAL: 18.78€

4.5.2 *Calculated weight*

- Accelerometer: 20 mg
- Gyroscope: 40 mg
- Board: 500 mg
- Capacitors: 0.26mg (1) → 1.6mg
- Solder: around 3 mg

TOTAL: 0.565 g

4.5.3 *Percentage reduction*

Weight: -89.54%
Size: -70.43%
Price: -73.11%

CHAPTER 5. INERTIAL PLATFORM SPACE VALIDATION

In order to avoid doubling the work, the validation test will be done with the final whole satellite instead of using each separate board or each prototype. It has to be remembered that the final satellite will be placed in the same board to reduce the weight and increase the robustness.

5.1 Radiation

Radiation effects can cause degradation but also failure of the electronic and the electrical systems.

Radiation in space is generated by particles emitted from variety of sources. The most important sources are the sun, other stars and novas and supernovas in our galaxy and beyond. These ionizing particles are influenced by Earth magnetic field to form radiation belts, called Van Allen radiation belts. The inner belt extends from an altitude of 100-200 km to 6,500km above the Earth surface and contains high concentrations of protons.

The South Atlantic Anomaly (SAA) is a region where a depression in the Earth magnetic field affects the Van Allen radiation belts. As result, the intensity of radiation in this zone is higher.

The usual unit used to specify radiation dose is the “rad” and the material is always specified in parentheses.

For satellites in inclination lower than 28º Low Earth Orbit (LEO) in both hemispheres, the typical dose rates are 100-1,000 rad(Si)/year. For satellites in higher inclinations (between 20 and 85 degrees) LEO in both hemispheres, the total dose rates are 1,000-10,000 rad(Si)/year because of the SAA.

For commercial components, typical hardness levels are between 2 to 10 krad.
We can predict the lifetime of the components. In high inclinations (worst conditions) the dose rate is about 2.7-27 rad(Si)/day. Taking the minimum hardness of 2 krad and the higher dose rate per day, we obtain an estimated lifetime of 74 days: more than enough for our satellite (actual simulations give us 8 days in orbit).

But radiation can also cause electronic malfunctions, like Single Event Upset (SEU) which means a bit reversal in digital signals.

So, to study the behavior of the inertial platform under radiation, we will do some tests using a radioactive source.

5.2 Vibrations

During the launch, the satellite will be working under high vibrations conditions. It is also normal that vibrations on the satellites are tested on ground to validate them. Space related facilities use big electrodynamic shakers and hydraulic shakers to test in a wide range in vibration testing.

With these shakers, they test the vibration under different frequencies in one or more axes.

We can build our own bench test, based on small electrodynamic shakers, or use a centrifugal machine.

The Moon2.0 simulator gives us the maximum g values that the satellite has to withstand. We will have to test under higher g forces to have a margin.

5.3 Temperature

In orbit, the temperature changes are fast and beyond the ranges inside the atmosphere. First, we have to study the thermal budget to know the temperatures range that has to withstand the satellite. Afterwards, we can do the tests under the minimum and maximum values to assure that it will not fail under the calculated thermal conditions.

We will use the calibrated oven for high temperatures and a freezer for low temperatures.

The test fast temperature change must be also tested but it will be more difficult to reproduce.

5.4 Electromagnetic compatibility

Before launching the satellite, we have to be sure that there are no interferences between inner components of the satellite and also from other electromagnetic sources. The electrostatic discharge has to be tested as well. Electromagnetic compatibility tests can be done using an anechoic chamber or a sniffer.

We will use an anechoic chamber to do these tests.

5.5 Vacuum

In vacuum conditions, out-gassing occurs in every material. Every day exposed materials become weaker. As it happens with under radiation conditions, we think that for the short lifetime of our satellite (8-9 days) we do not have to worry for the vacuum exposition. But we will also do the tests to be sure.

A high vacuum chamber of 10^{-5} atmospheres will be used.

5.6 Other

Near space tests will also be done using high-altitude balloons. These balloons have traditionally served as a test-bed for sub-orbital and orbital test technologies. The balloons are filled with helium (or hydrogen), go up to an altitude between 18 and 37 km where they pop and open a parachute for the descent. During this time, required tests are done. Afterwards, the load is recovered (using a GPS device for example) for examination and recovery of components.

A web based free simulator called Spenvis (Space Environment Information System) from ESA will also be used in order to check the effect of space environment over the satellite.

CHAPTER 6. Environmental impact

Our design will deliver a satellite to the space. In the last phase of the design, we have taken into account the disposal of the stages in the Earth.

The launch phase is the most contaminant source in the mission, but debris will reenter soon in the Earth atmosphere.

We have tried to optimize resources in order to reduce the impact to the environment: wasting the lowest electricity possible and reusing materials through the process.

6.1 Study and actuation plan for hazardous trajectories

Using the simulator Moon 2.0 (version 20100420_2350), the actuation plan for hazardous trajectories has been done.
For this simulation, the launch point has been placed in Tenerife but the real launch point has yet to be determined. This is an example of how the actuation plan has to be done. It will be useful to establish a pattern for the final actuation plan, the operation method, propose improvements for the simulator and so on.

6.1.1 *Aborting on stage 1*

It starts with a study of the mini-launcher trajectory in case of aborting on stage 1 (deployment). In this case, the results have been:

28.377807N, 009.994091W (without deployment) – yellow mark
28.376238N, 009.947660W (deployed) – pink mark

Both points are located in Assa-Zag province of Guelim-Es Semara region in Morocco. An analysis of the zone has been done.

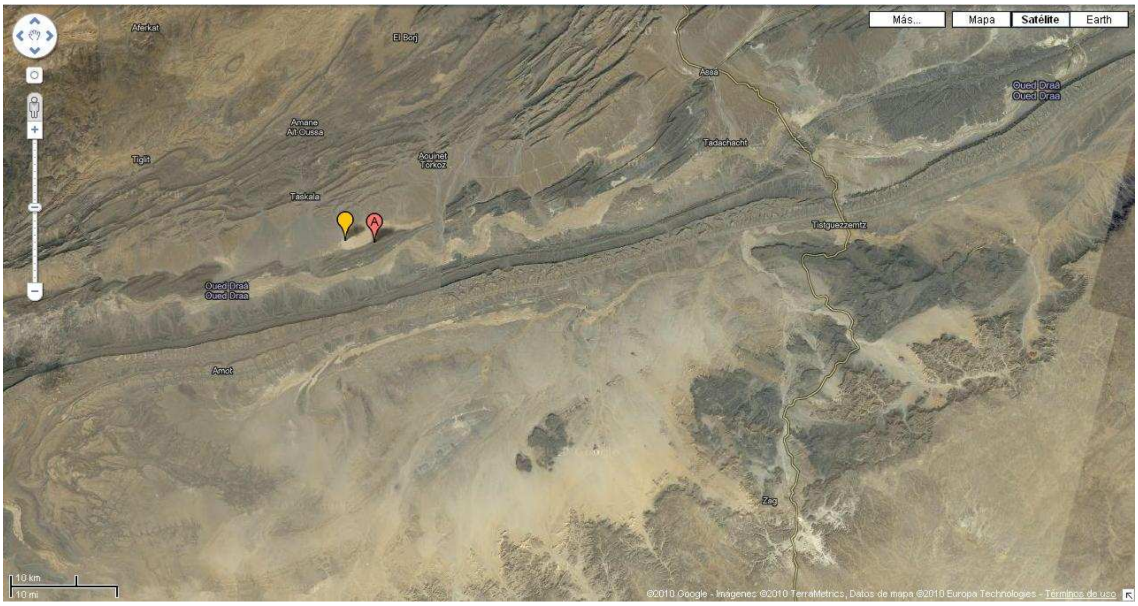


Fig. 6.1 Collision points when aborting on stage 1

The population of this province is estimated to be 58,952 people, 17,024 living in Assa and 23,909 in Zag.

This makes a total of 40,933 people amongst both cities. If we subtract this number from the total, the remaining population for the rest of territory is 18,019. Knowing that the provinces surface is 18,428 km², disregarding the surface occupied for both cities (or even taking up to 400 km²), we obtain a population density of less than 1 people/km². Taking into account that most of them must live in villages, this density is even lower in the unoccupied territory. We also have to bear in mind that the nearest village to the expected impact zone is Taskala. The shorter distance between these two zones (so taking the deployment trajectory) is approximately 10 km.

A study about forces and temperatures that have to withstand the rocket during the reentry has also been done. These are, temperatures higher than 1,500℃ for 21 seconds and higher than 2,000℃ for 14 seconds, reaching a maximum of 2,600℃ in the case with deployment. Having this data, some tests must be done to check if the rocket will disintegrate during the reentry and auto-destruction will not be necessary.

Before studying the decisions that we will take when the rocket trajectory falls into the sea, we will continue with the study over the different inland zones.

During the flight, following the normal trajectory for the selected heading, the rocket overflies 3 land zones before the deployment. Some possible collision points have been studied to determine the minimum and maximum IspV with which the rocket will fall to the ground. It is also important to know the characteristics of apogee and temperature for these cases. That way, we will be able to determine an actuation plan for each particular situation.

6.1.2 *Zone 1: Morocco*

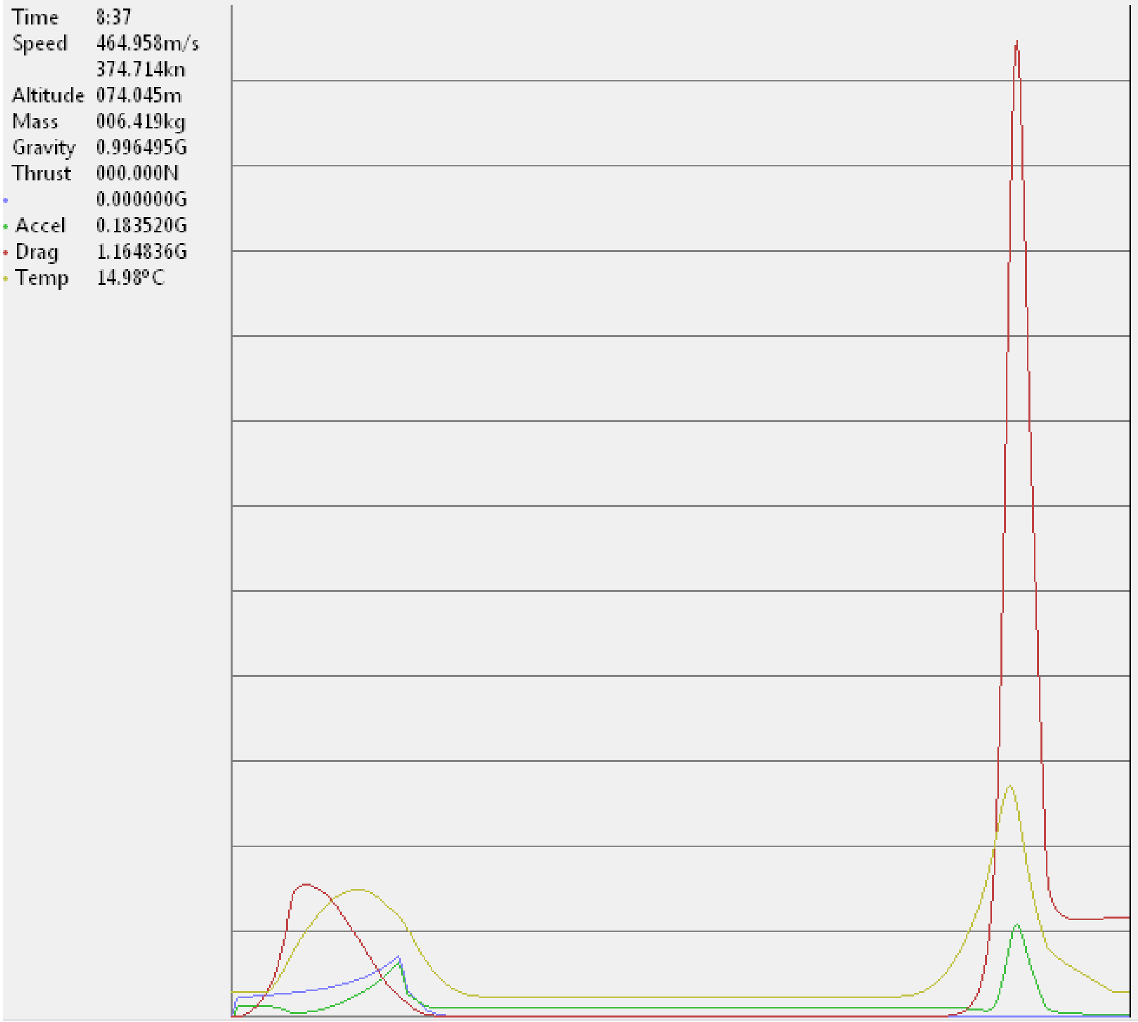
Fig. 6.2 Collision points in zone 1 (Morocco)

In order to know the IspV range with which the rocket will fall to soil, several simulations have been done changing the IspV value. First approximations have been done changing the tens value. When the limit ground-water has been determined, changes in units can be done to adjust the limit.

We can see the following example. I found the ground-water limit between 230 s and 240 s and adjusted it changing the unit value between them:

28.408482N, 011.664484W (IspV = 230 s)
28.405782N, 011.450280W (IspV = 234 s)
28.405038N, 011.396074W (IspV = 235 s)
28.400883N, 011.120406W (IspV = 240 s)

That is how we determine that the minimum IspV with which the rocket will fall in Morocco soil is 235 s. We can take a look at the forces and temperatures graph of this case:



Time 8:37
Speed 464.958m/s
374.714kn
Altitude 074.045m
Mass 006.419kg
Gravity 0.996495G
Thrust 000.000N
• 0.000000G
• Accel 0.183520G
• Drag 1.164836G
• Temp 14.98°C

Fig. 6.3 Temperature and forces graph for trajectory IspV 235

These temperatures are higher than 1,500℃ for 21 seconds and higher than 2,000℃ for 11 seconds, reaching a maximum of 2,400℃ in the case of deployment.

6.1.3 *Zone 2: Fuerteventura*

Fig. 6.4 Collision points in zone 2 (Fuerteventura)

The same study that has been done with Zone 1 to determine the maximum and the minimum margins to study the hazardous trajectories (when the rocket may fall down to ground):

28.411446N, 014.187890W (IspV = 174 s)
28.411791N, 014.152180W (IspV = 175 s)
28.413384N, 013.968720W (IspV = 180 s)
28.414225N, 013.854812W (IspV = 183 s)
28.414484N, 013.816222W (IspV = 184 s)

Like previously, these characteristics have been studied. Taking into account that the first of the trajectories to fall to the ground (IspV = 175 s) is the most restrictive, the study has been done with its thermal and force graph. The temperatures are: more than 1,200℃ for 20 seconds and a maximum of 1,500℃. An assay should be done with these conditions to determine if it is enough to burn the rocket or if it must be destroyed.

6.1.4 *Zone 3: Tenerife*

This zone is the most critical, since it is the same island where the rocked is launched from. In order to fall at the same island, a low IspV is needed. Therefore, the maximum height will also be low and the highest temperatures will not be high enough to burn the rocket.

To avoid this, we have thought of two possibilities:

The first one is to use an auto-destruction system. Since the rocket will not be able to receive instructions, the idea is to determine the optimum trajectory on-ground before the launch including an allowed tolerance. The inertial platform will determine the position and tell the MCU. The MCU will compare the position and take the decision to activate the auto-destruction system when needed. For this, we need to estimate the position with high precision.

The second option is to select a launch point next to a mountain. If we know the launch direction, the distance to the mountain, the height between the launch point and the top of the mountain in the selected direction and the distance from the top to the sea, we can calculate the launch angle necessary to crash to the mountain or to go over it and fall into the sea in case of failure.

6.1.5 Water zone

Using the website marinetraffic.org, graphics about traffic density in different ports and zones can be studied. Looking at the graphic from Las Palmas, we can see in which hours there is less density of traffic. We do this not only for the possibility to crash against one ship (that is very low), but also to avoid the possibility of sighting (not to frighten anyone).

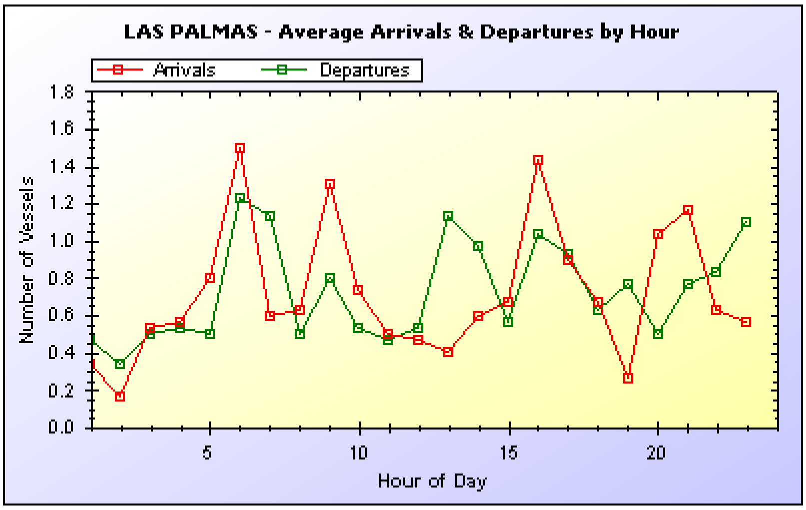


Fig. 6.5 Density of vessels versus hour graph in Las Palmas

6.1.6 Annotations

While doing these simulations, I have found a bug in the simulator and I have reported it to the programmer. In the new versions, this bug is corrected but IspV cannot be changed directly. However, the simulations can be done by changing the dry weight. In this new version, the simulator also shows the altitude of the rocket.

My proposal is to automatize this process: there is no need to show the rocket flying but an algorithm can be programmed to repeat the simulations changing the values with small step points. Some results could be saved when altitude is different to 0 (sea level), such as coordinates and temperature graph.

The thermal and forces behavior in re-entry must be studied. There are three options: the NASA has a program to reduce space debris and they provide a pair of tools to simulate the re-entry. The second option is to implement this kind of tool in our simulator. The third option is to do real simulations with rocket fuselage and some kind of oven or even fire.

The website marinetraffic.com does not have much coverage in some zones. Depending on the launch place, maybe some alternative has to be found.

Depending on where the final launch place is, the option of using a mountain as a protection wall can be hard to do. It will be difficult to find such a mountain. If we do, it may be inside a natural or national park or a World Heritage Site.

6.2 Assessment of the impact upon the environment

Because of the sizes we are working with and the low orbit we are going to use, this project does not mean an important impact upon the environment. The estimated time of the re-entry is between 8 and 9 days so we know that we are not generating space debris. The small size of the femto-satellite assures that it will be disintegrated during the re-entry. For the mini-launcher, we have to study all the cases but our idea is that it does not generate debris either. Moreover, the pollution generated is much lower than a big launcher would produce.

So the use of small mini-launchers not only signifies a reduction of costs, but also a reduction in pollution and a lower impact on the natural environment.

The generation of smaller technologies is also translated into power savings.

On the economic and social field, the use of low cost technologies for space uses can open a sector that has been inaccessible for many years. Governments, companies and organizations that until now were not able to afford the costs of space missions may benefit from this project.

CHAPTER 7. CONCLUSIONS

It has been demonstrated that:

- After the initial inversion, PCBs can be done with a low cost and adapted to the needs.

- We have been able to improve the performances of the commercial IMU, achieving reduction in size, weight and cost.

- Our inertial platform works correctly in Earth conditions. We will know if it also works with space conditions after doing the test for space, validating the satellite.

- We are able to work with MEMS technology and I²C bus.

- MEMS technologies are improving every day and the market seems to have a good present and better future.

- We are closer to facilitate the access to space by using small and low-cost technologies.

- It will be possible to control the rocket using the inertial platform but a high accuracy is required.

- This project means a reduction in pollution and a lower impact on the natural environment because of the reduced size.

BIBLIOGRAPHY

[1] Mohinder S. Grewal, Lawrence Randolph Weill, Lawrence R. Weill, Angus P. Andrews, *Global positioning systems, inertial navigation, and integration*, Wiley, New Jersey (2007)

[2] Jan G. Korvink, Oliver Paul, *MEMS: a practical guide to design, analysis, and applications*, William Andew, Inc. New York (2006)

[3] Nitaigour Premchand Mahalik, *MEMS*, Tata McGraw-Hill, New Delhi (2008)

[4] R. S. Khandpur, *Printed circuit boards: design, fabrication, assembly and testing*, Tata McGraw-Hill, New Delhi (2008)

[5] Joshua Tristancho, *Implementation of a femto-satellite and a mini-launcher*, Master Thesis, MAST – UPC (May 2010)

[6] http://www.csa.com/discoveryguides/mems/overview.php last visit 20-07-2010

[7] http://invensense.com/mems/technology.html last visit 20-07- 2010

[8] http://www.micron20.com/en last visit 20-07- 2010

[9] http://www.scienceprog.com/what-is-surface-mounting/ last visit 20-07-2010

[10] http://www.cadsoft.de/ last visit 20-07- 2010

[11] http://www.n-prize.com/ last visit 20-07- 2010

[12]http://www.sensorsportal.com/HTML/SENSORS/Accelerometers_Manuf.htm last visit 20-07- 2010

[13] http://www.mems-exchange.org/MEMS/what-is.html last visit 20-07- 2010

[14] http://code.google.com/p/moon-20/ last visit 20-07- 2010

[15] http://www.eng.uci.edu/node/1502 last visit 20-07- 2010

[16] http://www2.ing.puc.cl/~dmery/arqui/#material last visit 20-07- 2010

[17] http://www.marinetraffic.com/ais/ last visit 20-07- 2010

[18] http://large.stanford.edu/courses/2007/ph210/noriega1/ last visit 20-07-2010

[19] http://gazetteer.de/wg.php?x=&men=gcis&lng=fr&des=wg&geo=-6452&srt=npan&col=adhoq&msz=1500&geo=-134 last visit 20-07- 2010

[20]http://klabs.org/DEI/References/design_guidelines/design_series/1258jsc.pdf last visit 20-07- 2010

[21] http://www.jmnlab.com/pcb/pcb.html last visit 20-07- 2010 last visit 20-07- 2010

[22] http://www.electroiq.com/index/display/nanotech-article-display/0910361788/articles/small-times/nanotechmems/industry-news/2010/march/ti_-bosch__panasonic.html last visit 20-07- 2010

[23] http://www.yole.fr/ last visit 20-07- 2010

[24] http://www.ni.com/labview/ last visit 20-07- 2010

[25] http://www.arduino.cc/ last visit 20-07- 2010

[26] http://www.sparkfun.com/commerce/categories.php last visit 20-07- 2010

[27] http://www.wikisat.org/?p=166 last visit 20-07- 2010

[28] http://www.cs.unc.edu/~welch/kalman/kalmanPaper.html last visit 20-07-2010