Internship at the Institut de Physique du Globe de Paris Instrumental study : evaluation of the burying capacity of geophones used in actuator mode in the "geopod" for BASIX mission

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June-July 2010

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Abstract

Seismology is actually one of the most effective ways to study the internal structure of planets and small objects like asteroids. The *BASIX* mission is a seismic study of a very small NEO. As a consequence the gravity on its surface is very low which is a problem for an efficient installation of the seismometers. The technical solution foreseen is to use the geophones in actuator mode in order to vibrate the whole pod and bury the structure. This study is an evaluation of this technical option.

An experimental approach has been adopted : we made a CAD of a pod and created an on-board interface to control wirelessly the input signal of the geophones installed in the pod. The micro-gravity has been simulated by a counterweight system and the dust has been reproduced using polystyrene balls. The observations show that several physical parameters are involved in the burying process. The vibrations do not seem to be powerful enough to move the dust.

We also did a theoretical study of the system by implementing the equations of the dynamics into MathLab/Simulink. Simulations have shown the maximum displacement of the pod we can get is about $0,25\mu m$ in a *Galilean Referential*, which should not be enough to move the dust and bury the pod.

Contents

Acknowledgments

I would like to warmly thank Olivier Robert, my supervisor, and Philippe Lognonné for having offered me to work on this exciting project. I learned a lot from this first professional experience, thanks to their tutoring. I am also very grateful to all of the *Géophysique Spatiale et Planétaire* and *Géosciences Marines* teams who supported me during this internship, particulary Sylvain Tellier, Tanguy Nebut, Sébastien de Raucourt, Patrick Schibler, Shaobo Qu, André Langlade and Christophe Courrier who did not count their time to give me precious advice and new ideas. Thank you also to all the staff of the Neptune Observatory for their nice welcome.

1 Introduction

1.1 Situation

This internship is part of my masters degree in mechatronics (Applied Physics and Engineering Sciences), at the École Normale Supérieure. Its theme is instrumentation. This study deals with seismometry and particulary with a burying solution of a "seismo-pod" by vibrations. This pod will be used for a seismic study on 65803 - Didymos asteroid.

Discovery Program NASA has created the Discovery program in order to achieve "faster, cheaper, and more reliable mission offers". Contrary to other NASA missions, the budget is given at the outset and science and technology have to fit with the financial constraints.

BASIX project Boulder University, Colorado, has made a proposal [1] for a *Near Earth Asteroid* called 65803 - Didymos.
This little body is a small radius sphere (a little less than a mile long). As a consequence, gravity on it surface is very low ($0,2mm/s^2 \approx 2 \cdot 10^{-5}g$ on average). The mission is an active seismic study: seismic waves are created by explosions on the surface of the asteroid. To do so, five pods will be deployed on the surface of Didymos: some will be dedicated to the creation of the waves (with $5kg$ of explosives) and others will be the receptors. For the mission, Boulder has the explosive pod in charge, whereas the IPGP and the CNES are in charge of the design of the "Geopod" (in which all the instruments are on-boarded). The measures will be directly sent to an orbiter.

IPGP The "Géophysique Spatiale et Planétaire" laboratory of the "Institut de Physique du Globe de Paris" is specialized in the design of space seismometers. Indeed, seismometry is actually the most reliable way to study the internal structure of planets and other little bodies of the solar system.

Internship The main purpose of the internship was the assess of a technical solution: the burying of an instrument -a sismometer- in the ground by vibrating the pod of the sismometer. Indeed, in order to get good seismic data, it is prime to guarantee a tight contact of the instrument and the ground. As far as the gravity on the surface is very low and the waves created by the artificial explosions very powerful, the *geopod* needs to be deeply buryied in the ground.
The burying solution has been considered as far as we assume Didymos to be covered by a thick layer of dust. Because of weight/financial constraints (the cost of the mission is directly linked to the onboard weight), Philippe Lognonné[1] suggested to use the sismometers (geophones) as actuators in order to vibrate and bury the pod.
During this internship I was in charge of assessing this solution. On the one hand, a test bed has been designed: as the internship period was very short, I had to manage the orders in a way that I could receive several components and build the experiment. On the second hand, I worked on the conception of an electronic onboard interface in order to control the input signal of the actuators. A model of the vibrating and burying phenomenum is currently in progress.

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[1] Professor at Paris-Diderot University, IPGP

1.2 Issues

1.2.1 Physical constraints due to Didymos environment

This small asteroid has no atmosphere. Therefore the dynamics of the grain is hardly foreseeable. This phenomenum seems quite complex so we did not focus on the tackiness of the regolith. In this study, in order to simplify the model we did not consider the ground. We tried to specify the transfert function {movement of the pod}/{vibration of the geophones} considering the pod isolated from the ground. These estimations can then give good predictions to the effect on the movement of the dust around the pod.

1.2.2 A little sismometry...

A seismometer is a sensor that measures the movement of the ground and transforms it in an electronical signal.
On the physical point of view it is a mechanical deadened oscillating system excited by the ground movement. It is constitued of a weight which oscillates around an balanced position and deadened by a mechanical and/or an electromechanical strength (such as the figure 1 shows).

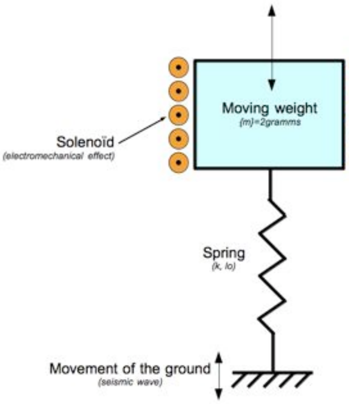

Figure 1: The movement of the ground is converted in an electrical signal by the solenoïd ; the oscillating system {moving weight + spring} is a classic pendulum.

Clearly such a system does not behave the same way in the whole field of the frequencies of the ground movement. In particular, the relative movement of the ground seems to disappear for very low frequencies.
Several types of seismometers exist, according to the frequencies they are sensible to : we can distinguish the "short periods" ($T \leq 1sec$) from the "long periods" ($T \geq 10sec$).

1.2.3 Geophones

The geophone is a very common short periods sismometer. It is based on the inducted current by the movement of a self in a magnet (*cf.* figure 1 and 2 [2]). The movement of the ground is communicated to the self in the geophone : the current is inducted and the tension on the pins of the captor is the image of the *speed* of the seismic wave.
Sometimes the geophone is used as a *Geophone Acceleration Captor* (GAC): a capacitor is connected to the ouput of the geophone so the standard response (speed of the wave) is derivated. The frequency response of such a system looks like figure 3.

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[2] Drawing by Aaron Barzilai *Stanford University*

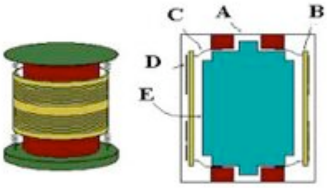


Figure 2: Diagram of a geophone *(A: the case, B: the cylinder, C: the return spring, D: the self, E: the magnet)*

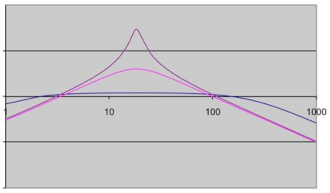


Figure 3: The response is flat (see in blue an example of *GAC Geophone*; in pink and purple classic geophones).

1.2.4 Constraints linked to the Boulder Pod

During the mission, the pods will be released from the orbiter and will land on the asteroid in an unknown position, that is why Boulder designed spheric pods.
The pod contains all the instruments for the seismic measures. In this study we did not consider the other components than the geophones. Therefore the experimental pod we studied is a sphere in which we have the three geophones (one for each direction of the space) and the electronic for a wireless control of the system.

2 Theoretical Model

We tried to build a simple model of a geophone and the weight of the whole pod in order to forsee the input current of the geophone to get the movement of the pod we want.

2.1 Parameters of the study

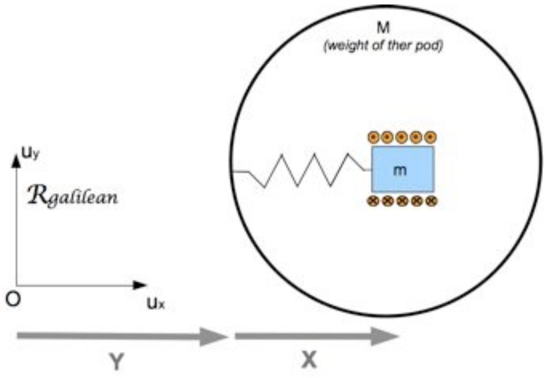


Figure 4: Parameters for the model : the Pod is isolated from the ground (*i.e.* we do not consider the interaction with the ground in this study)

2.2 Equations

We use Lagrange's method to find the equation of the dynamics of the system (in a Galilean referential).
First, we write the energies of the elements

$$E_{damping} = \frac{1}{2} \cdot \lambda \cdot \dot{x}^2 \tag{1}$$

$$E_{kinetic} = \frac{1}{2} \cdot M \cdot \dot{y}^2 + \frac{1}{2} \cdot m \cdot (\dot{x}^2 + \dot{y}^2) \tag{2}$$

$$E_{spring} = \frac{1}{2} \cdot k \cdot x^2 \tag{3}$$

Then we have $\overrightarrow{V_{1/2}} = \dot{x} \cdot \vec{x}$ which gives the energy coefficient $Q_x = F_{induction}$ because we have
$\overrightarrow{V_{1/2}} = \left\{ \begin{array}{c} \vec{0} \\ \dot{x} \cdot \vec{x} \end{array} \right\} = \dot{x} \left\{ \begin{array}{c} \vec{0} \\ \vec{x} \end{array} \right\} + \dot{y} \left\{ \begin{array}{c} \vec{0} \\ \vec{0} \end{array} \right\}$
Lagrange's equations can now be written:

$$\mathscr{L}_x : \quad \frac{d}{dt}[m(\dot{x} + \dot{y})] + \lambda \cdot \dot{x} + k \cdot x = F_{induction} \tag{4}$$

$$\mathscr{L}_y : \quad \frac{d}{dt}[M \cdot \dot{y} + m(\dot{x} + \dot{y})] = 0 \tag{5}$$

Considering:

- $F_{magn} = K \cdot i$ the electro-magnetic strength with i the current in the self and $K = \frac{e}{v}$ with v the speed of the moving mass in the pod: $v = \frac{d(x-y)}{dt}$;
- λ the damping;
- k the spring constant;
- M the mass of the whole pod;
- m the moving mass.

2.3 Simulation

Using Matlab/Simulink, we designed the block diagram of the system according to the Lagrange's equations :

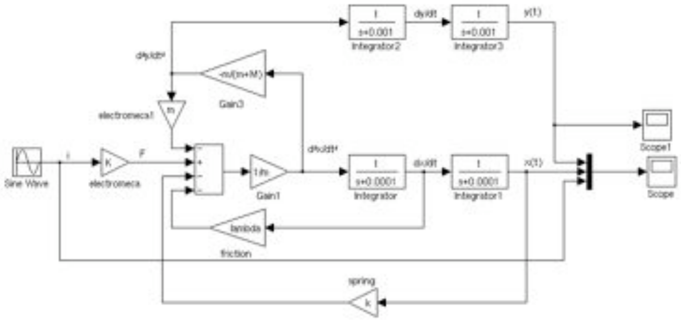


Figure 5: We used Matlab/Simulink to solve the differential system (*c.f.* equations 4 and 5)

By a "linear analysis" of the model, we found the resonance of the system : This information gives the frequency of the input signal, $i(t)$ if we want to get the higher amplitude for the ouput, $y(t)$.

Using this bloc diagram we can get the time behavior of the system. Figure 7 shows in yellow $y(t)$, $x(t)$ in purple, and $i(t)$ in blue. We can notice that $y(t)$ seems to be constant and equal to zero.

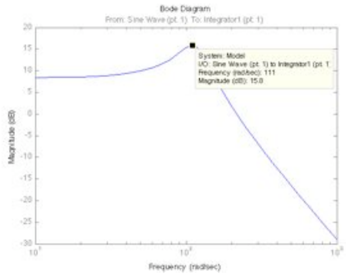


Figure 6: We found the resonance frequency of the system in order to adjust the input signal $i(t)$ at this frequency.

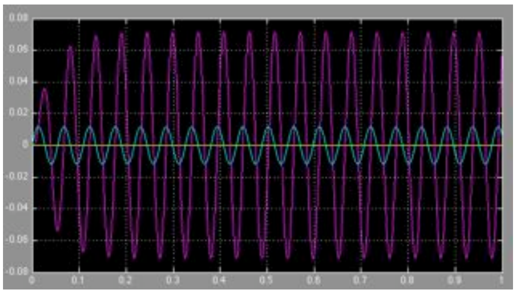


Figure 7: $y(t)$ in yellow, $x(t)$ in purple and $i(t)$ in blue (with $i(t) = I_0 \sin(\omega \cdot t)$ and $I_0 = 0,01A$)

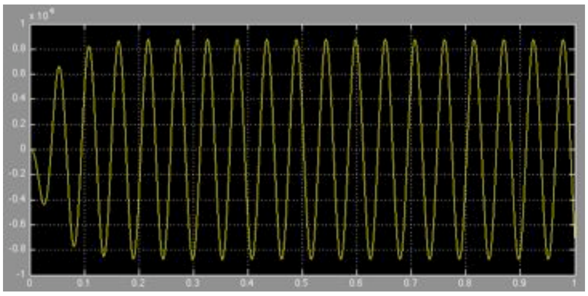


Figure 8: By zooming in, we can see the amplitude of $y(t)$: it is much smaller than $x(t)$ ($\sim 10^{-5}$ meters)

By drawing $y(t)$ on another graph (*cf.* scope 1 of 5) Matlab ajusts automatically the scale in a proper way (see figure 8).
As we see, the amplitude of the moving mass in the pod is much greater ($\sim 80mm$) than what we assume it clearance actually is (see $x(t)$, in purple, figure 7). That is why we tried to consider the abutment of the moving mass in the geophone by adding two springs to the mechanical model (these two springs have been considered to have a high deformation constant). To do so, we added a switch to the previous block diagram (see figure 9): the spring constant changes as $x(t)$ is equal to X_{max} which correspond to the clearance of the moving mass (we took $K_{max} = 10000$ and $I_0 = 0,01A$ for the scopes shown on figures 10 and 11).
By trying several values for the amplitude I_0 of $i(t)$ we understood the effect of the current on the movement of the moving mass during the shock: the more I_0 is high, the more violent is the shock (see figure 13).
That is why we tried to find the minimum value of I_0 which gives the maximum displacement $y(t)$. We found $I_0 = 0,0004A$ and $y_{max}(x) \approx 2,5 \cdot 10^{-7}mm = 0,25\mu m$ the maximum displacement of the pod.

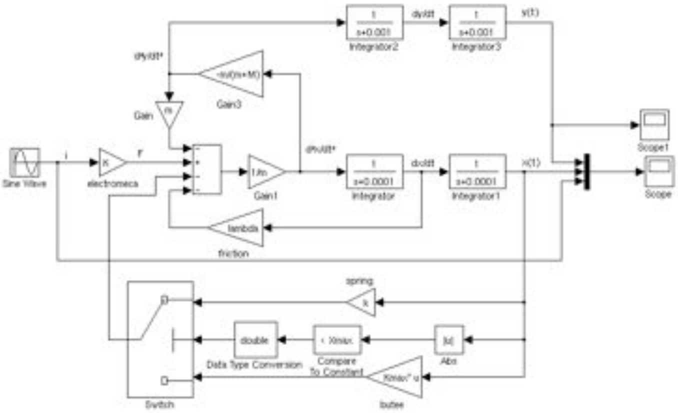


Figure 9: A switch has been added in order to reproduce the effect of the abutments of the moving mass in the geophone

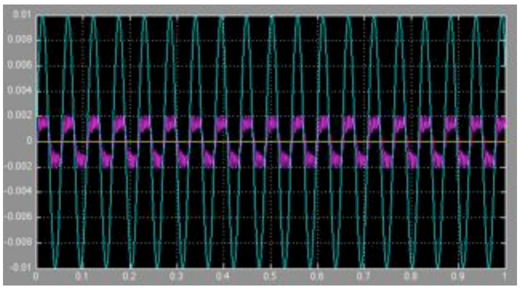


Figure 10: $y(t)$ in yellow, $x(t)$ in purple and $i(t)$ in blue. The amplitude of $x(t)$ is limited to $X_{max} = 2mm$ which limitates the amplitude of $y(t)$ (*c.f.* figure 11)

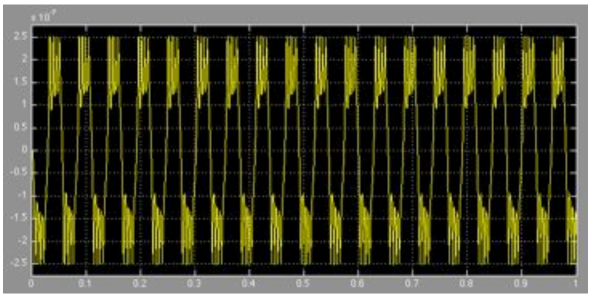


Figure 11: By zooming in, we can see the amplitude of $y(t)$: there are shocks each time the moving mass touches the abudments (*i.e.* each time $x(t) = X_{max}$)

2.4 Analysis of the simulation

As the system used in this study is an isolated system, we can say that it is conservative, which means there is no energy dissipation. Moreover, the center of gravity of the whole system does not move in a Galilean referential.

To simplify the model we isolated the pod from the ground. Therefore, no external action has been considered. That is why even the model in which we add the abutments does not reproduce the exact phenomenum.

During this internship, I did not had time to pursue this theoretical study so far. That is why I had to choose to continue this theoretical work or to try an experimental approach. The next section is dedicated to the experimental study (I came back to the theoretical study after my internship ended).

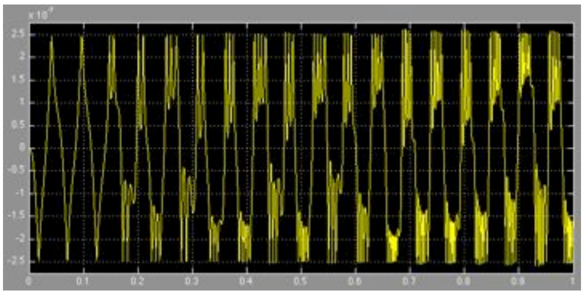


Figure 12: We started the simulation with $I_0 = 0,001A$ then we changed to $0,005A$ then $0,01A$ and $0,02A$ after two or three periods for each to show the quantitative effect.

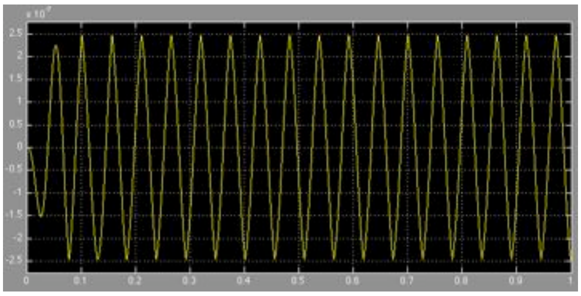


Figure 13: For $I_0 = 0,0004A$ the amplitude of $y(t)$ is maximum ($\sim 2,5 \cdot 10^{-7} meters$)

3 Experimental approach

3.1 Reproduicing Didymos Environment

3.1.1 Micro-gravity

For a seismic study, the captor must be closely in contact with the ground. Because of the small size of Didymos, the gravity on its surface is very low. That is why the geopod (*i.e.* the pod which measures the seismic waves) must be strongly maintained to the ground. The cheapest option to do so is to use geophones as actuators to vibrate the structure in a way to bury the pod under the dusty surface.

The experiment we made to assess this technical solution (burying the pod by the vibration of the geophones) had to be in a micro-gravity environment to represent the situation on the asteroid. We had two major options to do so. The first was to carry-out the experiment in a liquid for the Archimede force to compensate the weight so that the sum of those two forces equals the weight of the geopod on the asteroid. This option was very attractive because of the precision with which we could control the ratio of forces between the gravity and the Archimede force. But a major difficulty was to find the right fluids to use according to the size of the pod (Archimede force depends on it) and the density of the dust used for the experiment. In addition, a non-wanted effect were the fluid dynamics which could appear around the surface of the pod with it vibrations : on the asteroid there is no atmosphere and therefore particules move independantly one to the other, whereas in a fluid turbulences can appear and modify the movement of any particule around. That is why we decided to reproduce micro-gravity with a counter-weight as presented below :

3.1.2 Fluids used for the experiment

As we know so little about the dust on the surface of Didymos, we can assume it is regolith (it is the name given to the lunar ground). Its density is assessed to about 3.5. The geopod which is going to be used weight $17kg$ for a diameter of $270mm$ (the pods are spherical). Therefore we can calculate the equivalent density of the pod : for technical reasons (capacity of the 3D-printer), the module we made has a diameter of $180mm$.

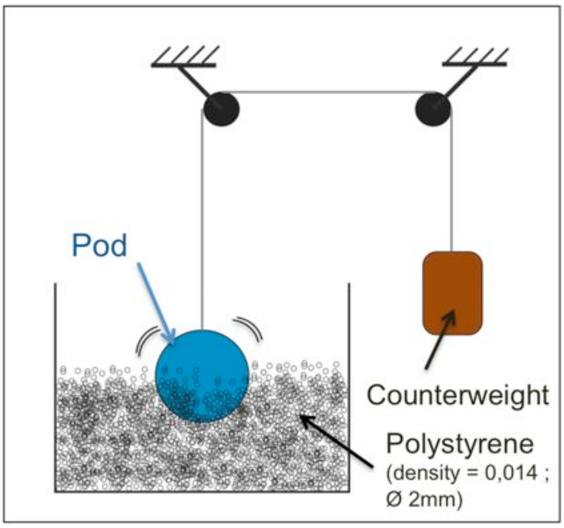


Figure 14: The regolith has been reproduced using polystyrene

3.2 The Pod

An experimental pod has been concepted in order to assess the solution of burying the pod by vibrations and to test different strategies of vibration. To do so we had to make footprints for the geophones which could allow changes of orientation. We also created an electronic interface in order to control the vibration strategy. The control was provided by an AVR ATmega microcontroller programmed in C langage.

3.2.1 CAD

We assumed that a vertical vibration could eject the pod from the asteroid because of the low gravity on the surface. Therefore we considered a configuration of the pod in which two of the three geophones were horizontal (*i.e.* parallel to the surface of the Asteroid). This is an ideal configuration because the whole action of each geophone is parallel to the ground : there is no vertical strength component. In this case the weight of the pod is the only vertical strength component on the dynamic. We count on the horizontal movement of the pod to dig the dust and on the weight to pull the pod down to the ground.
According to such considerations, we considered two main burying strategies :

1. in translation, so the dust is push away from the pod. As there is no dust, the gravity can attract the pod to the center of the asteroid :

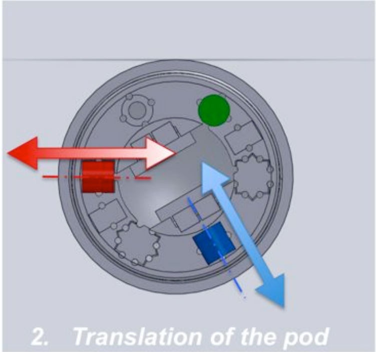


Figure 15: Translation

2. in rotation : the pod spins around the vertical axis. By contact with the hull of the pod, the dust moves and permits a vertical movement. A vertical action can be added by using the third geophone providing the module doesn't escape from the asteroid.

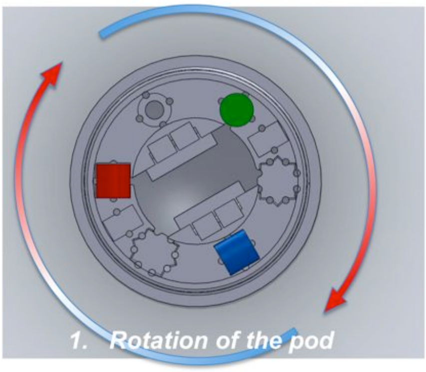


Figure 16: Rotation

As we can see in these pictures, we use the same footprint to ajust the orientation of the geophone whether in the "translation mode" or in the "rotation mode". These two options were found to be too simplistic, so we had other prints in order to combine both of the two first modes in several ways :

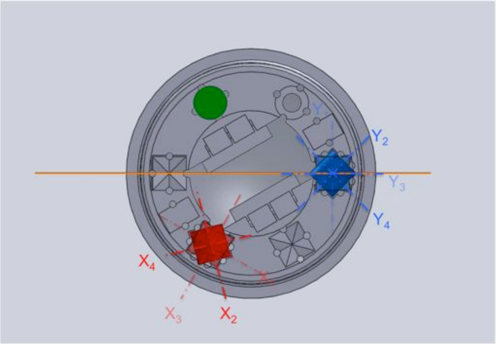


Figure 17: New orientations allowed (see axis 2 & 4)

3.2.2 Electronics

We developped an electronic interface to control the input of the geophones and to enable the communication between the pod and the computer by a wireless connection. To do so we created a three cards electronic which contains an alimentation card, a micro-controller card, and an interface card (*cf.* figure 18 for the global architecture). The software used is *Altium Designer*. The schematics of the electronics can be found in appendix.

Global architecture The three cards fit together by two header connections which allows to physically separate the several functions of the electronics in order to adapt this interface to other uses (see bellow fig. 19). In addition, this modular architecture of the electronics is a way to reduce the wires in the systems, for instance in order to minimize the vibration of other elements than the geophones.

Power supply card One of the three cards is dedicated to the management of the electric power. The supply voltage comes from two $9V$ battries or from an external alimentation. A charger can also be connected to load batteries.

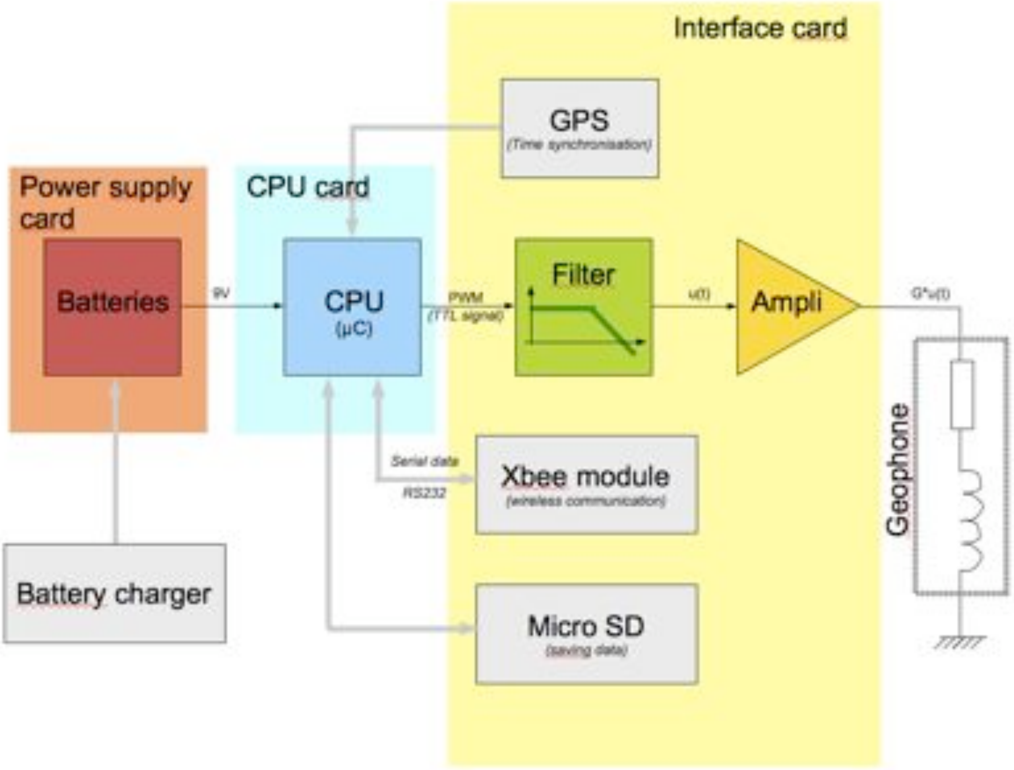


Figure 18: Architecture of the on-board electronic : there are three independant geophones *(the input signal can be different from one geophone to another)*

We can notice the 78ACS712 component which is a *Hall Effect* captor and allows for the measurement of the current.

CPU card The second card is designed to be plugged into the power supply card and contains the AVR ATmega microprocessor (644P). The ATmega 644P is a high-performance, low-power AVR 8-bit Microcontroller. It maximum speed of processing is $20MHz$, which allows quite a large panel of applications.
On the schematics we can distinguish the cristal which gives the clock to the AVR, an on/off button and a LED, a test button and a LED connected to one of the ouput of the microprocessor to manage the first tests of the card.
We can notice the connections for a Xbee module, which enables the wireless communication between the PC and the onboard electronics without adding any other card. Xbee modules are build with the Zig-bee protocol. They are very easy to use because of their very simple configuration.

Interface card This card is the application and communication card. There are connections for an Xbee module in order to communicate wirelessly with a PC [3] (for instance if we want to change the input signal of the geophone, we can activate wirelessly different modes of vibration). There is also the classic RS232 serial connection which has been reproduced using a home-made 3-pins connector (to reduce it size).

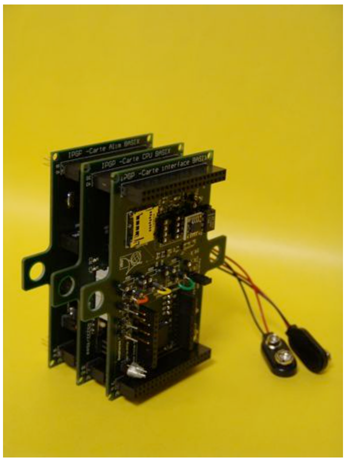
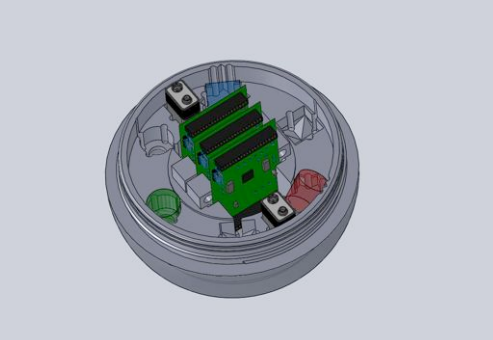


Figure 19: This set is then settled in the pod thanks to a rack



The GPS is very usefull when a timing is required for the experiment, so we put one on this card, with the whole configuration connections and ports. The modulus used is the Copernic one.
Two selectors allow the selection of the wireless/serial connection mode and the configuration/in use mode of the GPS module.
Saving data is possible thanks to a micro-SD slot.
All the schematics can be found in appendix.

3.2.3 C program

As I had a very little time for this internship, I just wrote an elementary code in order to debbug the system. There is only one mode of vibration : the ramp form.
In this program the two output channels (PD6 and PD7) work in opposite ways.
The C programm can be found in appendix.

3.3 Results and conclusions of the experiment

We tried several waveforms and frequencies for the input signal of the geophones. Apparently, the pod is not buried : no movement of the dust (polystyrene balls) can be brought to light. The only thing we noticed is the electrical effect of the plastic pod on the polystyrene : each time we left the pod bury itself in the fluid by lifting the counterweight, more and more polystyrene stuck around the pod :

Critics of the experiment This interaction may not interfere with the burying process of the pod but we cannot be sure.

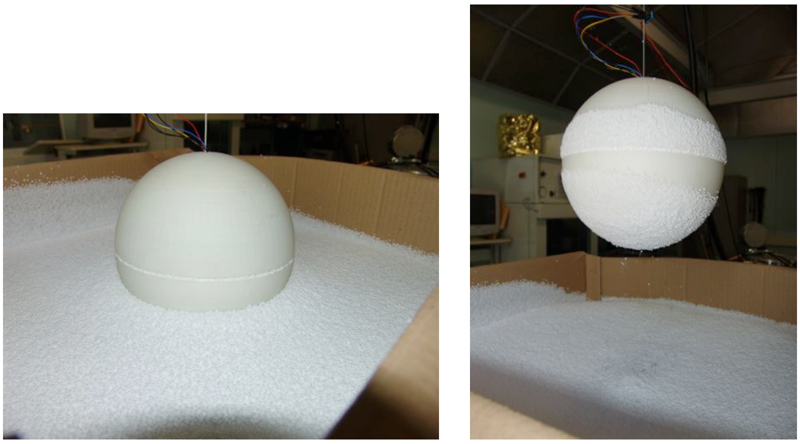

(a) (b)

Figure 20: (a) counterweight lifted ; (b) after having buried manualy the pod

Anyway, we have to consider several other points which can be as many reasons for the pod not to bury itself. On the one hand, we chose the pendulum option to reproduce the microgravity of the asteroid. This technical solution has the disavantage of introducing friction (in particular in the pulleys). Indeed, we observed a stick-slip phenomenum because of the friction in the pulleys and the inertia of the counterweight : when the counterweight is slowly stabilized with the hand, the system does not move, whereas the pod accelerates when the movement is initialized manualy (by slightly touching the counterweight or the pod). This movement is then followed by a partly burying of the pod in the polystyrene (because of the weight of the pod, not because of the vibrating geophones, see (a) of fig. 20).

Another element of the system which can interfere with the vibration of the geophones is the cable of the pendulum: first, as any solid, it has an elasticity coefficient which reduces the vertical movement, then as a pendulum, there can be interactions between the natural frequency of the pendulum and the frequency of the input signal of the geophones.

Opening The main problem we had in this experiment was to reproduce the micro-gravity without adding other factors and constraints such as friction and fluid dynamics. Unless the *Zero-G* flight by the CNES, there is actually no way to reproduce such a low-gravity environnement. The major problem of this solution is the short duration of the experiment (it lasts less than a minute).

In addition, many hypothesis have been made to consider the dust of the asteroid, by taking regolith caracteristics for instance. This point is a major issue for modeling the burying process of the pod and to reproduce the ground on Didymos.

References

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