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TÍTOL DEL TFC: Millores en un sistema de control vectorial per a una mini-llançadora basat en materials compostos

TITULACIÓ: Enginyeria Tècnica Aeronàutica, especialitat Aeronavegació

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Título: Mejoras en un sistema de control vectorial para una mini-lanzadera basado en materiales compuestos

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Resumen

El objetivo principal de este trabajo es diseñar e implementar un sistema de control vectorial basado en gas frío que sea muy ligero, fácil de construir y fiable; si hay tiempo, además probarlo. El trabajo es una continuación de un TFM en el que se estudiaba un sistema de control vectorial basado en la purga de presión de combustión y a través de cuatro micro-válvulas y unas pequeñas toberas se le daba 6 grados de libertad en el eje X, Z y rotación a través del eje Y; siendo el eje Y la dirección de vuelo.

La mejora consiste en utilizar materiales compuestos para que, a través de un molde y pequeñas operaciones de mecanizado se controle el paso del gas licuado, se permita expandir dicho gas y a través de una tobera acelerar a la máxima velocidad posible el gas para lograr el mayor impulso específico.

Este trabajo final de carrera se realiza en colaboración con el grupo WikiSat. El sistema de control vectorial será utilizado en la lanzadera WikiLauncher que pone pequeños satélites en órbita (Hasta 6 femto-satélites). De esta manera será posible hacer algunas pruebas de concepto e intentar validar el sistema, por lo menos con pruebas estáticas. Si el tiempo lo permite se realizarán pruebas reales en vuelo como parte del programa de espacio del grupo WikiSat.

Palabras clave:

Gas frío, Materiales compuestos, Mini-lanzadera, Femto-satélite

Title: Improvements of a vector control system for a mini-launcher based on composite materials

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Overview

The main objective of this work is to design and implement a vector control system based on cold gas that is very light, easy to build and reliable; to test it if on time. The work is a continuation of a Master Thesis about a studied of a vector control system based on the combustion pressure purge and through four micro-valves and tiny nozzles gave 6 degrees of freedom in the X and Z axes and rotation through the Y axis, being the Y axis the direction of flight.

The improvement is to use composite materials for which, through a casting of a resin and few machining operations, the liquefied-gas passage is controlled, expanded, and through a nozzle, the gas is accelerated to the highest possible speed to achieve the higher specific impulse.

This final bachelor work (TFC) is in collaboration with the WikiSat group. The vector control system will be used in the WikiLauncher. This launcher is able to put up to six small satellites (femto-satellites that are less than 100 grams of mass). That way it will be possible to do some proof of concept and try to validate the system, at least in static tests. If time permits, additional real flight tests will be performed as part of the WikiSat space program.

Keywords:

Cold-gas, Composite materials, Mini-launcher, Femto-satellite

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ACRONYMS, ABBREVIATIONS AND DEFINITIONS

Assy.	Assembly
CATIA	Computer Aided Three-dimensional Interactive Application
CFD	Computed Aided Design
DoF	Degrees of Freedom
EETAC	Escola de Enginyeria de Telecomunicació i Aeroespacial de Castelldefels
IDeTIC	Instituto para el Desarrollo Tecnológico y la Innovación en Comunicaciones
Isp	Specific impulse. The time required to burn 1 kg of propellant at 1 Nw of thrust
ISS	International Space Station
LEO	Low Earth Orbit
NBR	Acrylonitrile Butadiene Rubber
TFC	Final Bachelor Work
UART	Universal Asynchronous Receiver/Transmitter
UPC	Universitat Politècnica de Catalunya
ULPGC	Universidad de Las Palmas de Gran Canaria

INTRODUCTION

The main objective of this work is to design and implement a vector control system based on cold gas. It should be very light, easy to build and reliable. The work is a continuation of Roberto's Master Thesis about a studied of a vector control system based on the combustion pressure purge and through four micro-valves and tiny nozzles provided 6 degrees of freedom in the X and Z axes and rotation through the Y axis, being the Y axis the direction of flight.

The improvement is to use composite materials for which, through a casting of a resin and few machining operations, the liquefied-gas passage is controlled, expanded, and through a nozzle, the gas is accelerated to the highest possible speed to achieve the higher specific impulse.

This final bachelor work (TFC) is in collaboration with the WikiSat group. The vector control system will be used in the WikiLauncher. This launcher is able to put up to six small satellites (femto-satellites that are less than 100 grams of mass). That way it will be possible to do some proof of concept and try to validate the system, at least in static tests. If time permits, additional real flight tests will be performed as part of the WikiSat space program.

The chapter 1 explains the state of the art and the situation of the proposed vector control system inside the WikiSat project.

The chapter 2 is a list of requirements for the vector control system inside the rocket.

The chapter 3 has some baseline ideas and interface proposals to be used in the spiral design process.

The chapter 4 is a report of each prototype generated in the spiral system design.

The chapter 5 has the Computed Added Design (CAD) model, drawings and some Computational Fluid Dynamic (CFD) simulations.

The chapter 6 has the manufacturing process, the system performances, an example of trajectory and a static flight test proposal.

The chapter 7 has the conclusions of this final bachelor work, future work and environmental impact.

Finally, chapter 8 has the bibliography and after of that, the annexes.

CHAPTER 1. WIKISAT MISSION

This chapter explains the the state of the art as well as the situation of the proposed vector control system inside the WikiSat project.

1.1 State of the art

There are many methods for thrust vector control. In missiles, the movement of fins changes the missile trajectory very quickly. But in space, there is no air and the most common method is to move the nozzle. Other methods are moveable vanes, auxiliary gimballed nozzles, secondary flow injection, etc. For orbit corrections, the most often used methods are small oriented nozzles that rotates the body around the center of gravity. In the WikiSat Space program, Roberto Rodríguez in [6].has been proposed to purge some pressure from the combustion chamber but experimental tests has demonstrated that the overheat makes difficult to implement such a system due to valves should be metallic. Our proposal is to use a mix of composite materials and cold gas.

1.2 WikiSat Space Program

WikiSat is a team participating in the so called N-Prize contest to put in orbit a tiny less than 20 grams satellite by a cost of less than 1,200€. These satellites are inside the category of femto-satellites with a mass less than 100 grams. The team has developed a space program in collaboration with the *Universitat Politècnica de Catalunya* (UPC) and *Universidad de Las Palmas de Gran Canaria* (ULPGC) universities, in addition to some partners like Mecanitzats PARES, the *Escola de Enginyeria de Telecomunicació i Aeroespacial de Castelldefels* (EETAC), a faculty from the UPC and the *Instituto para el Desarrollo Tecnológico y la Innovación en Comunicaciones* (IDeTIC), a technological center from the ULPGC. WikiSat team works under an open source free hardware philosophy; they want to transfer this technology to small countries that have not their own launcher.

The team is composed by scientists, teachers, students and enthusiasm people that like the space exploration. They want to put low-cost satellites for Responsive Space missions like Disaster Management applications that are available to universities and small enterprises. They want to use very Low Earth Orbit (LEO) for Earth Observation tasks in such a way satellite live is one or two weeks, releasing the orbit for other short satellite mission. The proximity of the orbit reduces the launch effort and the required communications energy. It allows more relaxed optic requirements, faster period (1.8 hours) and revisiting time (24 hours). Each satellite has a single and dedicated mission to cover a small area over the Earth surface; the rest of the time, the satellite will remain in idle to save energy.

1.3 WikiLauncher rocket

To inject small satellites constellation or swarms, the WikiSat team proposes to use a Rockoon, a combination between a balloon and a rocket that is inside the category of Mini-Launchers (Less than 100 kg). The rocket called WikiLauncher starts from 32 km in the stratosphere and it has at least two stages, the first stage is responsible for reach the 250 km orbit (Below the International Space Station at 350 km) and the last stage is responsible to achieve the orbital speed of 7.6 km/s. Satellites are injected in orbit only 4 hours after the balloon release. The payload mass is about 100 grams (Up to six femto-satellites) while the launcher mass restriction is less than 10 kg and less than 2 meters of length.

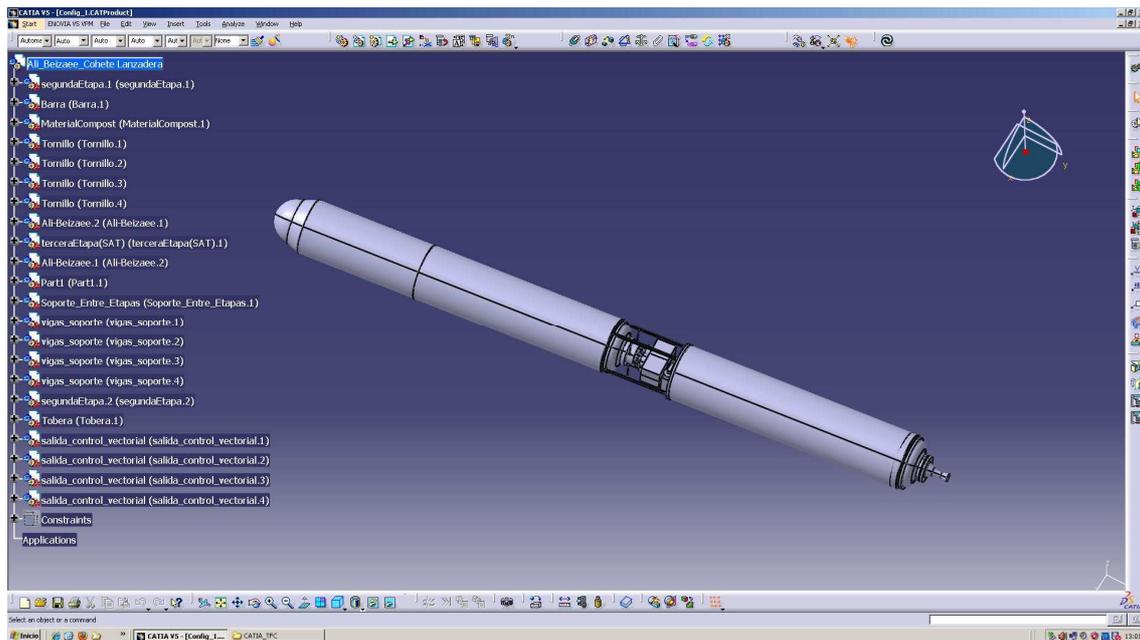


Figure 1 – WikiLauncher 3D model

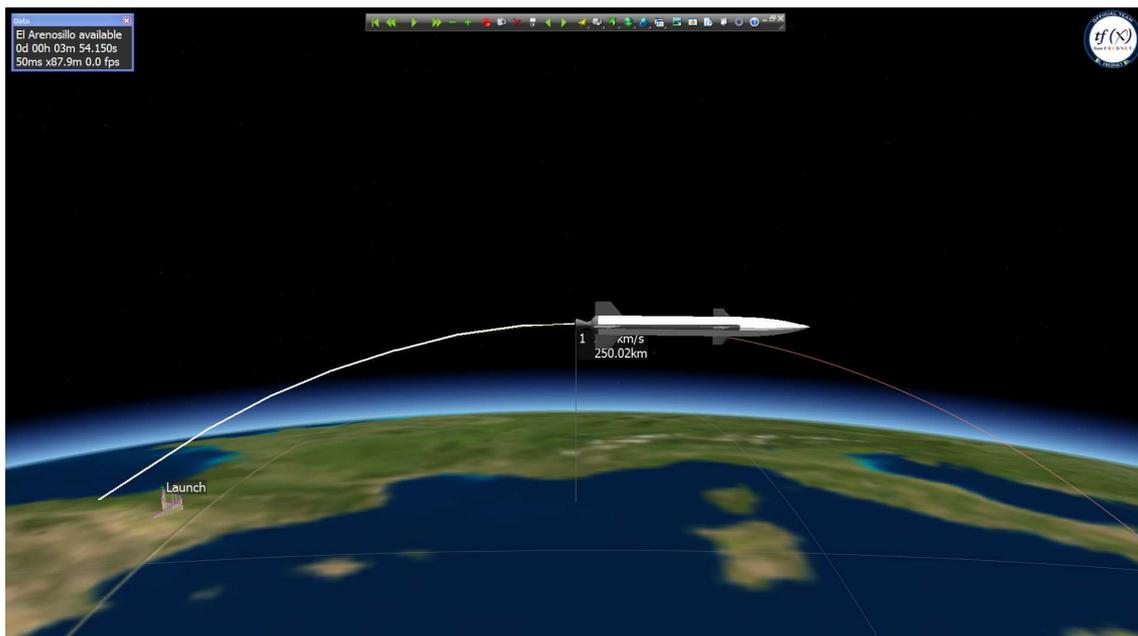


Figure 2 – Trajectory simulation for a Disaster Management mission

The trajectory is a parabolic flight, followed by a correction maneuver in the apogee, before to ignite the last stage. For this reason, the vector control system shall to correct the rocket attitude during the unstable phases of the flight. The correction maneuver consists of pointing towards the correct direction and to turn around it to provide a minimum spin to the last stage. After the jettison, this module is discarded with the previous stage and last stage engine increases the speed until the orbital speed is achieved. After then, satellites are released. Figure 2 shows the prediction of a Disaster Management mission trajectory simulation [4]. The Vector control will work only when engine is burning and during the correction maneuver.

1.4 Cold gas method for the vector control system

There are many ways to control the rocket vector. The most used method is by the use of a moveable nozzle. For the WikiLauncher, it represents too much complexity. For this reason, WikiSat team decided to use cold-gas and few small nozzles that will apply small forces guarantees the flight stability as proposed by Laia Navarro in [9] in page 56 (Fig. 3) and implemented by Roberto Rodríguez in [6]. The use of 4 small nozzles with a certain angle gives freedom for 4 displacements and 2 rotations that are 6 degrees of freedom.

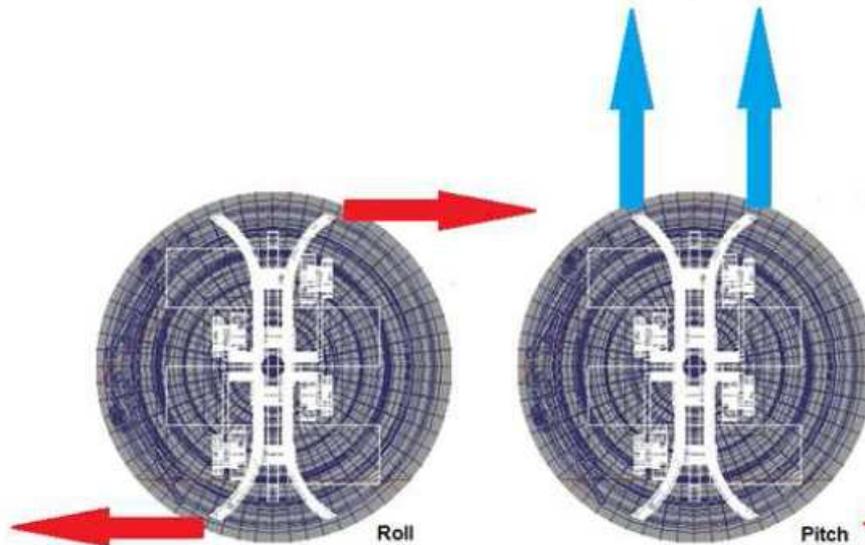


Figure 3 – Four small nozzles have 6 DOF for the vector control

As showed in figure 4, butane is liquefied at room temperature when pressure is relatively low. This fact means that the container will be light and a large quantity of butane could be stored in liquid phase. In addition, this gas has a good specific impulse of about 80 seconds [5].

Previous designs of the vector control were studied by other students [1, 6, 7, 8]. Our objective is to reduce the mass and increase the reliability of the module to be implemented while improving the manufacturing complexity and maintainability. Figure 5 shows the baseline idea to achieve this goal. This novel idea consists of to assemble four servos in the same pack attached each other by a strap.

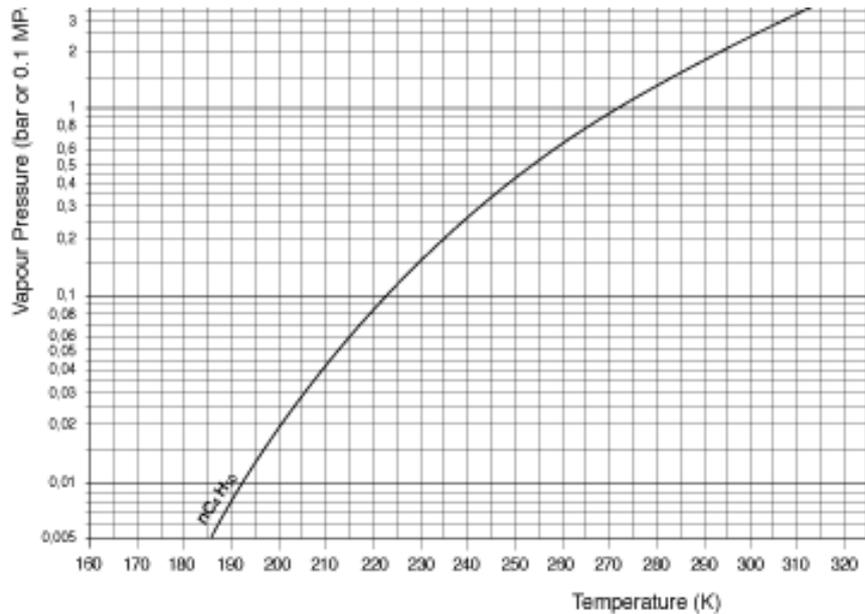


Figure 4 – Butane vapor pressure vs temperature



Figure 5 – Servo assembly – The baseline design

To implement the system, we will begin from a minimum number of requirements and then we will start a spiral design process to test the interface proposals [2] based on Commercial-off-the-shelf (COTS) by building prototypes. Seven prototypes were generated in this spiral.

Finally, having the best prototype produced in the spiral, we will generate the system specifications and we will validate the implementation through some functional tests and hardware-in-the-loop simulations as designed by Navarro in [9] if time.

CHAPTER 2. SYSTEM REQUIREMENTS

This chapter has a list of requirements for the vector control system inside the WikiLauncher rocket.

2.1 System requirements

System requirements were based on Tristancho's femtosatellite system requirement list in [1] and the technological constrains proposed by Jove-Casulleras in [8] for the mini-launcher:

- SR01 The vector control system should fit into a diameter of 55 mm
- SR02 The vector control system should weigh less than previous version in 136 grams for the Roberto's prototype and 91 grams for the Brass's prototype (See annexes for details about previous implementations)
- SR03 The vector control system should have the lower number of valves
- SR04 The vector control system should use a ROTHENBERGER Propan/Butan mix bottle. Content 338 grams of butano65/propano35 and 600 ml. Dry mass 125 grams. Wet mass 462 grams. Operative range from -15 to 50 °C but can be improved through tests. Threat 7/16" type 1.
- SR05 The vector control system should use the Tower Pro micro servos model MG 90S

2.2 High level requirements

High level requirements were extracted from the technological constrains stated by Jove-Casulleras in [8].

- HLR01 The vector control system shall control the rocket attitude during the unstable phases of the flight
- HLR02 The manufacturing of the system shall be simple and repeatable

2.3 Low level requirements

Low level requirements were adapted from the technological constrains presented by Jove-Casulleras in [8]:

- LLR010 The vector control system shall displace laterally the rocket in the four directions around the flight path
- LLR011 The vector control system shall rotate the rocket in the flight direction and two way
- LLR012 The vector control system shall be inactive during the stable phases of flight
- LLR020 The vector control system shall use Commercial-off-the-shelf components

- LLR021 The vector control system shall be easy to adjust
- LLR022 The vector control system shall not require maintenance during the storage phase
- LLR023 The vector control system shall have a replaceable gas container for the certification process

CHAPTER 3. INTERFACE PROPOSALS

This chapter has a set of ideas and components proposals that initially are suitable to be used in the spiral system design and they will put to the test in every design cycle. Many of these ideas or components will be discarded and only the most suitable ones, it will remain in the final design. The design starts from the use of Commercial-off-the-shelf (COTS) components available in the market as Morisca defines in [2] but extended to the hardware market.

3.1 Baseline ideas

The following section has a summary list of baseline ideas that are concepts or approaches to achieve the requirements. Through the spiral system design process we will see in the next chapter, these ideas will be tested and discarded those ideas or approaches that are not useful or not good enough for the final design.

- **Blowtorch bottle.** Butane is the best specific impulse cold-gas for vector control. We can use a blowtorch bottle because are light and commercially available.
- **Four valves are enough.** Four nozzles placed in 45 degrees could be combined properly in order to have six degrees of freedom: Four displacements and two rotations.
- **Compact assembly.** Four servos will be placed in a compact configuration in such a way that the four shafts are in the proper circle that corresponds to the bottle. The components will be in the center because is a compact assembly, the inertial moment will be lower than other configurations. The rocket will turn faster or easier.
- **Epoxy block.** We propose to assemble all the valves in the same block or bed. A single cast will fix the problem; no mechanical processes are required.
- **Rotary valves.** A drill in a cylindrical shaft could be used as a valve in order to avoid levers, tensioners and cams. We propose to use a bolt inside the block with a lateral drill that will work as rotary valve. The thread does not allow lateral displacements.
- **Direct drive.** The servo has a range of 180 degrees. It could be enough to close and open a rotary valve. In this case we can have a direct drive from the servo to the valve shaft. We propose to use the same bolt and a nut to fix the bolt to the servo. This nut can be used for the rotation adjustment. The shorter the rotation, the faster the operation of the vector control.
- **Lateral drill.** Rotary valves have complicated adjustments. We propose a single drill for each valve. A single drill will be enough to pass through the central collector, the bolt, the wall and also will work for the nozzle pipes.

- **Epoxy threat.** The blowtorch bottle does not have a normalized threat. We propose to embed the epoxy block around the bottle threat that will fix this problem if it is stronger enough.
- **Epoxy insulator.** The first stage rocket is closer to the vector control system. We propose to use an epoxy block to isolate the components from the heat.
- **Four shafts as support.** Four shafts also will work as support for the servo assembly, simplifying a lot the design.
- **Four shafts as torque lock.** Four shafts avoid the torque of each rotary valve. Extra structural components are not required while servo assembly is free to move.
- **Four valves as main valve.** Four valves will work as a main valve if the four valves are closed and they have not leaks. Progressive control is feasible.
- **Bottle valve as main valve.** In case of valves have some leak; we propose to use the bottle check valve punctured by a fifth servo. Pulse control can use in this case instead of progressive control.
- **The bottle as a cast.** The block is complicate to build within same manner. We propose to use proper aluminum pipe with the same diameter of the bottle neck as a cast extension. The bottle neck inner shape and the thread will be used as the inner cast.
- **Plasticine as a mold.** To avoid epoxy ingestion in the bottle check valve, we propose to pot a small quantity of Plasticine in the hole in such a way that will work as a central collector and it can be removed later during the adjustment process.
- **Countersunk head as a limit.** The use of a bolt with countersunk head and some Plasticine will work as a limit for the rotation and also will give some stiffness to the rotation. We propose to fill the countersunk head of the bolt with Plasticine to avoid the epoxy lock in the bolt head.
- **Brass piping.** The exhaust nozzles require the proper orientation. We propose small brass pipes because are easy to bend and to be placed in the single drill performed before.

3.2 Component selection

In this section, a list of Commercial-off-the-shelf (COTS) components is selected to be used in the system. These components were manufactured for the domestic public and through a validation process; the ones that can resist the space environment will be selected.

- **TowerPro MG90S** Micro servo. This is a component used in amateur aeromodels and is strong and light. This component was tested in the WikiSat Near space expedition number [3](#) and number [12](#).
- **ROTHENBERGER Propan/Butan mix** Bottle of 660 ml. This component was designed in blowtorch for soldering or for applies flame. This component was tested in the WikiSat Near space expedition number [5](#) and others.

- **Palatal P4TV-129/5kg** Fiberglass resin. This material was used several times in WikiSat Near space expeditions and is recovered by the NASA report [3] number SP-8108.
- **DIN661 M2.5 countersunk bolt**. This is a metallic material and it is suitable for near space.
- **DIN934 M2.5 nut**. This is a metallic material and it is suitable for near space.
- **N1.5 mm brass pipe**. This is a metallic material and it is suitable for near space.
- **NBR O-Ring**. Made of nitrile rubber that is a material used several times in WikiSat Near space expeditions. This material is recovered by the NASA report [3] number SP-8108.

CHAPTER 4. SPIRAL SYSTEM DESIGN

This chapter is a report of each prototype generated in the spiral system design. Each prototype will test some ideas or interface parts proposed in the chapter 3.

4.1 Prototype number 1

The prototype number 1 is a set of valve implementations in order to test how the epoxy and the steel behave before use a bottle as a mold. The concept to test is: an embedded bolt with a lateral drill will work as a rotary valve in such a way that this bolt is rotated directly by the servo. This test was performed in Friday March 1st 2013.

Four aligned bolts were embedded inside a rectangular mold, screwed in the tip by a support while the countersunk head of each bolt is inside the resin in the mold. To avoid blocking the head by the resin, thermal glue was used. The case for each bolt was as follows:

- First was soaked in oil as well. The head was filled with a lot of thermal glue to after allow the rotation and some stiffness. Oil will increase the tolerance between the resin and the thread but also will leak the gas pressure.
- Second bolt has water wet threads. The head was filled with much thermal glue to after allow the rotation and some stiffness. There is no tolerance between the resin and the thread and there is not any gas leak but rotation will be impossible.
- Third bolt has dried threads. The head was filled with some thermal glue to after allow the rotation and some stiffness. There is a small tolerance between the resin and the thread and an little gas leak but rotation will be hard to move is the initial stiff is overcome.
- Fourth bolt has dried threads. The head has not any thermal glue but the head has not any hole. There is a small tolerance between the resin and the thread and a little gas leak but rotation will be too hard. Also, rotation is not possible because the bolt cannot advance in the screw movement.

Referred to the lateral drill, it is difficult to ensure that the bit will go through the bolt because the opacity of the resin makes hard to see where the bolt is. Also, due to the weakness of the resin, sometimes the bit strafes or moved laterally. Once the drill is done, the bolt works as a rotary valve.

Conclusions for this prototype are as follows. The idea of embedded bolt is only feasible if both, head has something elastic (Like thermal glue) and the thread is soaked in oil or at least has dried thread but never soaked in water. Next test should be focused in the bottle assembly.

4.2 Prototype number 2

The prototype number 2 was done to test four valves located in square and held by four pattern servos. Technique used will be the same as the previous prototype but an aluminum cylinder will be used as a cast. In this test, it is proposed to use the four servos, to see if they are able to rotate the screws, located within the resin.

In this case nuts is thermal glue on head servos having a neutral position of 90 degrees. The screws about the bottom of the servo axis and has joined the nuts every servo axis. In the center is placed a straw filled with wax and a screw invested within the wax. It closes the straw M3 nut. In the bottom of the mold is added a piece of fiberglass to avoid cracks.

The mold resin is added to reach the four nuts on the axes.

The amount of resin that is above the center screw nut is a small amount and cannot guarantee good insulation. Is not easy to hold the four servos perpendicular to the table

The first resin has been placed inside the mold, and then the system has got the four axes, making it difficult to put exact amount of resin.

Another way is to put first axis and then add resin, which makes it very difficult to add the resin to the mold.

Test of 4 valves. Thursday on March 7. Following them same steps of the previous test, this time the own servos were used as supports, giving the possibility of reuse of the servos, before some failure in the tests.

In this test it proposes to verify if the servos for if alone they are capable of turning the screws, before some failure acquaintance to use the tool of torque.

In order to be able to realize this test, the following points have been done:

- A pipe of 30x18 mm (D25mm nominal) of aluminum impregnated in oil.
- Screws with a drop of thermal glue in the head.
- Servos located in a neutral position of 90 degrees.
- The screw does ceiling at the back of the axis of servo.

Once located everything, the nuts have been screwed in the respective servos. After there has been located a straw full of wax and a screw invested inside this wax, closing it with a nut of M3.

Previous conditioning that has been done has been to locate a socket-pan of glass fiber at the back of the mold. Later it has been processed to filling the space with resin up to coming just before the nuts of four screws.

With this we could have observed that there is few quantity of resin in the center so it is possible not to obtain the needed water tightness, impede to hold the servos so that they could his perpendicular dad preserves.

In this process it proposed to fill with resin first and then to introduce four screws, but I reject for the difficulties of calculating the quantity of necessary resin, in case of filling after resin the difficulty it consists of avoiding the formation of bubbles inside the resin.

The March 07th, 2013 as soon the epoxy was cured, it was removed from the mold easily. Wax was not easily removed and thermal glue is difficult to remove. No servos were able to turn any of the bolts; the shafts were unlocked by hand. The lack of oil was the reason of the shaft stiffness. The servo assembly and the shafts should be as centered as possible. Caution should be taken to do not fill too much, avoiding epoxy in the nuts. Thermal glue is not recommended.

We recommend unscrewing the assembly from the bottle to process the part and also to certify the assembly alone. That way, the bottle could be replaced. An O-Ring seal will be mandatory for this purpose.

It is very difficult to drill the shaft and to ensure that the hole is at the center when the drill is performed in epoxy. Looks like this will be an issue to overcome. In any case, valve sealing is not allowed through an epoxy-steel closure.

4.3 Prototype number 3

This prototype done in March 8th, 2013 is the same as the number 2 but using the bottle throat as the mold to cast the manifold assembly in the hope the manifold could be unscrewed. Some holes are filled by plaster. The bottle hole is protected as well to avoid the use of thermal glue and wax. Bubbles must be avoided during the filling process. An O-Ring will be required if bottle is replaceable from the manifold part. Servos are placed in a neutral position of 90° to allow a later adjustment. Oil is sprayed this time in all the mold surfaces. It is difficult to know the level of epoxy introduced during the filling; we recommend making a lateral drill in the mold extension.

As soon the jammed bolts are released by the screwdriver, the servos are able to turn the shafts properly. A lateral drill was performed in every shaft. The servos were adjusted and an Arduino was programmed in order to turn separately each servo.

On March 09th, 2013 a stress test is performed in order to know the wear of the valves. The servos were supplied with the minimum operating voltage at 4.4 volts. During the test, a single servo required 1.2 A to turn the valve but at the end of the test, the servo only required 1.1 A due to the wear. The idle consumption of the overall system is 90 mA. The test consisted in more than the 23,400 cycles during one day. After of then, valves have got similar leakage as the beginning. We recommend the use of inserts for the valve in order to

have a metal-metal closure of the shaft. During the installation, the reduction box of the servo was destroyed when the nut was tithed. Shaft must be locked with the pliers while the nut is tithed with the wrench.

On March 11th, 2013 we detected that some servos are not good even the "Q.C." stick. Quality control is mandatory for every servo before use it.

4.4 Prototype number 4

This prototype was performed on March 11th, 2013 repeating the previous casting process. After the assembly is removed from the bottle and the assembly, the head of the screws must be reached without destroying the threat. This time, the threat was broken and the prototype must be repeated. Lateral drills were done but still an issue.

4.5 Prototype number 5

This prototype was performed on March 12th, 2013 repeating the previous casting process but adding some fiberglass inside the epoxy. A part of the seal in the bottle neck side was broken. The prototype will work but it cannot be used in a real launcher because it has a defect. Functional test was performed and each valve closes but sealing is not achieved due to the remaining screw swarf. A fifth servo is mandatory to open and close the bottle.

4.6 Prototype number 6

This prototype was performed on March 12th, 2013 and is based on the same manufacturing procedure but putting an insert in every threat. This time, the assembly was manufactures properly but one drill was now centered, even the valve works. The epoxy has little quantity of catalyst so next time mixture of the epoxy should have a bit more. Once, the valves work fine but sealing is not guaranteed so a fifth servo is mandatory. This is the best prototype we have and this is the one will be used in the specification tests.

4.7 Prototype number 7

This prototype was performed on March 12th, 2013 and is based on the same manufacturing procedure but putting a metallic embedded ring to manufacture four screwed holes. We used a M12 nut that is the proper size to fit inside the bottle neck. It was unable to make the threat in the holes so idea is discarded and anyway, a main valve is required during the storage. Sealing is not feasible.

4.8 Summary of the spiral

In this spiral cycle we have performed seven cycles generating seven prototypes in order to test different concepts until the final design is achieved.

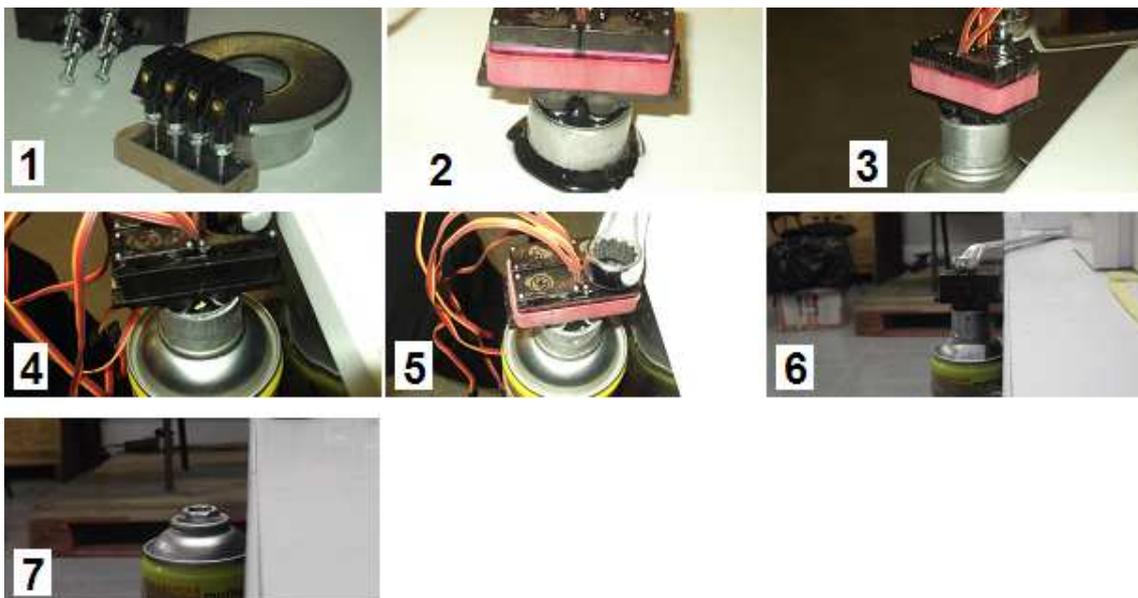
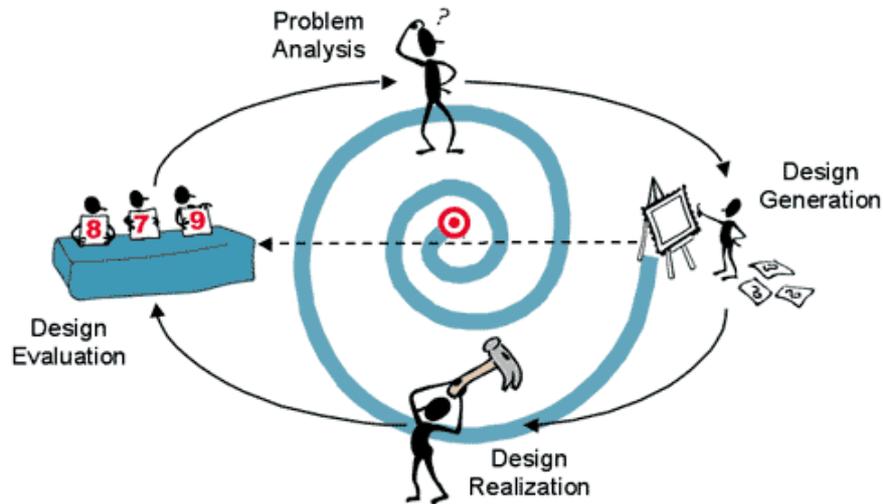


Figure 6 – Spiral development concept (a) and Prototype implementations (b)

Figure 6(a) shows the concept of spiral development³ by creating a complete prototype each cycle. From cycle #3 to #6 was the same prototype repeated in order to improve the bottle neck casting and the drill procedure. Metallic manifold was not a good solution in cycle #7 due to the increase of weight and manufacturing cost. Figure 6(b) shows a picture for each prototype implemented in this spiral process. In addition, Table 1 summarizes main idea or interface to test in each spiral cycle, the results obtained in this implementation and conclusions/recommendations for the next iteration.

³ Source: http://teced.com/wp-content/uploads/2011/05/spiral_model.gif

Table 1 – Prototype summary

	Idea/interface	Results	Conclusion
#1	An embedded bolt with a lateral drill will work as a rotary valve	<ul style="list-style-type: none"> - A soaked in oil threat allows the rotation but it leaks - A dried threat will be hard to break the stiff but small leak - A soaked in water threat is useless, the bolt is stiff - The lateral drill is hard to do 	To embed a soaked in oil bolt with a lateral drill is feasible and could be implemented in the bottle
#2	Use of a ring as a cast, assembly will remain in the bottle neck forever. Use of thermal glue	<ul style="list-style-type: none"> - The lack of oil provoke the shaft was locked - Assembly should be centered - It is not feasible to keep the assembly for ever - Assembly can be unscrewed - Sealing is not achieved in a epoxy-steel valve 	Thermal glue is not recommended and the rotary valve concept should be improved
#3	Use the bottle neck and an extension ring as the mold	<ul style="list-style-type: none"> - Carefully, the manifold could be unscrewed many times - An O-Ring will be required - Bubbles must be avoided - It is difficult to know the level of epoxy when filling - Servo's gearbox is destroyed if shaft is not locked during tight - Stress test demonstrated that servos can work for many cycles - Some new servos are bad 	Manifold will be adjusted and certified separately from the bottle by an O-Ring. Servos must be tested in order to discard the badly one
#4	Improve previous process to ensure repeatability	<ul style="list-style-type: none"> - The threat is destroyed when reaching the head of the screw 	Prototype was destroyed
#5	Improve previous process adding fiberglass	<ul style="list-style-type: none"> - Stronger assy. than previous - Bottle neck seal has a defect - The valves worked fine but cannot be used for a real flight - Sealing is not achieved 	Sealing is not achieved and it is mandatory to use a fifth servo
#6	Use inserts to see if valves achieve the sealing	<ul style="list-style-type: none"> - The assembly was manufactures properly - There was a lack of catalyst - One lateral drill was not centered but worked anyway because the metal-metal closure - Sealing is not achieved 	Using this technology, sealing is unachievable so a fifth servo is mandatory
#7	Use a metallic embedded ring	<ul style="list-style-type: none"> - Threats are not possible to be manufactured 	Useless idea. Sealing is not feasible

CHAPTER 5. SYSTEM MODELING

This chapter contains the Computed Added Design (CAD) model, its drawings, the launcher drawings and the Computational Fluid Dynamic (CFD) simulations for the maximum angle of attack and the vector control nozzles effect.

5.1 Computed Added Design model

The vector control assembly was modeled in CATIA [12]; the whole launcher was modeled as well. Figure 7(a) shows a 3D view of the vector control system (08) mounted in the butane bottle (5). The final functional prototype weighs 79 grams. The control vector system is located between the payload and the stages in such a way that, when the stage1 is empty, the center of gravity is closer to the nozzles in order to reduce the nutation effect during the apogee maneuver.

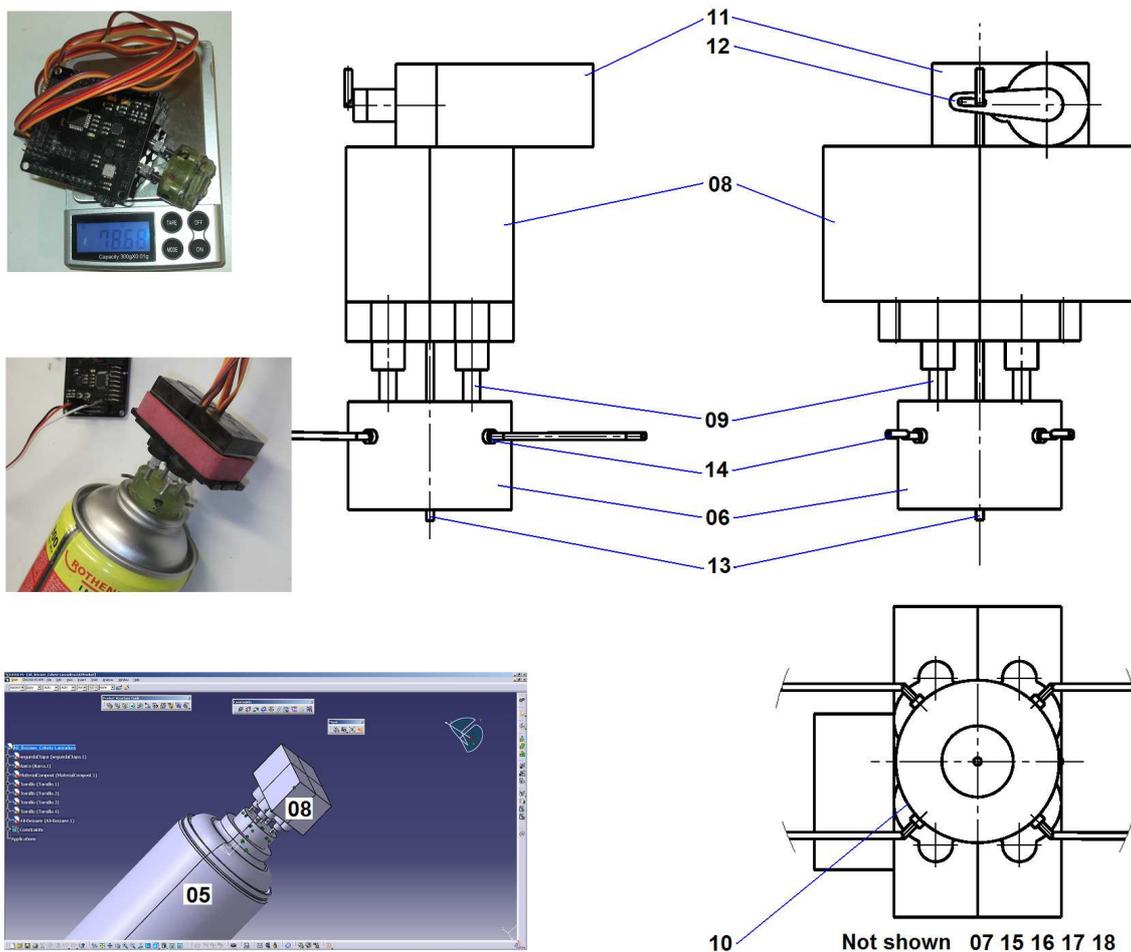


Figure 7 – Pictures and 3D model in CATIA (a) and the assembly diagram (b)

The whole vector control assembly is inside a Cover (19) not shown in the figure 7(b). Four Servos (08) are attached together by a lateral strap. The four Shafts (09) are introduced inside the epoxy Manifold (06) and adjusted by a nut (Not shown in the figure). The assembly is connected by a thread to the Bottle

(05) filled with Butane and sealed by an O-Ring (10). The Cold-gas (07) not shown, is released through a Needle (13) actuated by a Servo (11) and a Rod (12). The gas passes through a Piping (14) in order to make a small force or moment depending on the combination of valves selected by the Computer (15) not shown, supplied by the LiPoly Batteries (17) not shown and the Wirings (16) not shown for the sake of the clarity. For safety, there is a Jumper (18) that connects the battery supply before flight.

5.2 Drawings

This section presents some sketches about the vector control and other assembly sketches, the Part List, the WikiLauncher configurations, the Payload and inter-stage assembly. Detailed drawings are located in annexes. The WikiLauncher has from top to bottom the following subsystems:

- Fairing subsystem
- Payload subsystem
- Vector control subsystem and
- Propulsion subsystem

5.2.1 Vector control assembly sketches

In the figure 8 the vector control sketches are presented having the assembly main measurements.

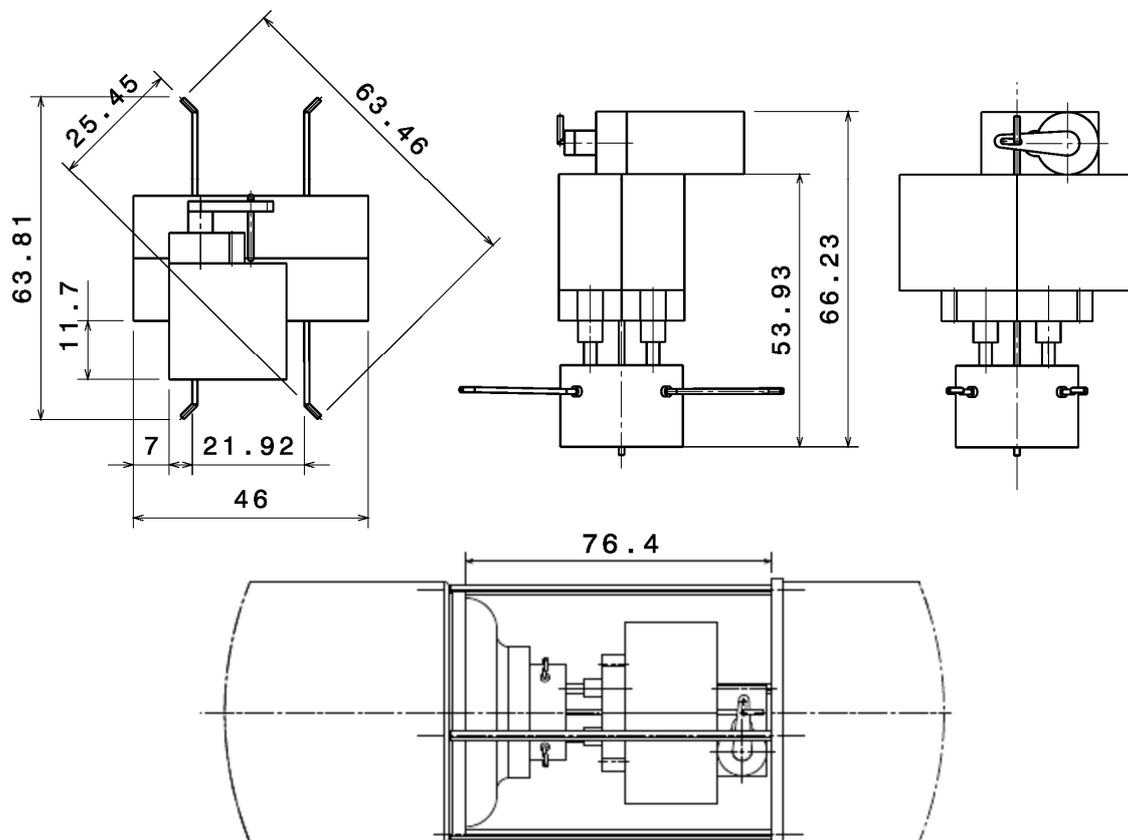


Figure 8 – Vector control sketches

The separation arm between two opposite nozzles during rotation maneuvers is about 25.5 mm. These two opposite nozzles are injecting gas to generate a

torque. The separation between two consecutive closer nozzles in Pitching maneuvers are about 23 mm. The separation between two consecutive far nozzles in Yawing maneuvers is about 64 mm. The separation between stages is about 76 mm.

5.2.2 Other assembly sketches

The figure 9 shows details about the fairing subsystem with the payload measurements. The payload volume is defined as a cylinder of 62 mm of diameter and 130 mm of height. The total length of the WikiLauncher in configuration 1 is about 838.21 mm and configuration 2, its length is about 1,176.51 mm. Other WikiLauncher configurations are available in table 3.

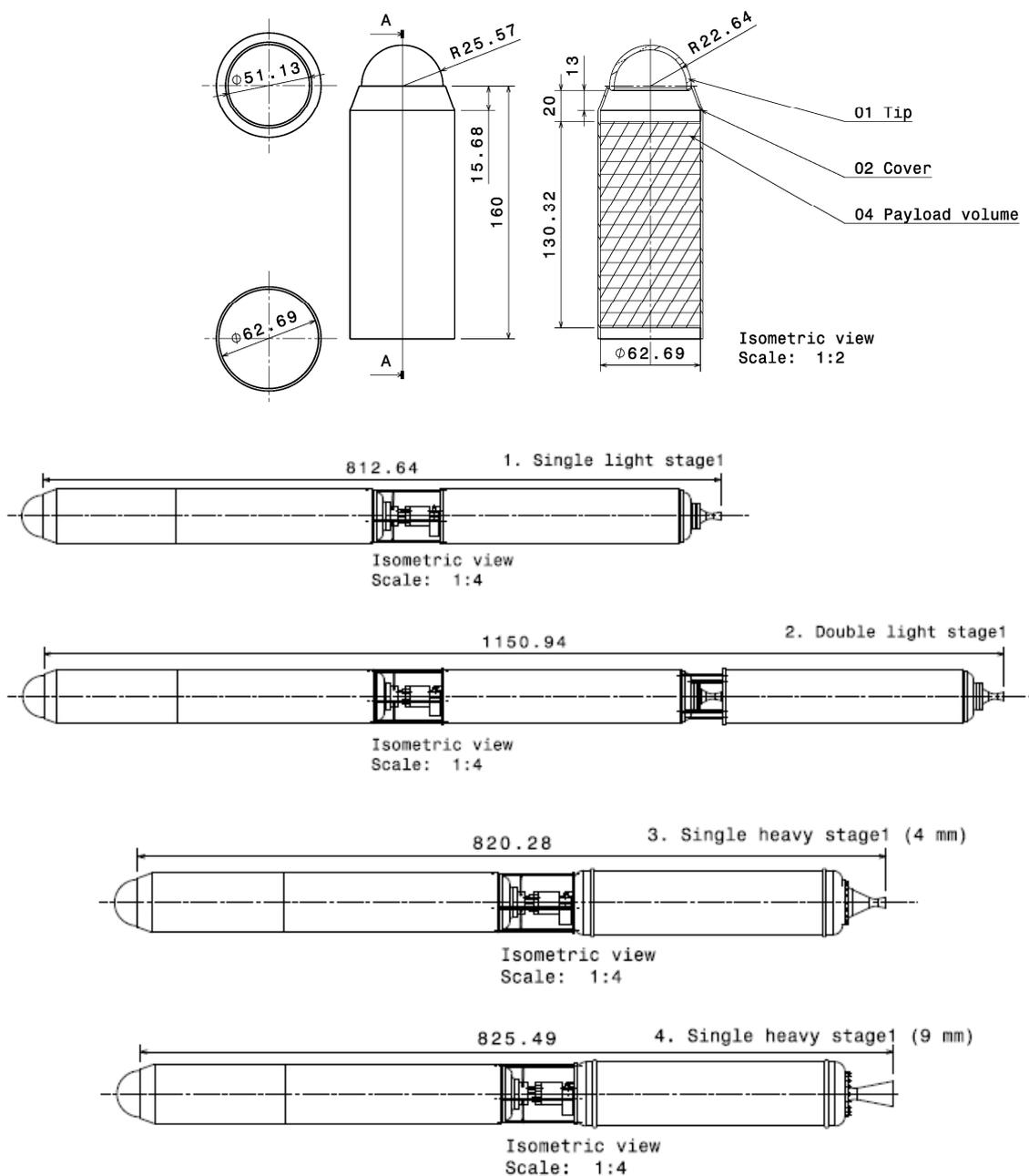


Figure 9 – Other sketches

5.2.3 WikiLauncher part list

Table 2 presents the part list for each subsystem and includes the totals for various combinations of light or heavy stage1 and 4 or 9 mm nozzle. The bill of materials is also included. We have considered all the WikiLauncher configurations to facilitate future flight tests.

Table 2 – Part list

Item	Subsystem	Description	Material	Mass	Cost
01	Fairing 156.2 gr 4.60€	1x Tip	Glass	26.0 gr	0.70€
02		1x Cover	Aluminum	130.0 gr	1.20€
03		1x Strap	Aluminum	0.2 gr	2.70€
04	Payload	1x Volume	PVC	684.0 gr	-
05	Vector Control 597.8 gr 72.85€	1x Bottle	Steel	200.0 gr	8.90€
06		1x Manifold	Fiberglass	15.0 gr	0.50€
07		1x Cold gas	Butane	258.0 gr	4.50€
08		1x Servo assy.	PVC	48.0 gr	6.20€
09		4x Shaft	Steel	3.1 gr	0.70€
10		1x O-Ring	NBR	0.1 gr	0.70€
11		1x Servo5	PVC	12.0 gr	2.60€
12		1x Rod	PVC	0.2 gr	0.45€
13		1x Needle	Steel	0.6 gr	0.05€
14		4x Piping	Brass	0.4 gr	0.15€
15		4x Computer	PCB	14.8 gr	43.00€
16		4x Wiring	Copper	2.6 gr	1.10€
17		2x Battery	LiPoly	41.6 gr	0.70€
18		1x Jumper	PVC	0.2 gr	0.70€
19		1x Cover	Fiberglass	1.2 gr	2.60€
20	Propulsion (Light stage1) 1,931.9 gr 220.30€	1x Structure	Steel	200.0 gr	3.90€
21		1x Nozzle 4 mm	Steel	22.0 gr	6.50€
22		1x Propellant	APCP	1,630.0 gr	200.00€
23		1x Clip	Steel	0.8 gr	1.50€
24		1x Seal	Epoxy	3.0 gr	0.50€
25		1x Ablative	Fiberglass	60.0 gr	1.40€
26		1x Igniter	Powder	0.6 gr	2.20€
27		1x Wiring	Copper	2.3 gr	1.10€
28		4x Strut	Steel	12.0 gr	0.60€
29		1x Cover	Fiberglass	1.2 gr	2.60€
30	Propulsion (Heavy stage1) 3,080.1 gr	1x Structure	Steel	1,081.0 gr	18.00€
31		1x Nozzle 9 mm	Steel	81.0 gr	6.50€
32		1x Propellant	APCP	1,839.0 gr	200.00€
33		18x Bolt	Steel	4.0 gr	4.50€
34		1x Seal	Epoxy	3.0 gr	0.50€
35		1x Ablative	Fiberglass	60.0 gr	1.40€
36		1x Igniter	Powder	0.6 gr	2.20€
37		1x Wiring	Copper	2.3 gr	1.10€
38		4x Strut	Steel	8.0 gr	0.60€
39		1x Cover	Fiberglass	1.2 gr	2.60€

1. Single light stage1 (4 mm nozzle)	Total	3,369.9 gr	297.75€
2. Double light stage1 (4 mm nozzle)	Total	5,301.8 gr	518.05€
3. Single heavy stage1 (4 mm nozzle)	Total	4,498.1 gr	314.85€
4. Single heavy stage1 (9 mm nozzle)	Total	4,518.1 gr	314.85€
5. Three stage1 (4 mm nozzle)	Total	8,361.9 gr	755.45€

5.2.4 WikiLauncher configurations

As it was seen, there are four main WikiLauncher configurations depending on the type or number of stages or type of nozzle used. Fifth config. is discarded.

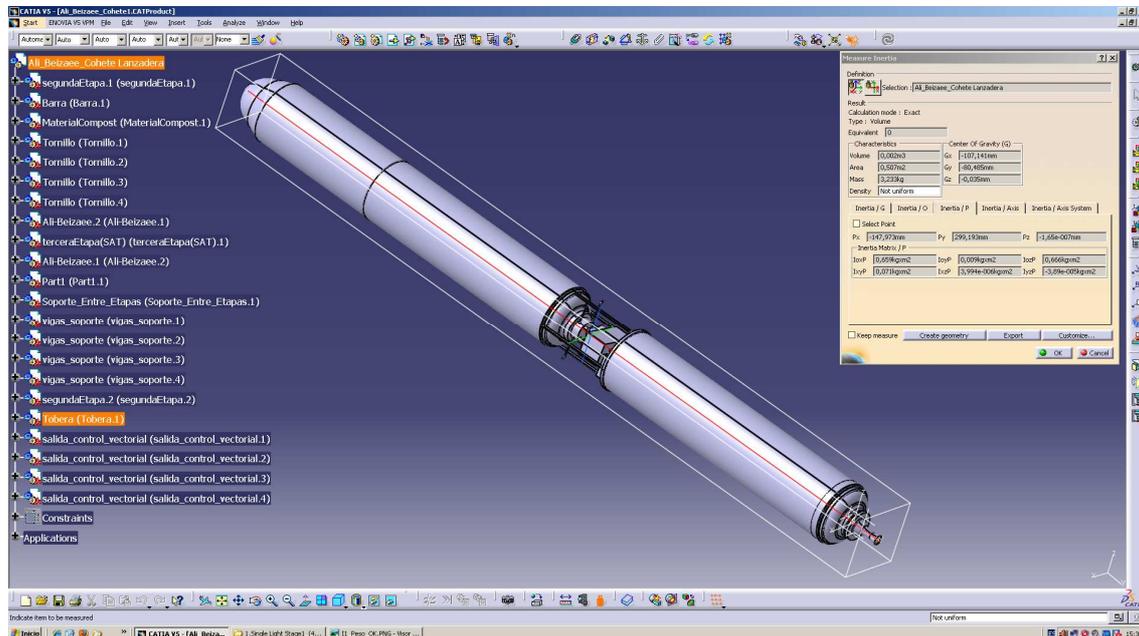


Figure 10 – WikiLauncher with single light stage1 and 4 mm nozzle

Figure 10 shows the WikiLauncher in light configuration, the bill of materials is about 300€ and it is composed by three sections: The payload section, The vector control section and the propulsion section. The center of gravity is marked in green closer to the vector control Piping (14).

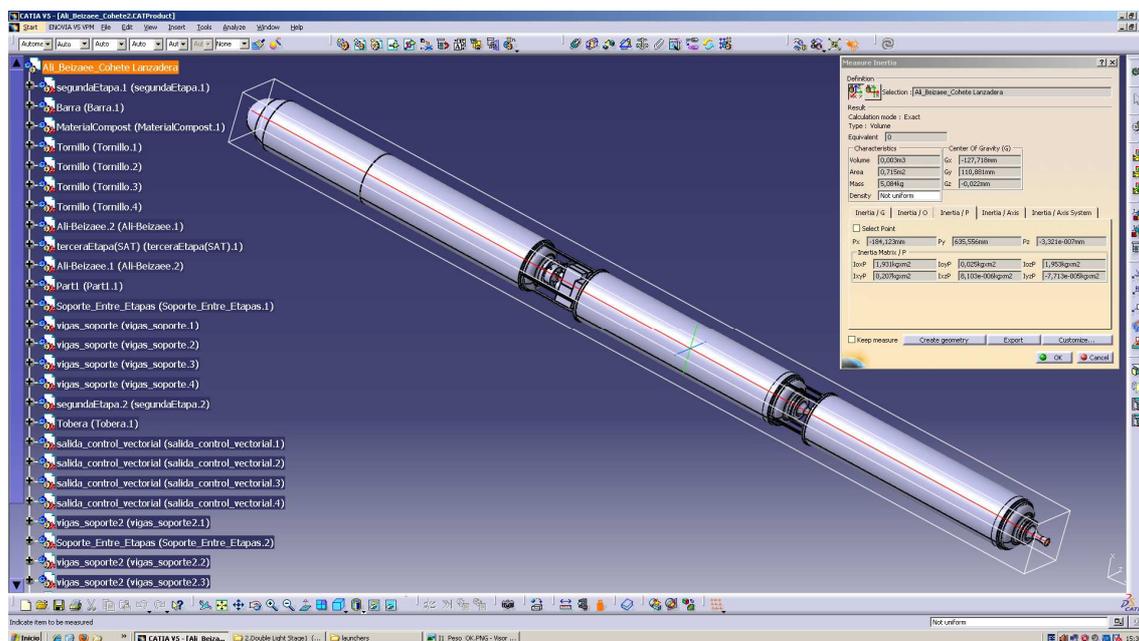


Figure 11 – WikiLauncher with double light stage1 and 4 mm nozzle

Figure 11 shows the WikiLauncher in configuration of double stage1, the bill of materials is about 520€ and it is composed by four sections:

- The payload section
- The vector control section
- The propulsion section #2 and
- The propulsion section #1

The center of gravity is marked in green closer and is located in the propulsion section #2 at the beginning of flight and closer to the vector control Piping (14) at the end of burn.

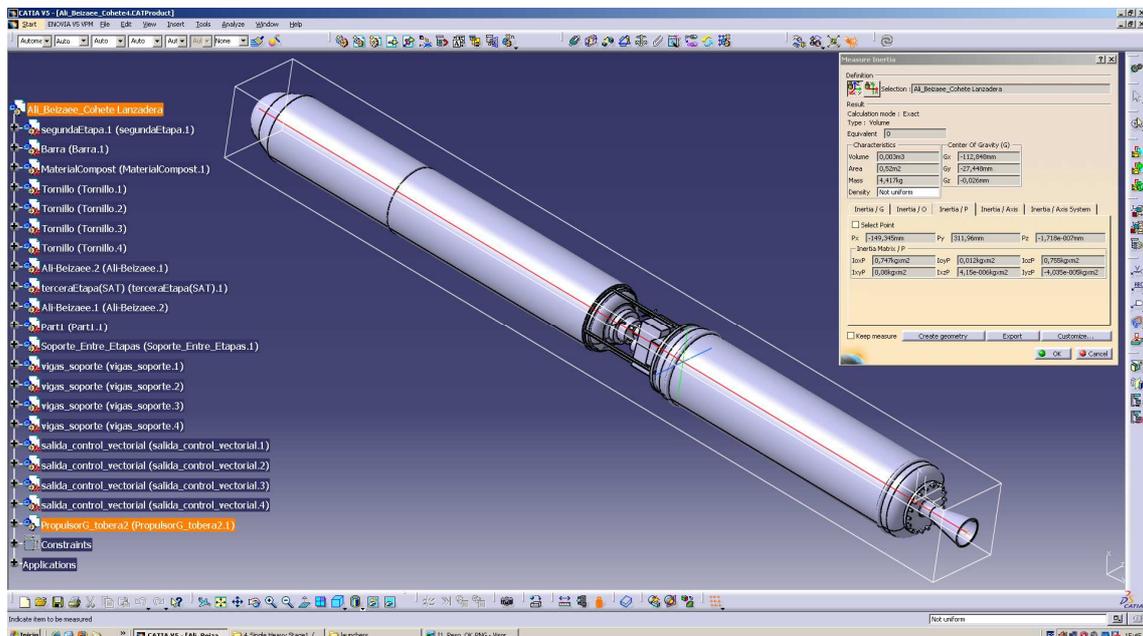
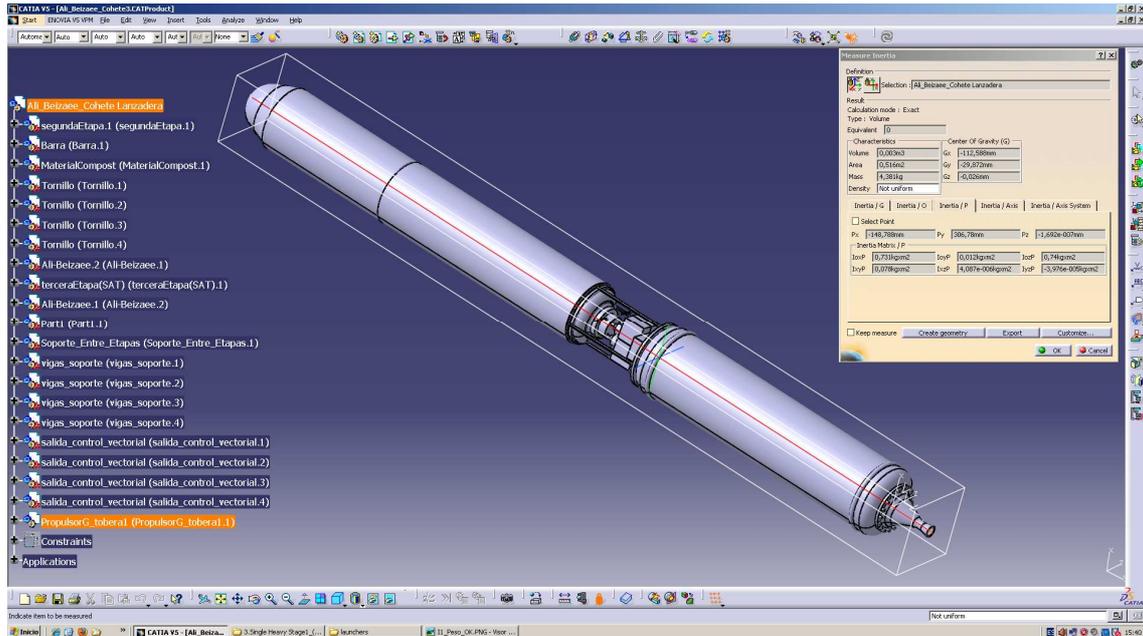


Figure 12 – WikiLauncher with single heavy stage1 and 4 mm (a) and 9 mm nozzle (b)

Figure 12 shows the WikiLauncher in configuration of heavy stage1 for a 4 mm nozzle 12(a) and 9 mm nozzle 12(b), the bill of materials is about 320€ and it is composed by three sections:

- The payload section
- The vector control section and
- The propulsion section like the light configuration

The center of gravity is marked in green in every case, closer to the end of the propulsion section but closer to the vector control Piping (14) before ignition.

Table 3 presents a summary of some WikiLauncher configurations, the total length, the center of gravity, the total mass and the bill of materials cost.

Table 3 – WikiLauncher configuration summary

WikiLauncher Configuration	Length	CG ⁴	Gap ⁵	Mass	Cost
1. Single light stage1 (4 mm)	838.21 mm	243	270	3,369.9 gr	297.75€
2. Double light stage1 (4 mm)	1,176.51 mm	461	348	5,301.8 gr	518.05€
3. Single heavy stage1 (4 mm)	845.85 mm	341	-	4,498.1 gr	314.85€
4. Single heavy stage1 (9 mm)	851.06 mm	339	-	4,518.1 gr	314.85€
5. Three stage1 (4 mm)	1,517.51 mm	663	-	8,361.9 gr	755.45€

5.2.5 Payload and inter-stage assembly

The payload (04) is defined as a volume of 500 cc inside a cylinder of Ø65.5x154.0 mm and a mass of 684 grams. Average payload density is 1.368 g/cm³. Obviously, the inertial matrix will change respect to the computed trajectory used in this work when a new payload is introduced but the change is not significant. The payload is protected by the Fairing Subsystem composed by a Tip (01) and the Cover (02). This fairing is attached to the Vector control subsystem bottle (05) through a thin strap (03).

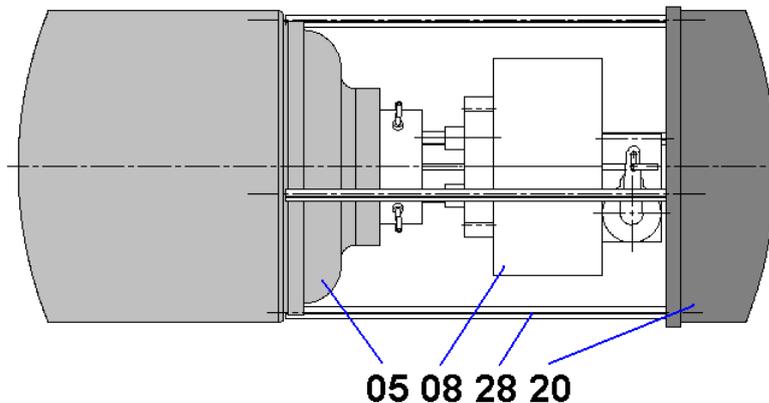


Figure 13 – Attachment system between sections

Each stage is attached through 4x M3 bolts or struts (28) or (38) that support the thrust when engine is burning as presented in figure 13. The jettison system breaks these 4 bolts during the ignition because they are designed to work in compression and released in traction. When next engine starts, the bolts releases with a minimum thrust and ignition subsystem wirings are also burned. Vector control (08) will compensate jettison asymmetries. Everything is managed by the MCU Computer (15) and connected by Wires (27) but control is satellite's responsibility. The MCU has two power supply batteries (17) and a

⁴ Center of Gravity measured from the end of the nozzle in mm

⁵ The Center of Gravity displacement when propellant and cold gas is over in mm

safety Jumper (18) marked as “REMOVE BEFORE FLIGHT”. One battery (3.3 V) feeds the MCU the other (7.2 V) feeds the servos and igniters (26) and (36).

5.3 Computational Fluid Dynamics simulations

Few Computational Fluid Dynamic (CFD) simulations [10] were run in order to see the shockwaves at various angles of attack, as well as the vector control nozzle flow effects. The simulations have 262,000 fluid cells of mesh and a supersonic solver was used in the CFD module in Solid Works; annexes contain details about these simulations.

The maximum allowed angle of attack at 8 Mach is 4 degrees as can be seen in figure 14(a), this is the faster speed that stage1 has got in the trajectory simulation as presented in section 6.3 achieved at 104.6 km of altitude.

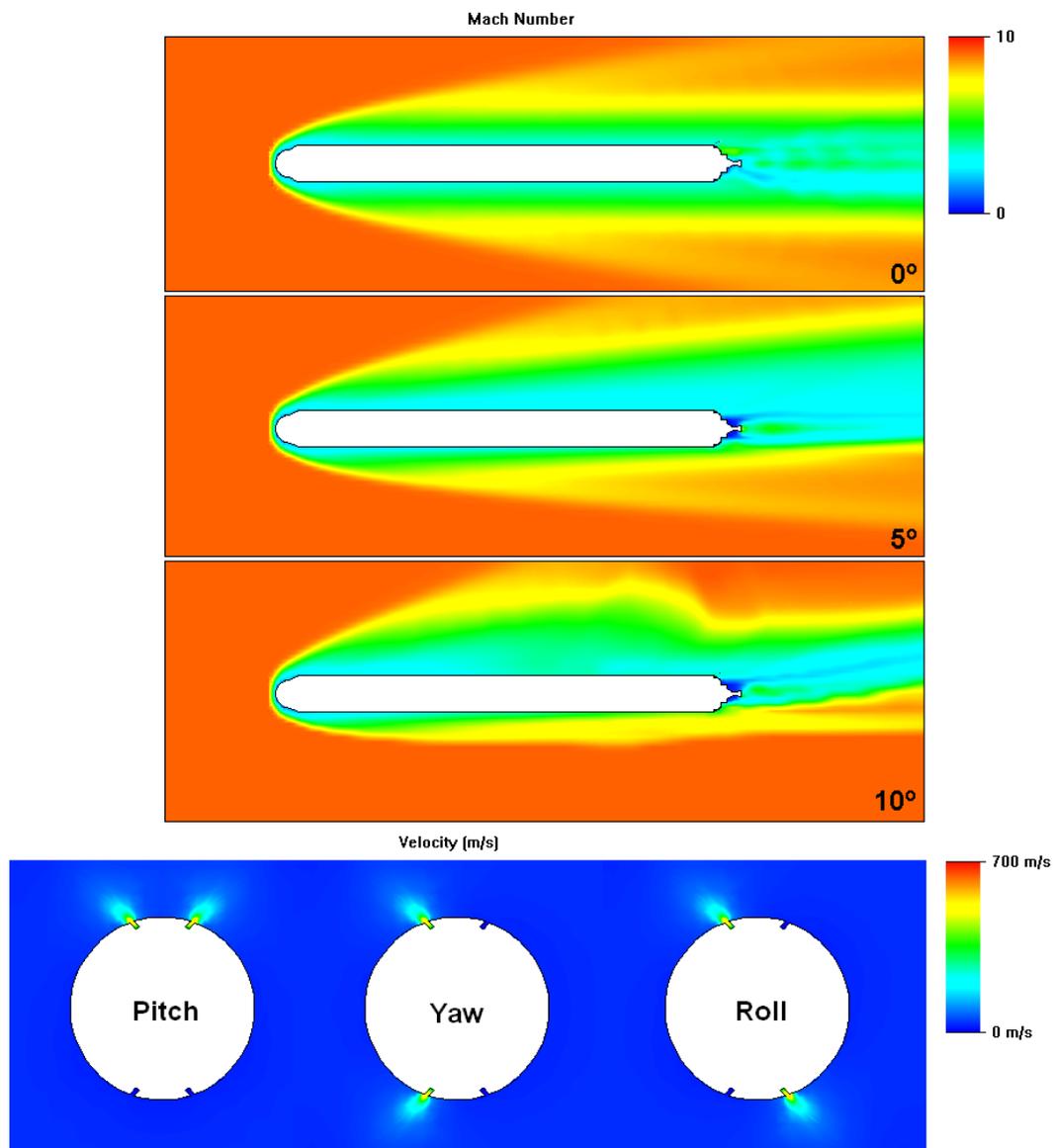


Figure 14 – CFD simulations – Angle of attack at 8 Mach 8 in near space (a) and nozzle configurations to generate the launcher Pitch, Yaw and Roll (b)

The previous CFD simulation seen in the figure 14(b) was the flow of the vector control nozzles in three cases: Pitch, Yaw and Roll.

In the Pitch configuration, two consecutive closer nozzles were used in order to generate a force and the launcher pitch rotation.

In the Yaw configuration, two consecutive far nozzles were used to generate a force and the launcher yaw rotation.

In the Roll configuration, two opposite nozzles were used to provoke a rotation around the launcher Y axis.

Simulation was run in the same conditions as the previous CFD figure 14(a). In this case a flow of 2 g/s of butane and 9 atmospheres were applied at each active nozzle. CFD simulations should be compared with real experiments.

CHAPTER 6. SYSTEM IMPLEMENTATION

This chapter contains the manufacturing process, the system performances, an example of trajectory and a static flight test.

6.1 Manufacturing process

The final prototype where functional tests are performed is based on the idea of to use the butane bottle neck as a cast for composite material based on epoxy (Styrene) as matrix and fiberglass as reinforcement. Inside, before curing, four bolts with inserts attached to four pattern servos will be introduced in the correct position. The threads of each bolt will be oiled in order to avoid the epoxy is attached to the thread. The mold is easy to dismount after curing.

Four lateral drills will be performed to the block assembly but without the bolts. Later, bolts will be positioned with the final servos and locked through a nut in each bolt. These servos will be adjusted to a neutral position then a mark will be performed to the bolts by the bit and each bolt head will be marked to show the location of this mark. One by one, each bolt will be drilled. Thread will be rebuilt avoiding dirty in the thread. That way, it is easier to drill in the middle of the bolt; otherwise, the bolt could be broken or will not be aligned properly. Never should be removed more than one bolt at the time in order to do not lose the adjustment. Servos do not have a support and relative position is granted by the four bolts.

6.2 System performances

The WikiLauncher in configuration of single light stage1 (Config. 1) has the so called Gimbal Lock⁶ problem. The figure 15 shows how the center of gravity is very close to the nozzles and displaced 270 mm when stage1 is burned. The WikiLauncher is aerodynamically unstable but thanks to the flight is in the weak atmosphere, the aerodynamic forces will be small. The arm between the forces and nozzles are small and becomes smaller when stage1 burns due to the type of propellant is an End Burner.

During the first moment of flight, the launcher has to make a turn in Pitch of few degrees so it is mandatory to have a larger vector control arm changing the mass distribution or adding ballast.

In the Correction maneuver at the apogee, the center of gravity should be as closer as possible to the nozzles in order to reduce the effects of nutation when the payload is spinning.

⁶ http://en.wikipedia.org/wiki/Gimbal_lock

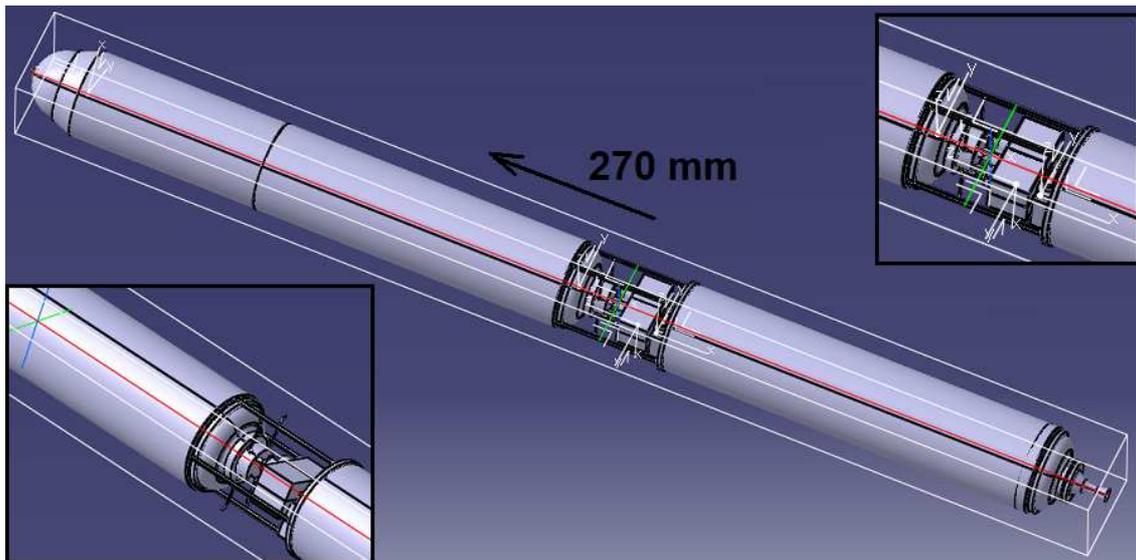


Figure 15 – Gimbal Lock problem of the Vector Control

Functional tests are performed to ensure that servos are able to turn the bolts opening and closing the rotary valve. Overall consumption should not be more than 400 mA in every maneuvering. The servo current was 1.1 mA at 4.5 V. Pressure should be kept in closed position and released in open position.

The cold gas bottle has a total of 258 grams of gas that can work for 60 seconds. A flow of 2 g/s of cold gas at 9 atmospheres were assumed at each active nozzle. Estimated total flow is $258 \text{ g} / 60 \text{ s} = 4.3 \text{ g/s}$. The fifth servo is able to open and close the manifold pressure in 50 ms that means 20 maneuvers per second and an average total of 1,200 cycles. The servos were tested for more than 23,000 cycles working properly.

6.3 Example of trajectory

In this section, the implemented prototype is validated through some functional tests and hardware-in-the-loop simulations as designed by Navarro in [9]. The launcher lifts-off from a balloon at 32 km of altitude reaching the orbital altitude.

Figure 2 from chapter 1 showed the trajectory simulation that has followed the launcher. The rocket attitude is controlled by the vector control and depicted in bold white color. The predicted trajectory that stage1 will follow was marked in thin pink color. The vector control MCU is connected through an UART interface to a serial port in the computer where the simulator closes the hardware-in-the-loop.

During the simulation some specifications are tested such as the reaction time and the inertial effects over the roll control (That are rotations) and over Pitch and Yaw controls (that are lateral displacements). The simulator requires the inertial matrix which changes depending on the launcher configuration (See table 3). The reference systems are many and we propose to use a standard

[11] like the aeronautical one⁷. Anyway a summary of reference systems and its application used in this work is presented in the annexes.

Following subsections will show the center of gravity location respect to the end of the nozzle and its inertial matrix for each case seen in section 5.2.4 where Y axis is the flight direction. Fifth configuration is not studied in this work.

6.3.1 Config1. Inertial matrix with single light stage1 and 4 mm nozzle

The case for the WikiLauncher in configuration of single light stage1 has a total mass of 3,370 grams. This case is composed by the payload section, the vector control section and a light stage1 with a 4 mm nozzle. The inertial matrix in $\text{kg}\cdot\text{m}^2$ respect to the exhaust nozzle is showed in (5.1) marked as I_1 and the center of gravity is located at $I_{CG1} = (0 \ 297 \ 0)\text{mm}$ respect to the thrust vector.

$$I_1 = \begin{vmatrix} 0.659 & 0.071 & 0 \\ 0.071 & 0.009 & 0 \\ 0 & 0 & 0.666 \end{vmatrix} \quad (5.1)$$

The inertial matrix in $\text{kg}\cdot\text{m}^2$ respect to the exhaust nozzle when dry (First stage burned) is showed in (5.2) marked as I_{1Dry} and the center of gravity is displaced 270 mm forward. It is located at $I_{CG1Dry} = (0 \ 567 \ 0)\text{mm}$ respect to nozzle exit.

$$I_{1Dry} = \begin{vmatrix} 0.590 & 0.063 & 0 \\ 0.063 & 0.008 & 0 \\ 0 & 0 & 0.597 \end{vmatrix} \quad (5.2)$$

6.3.2 Config2. Inertial matrix with double light stage1 and 4 mm nozzle

The case for the WikiLauncher in configuration of double light stage1 has a total mass of 5,302 grams. This case is composed by the payload section, the vector control section and two light stage1 with a 4 mm nozzle in both stages. The inertial matrix in $\text{kg}\cdot\text{m}^2$ respect to the exhaust nozzle is showed in (5.3) marked as I_2 where the center of gravity is located at $I_{CG2} = (0 \ 461 \ 0)\text{mm}$ respect to the nozzle exit.

$$I_2 = \begin{vmatrix} 1.931 & 0.207 & 0 \\ 0.207 & 0.025 & 0 \\ 0 & 0 & 1.953 \end{vmatrix} \quad (5.3)$$

The center of gravity is displaced 270 mm forward when first engine is burned. It is located at $I_{CG2Dry} = (0 \ 731 \ 0)\text{mm}$ respect to the nozzle exit. The displacement when both engines are empty is 384 mm but in this case, engine 1 was jettisoned and the reference point has changed.

⁷ [http://en.wikipedia.org/wiki/Flight_dynamics_\(fixed-wing_aircraft\)](http://en.wikipedia.org/wiki/Flight_dynamics_(fixed-wing_aircraft))

6.3.3 Config3. Inertial matrix with heavy stage1 and 4 mm nozzle

The case for the WikiLauncher in configuration of single heavy stage1 and 4 mm nozzle has a total mass of 4,498 grams. This case is composed by the payload section, the vector control section and a heavy stage1 with a 4 mm nozzle. The inertial in $\text{kg}\cdot\text{m}^2$ respect to the exhaust nozzle is showed in (5.4) marked as I_3 where the center of gravity is located at $I_{CG3} = (0 \ 441 \ 0)\text{mm}$.

$$I_3 = \begin{vmatrix} 0.731 & 0.078 & 0 \\ 0.078 & 0.012 & 0 \\ 0 & 0 & 0.740 \end{vmatrix} \quad (5.4)$$

6.3.4 Config4. Inertial matrix with heavy stage1 and 9 mm nozzle

The case for the WikiLauncher in configuration of single heavy stage1 and 9 mm nozzle has a total mass of 4,518 grams. This case is composed by the payload section, the vector control section and a heavy stage1 with a 9 mm nozzle. The inertial matrix in $\text{kg}\cdot\text{m}^2$ respect to the exhaust nozzle is showed in (5.5) marked as I_4 where the center of gravity is located at $I_{CG4} = (0 \ 339 \ 0)\text{mm}$.

$$I_4 = \begin{vmatrix} 0.747 & 0.080 & 0 \\ 0.080 & 0.012 & 0 \\ 0 & 0 & 0.755 \end{vmatrix} \quad (5.5)$$

6.4 Static flight test

This section proposes a static flight test based on a hardware-in-the-loop experiment. These tests are required before a real flight.

6.4.1 Hardware-in-the-loop experiment setup

Rodriguez-Miguel in [6] studied a similar vector control implementation, studying the proper control loop required for this purpose, but never tested in a WikiLauncher. For this reason, the launcher was placed in the gimbal, providing 2 DoF; Yaw is locked at this time. Arduino computer keeps the zenith, orienting the Pitch rotation normal to North seen from our laboratory location (Figure 16).

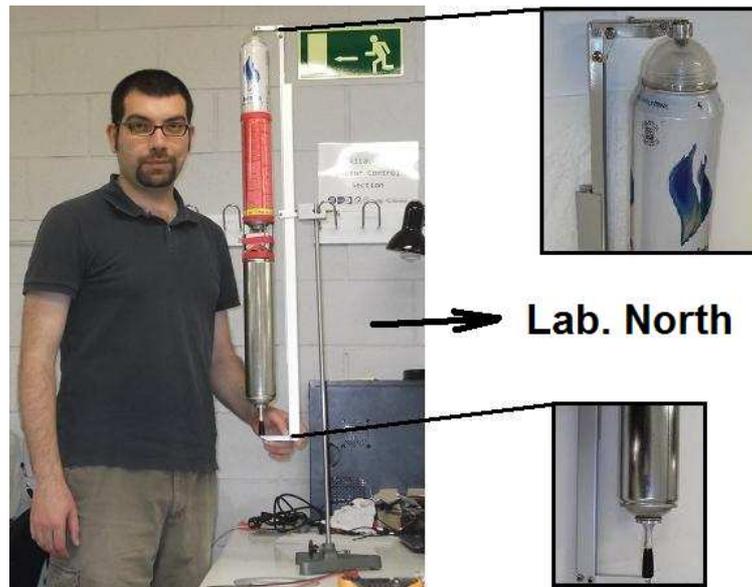


Figure 16 – WikiLauncher gimbal

The Link panel was configured in order to communicate with the Arduino computer in the launcher as showed in figure 17. The external link mode is set to “Control” mode. The link port is set to the available COM port at “4800 bauds” and settings “8,1,N,N”. The hardware-in-the-loop option is activated by selecting “Launch Trajectory”: Arduino controls the rocket when running the trajectory simulation. Attitude control is done by changing Pitch, Roll and Yaw angles. In this case, Yaw is locked to 0° . Pitch is kept at 90° while Roll is set at 90° .

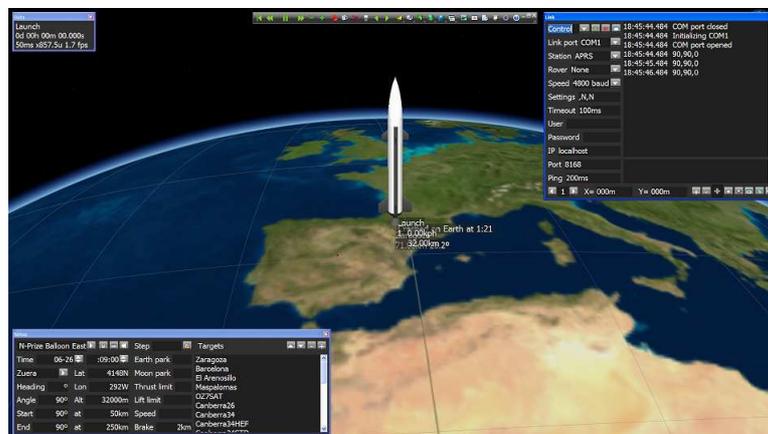


Figure 17 – Link panel configuration – Moon2.0 simulator

The Arduino board has 11 DoF (See annexes for details about the Arduino specifications) so it was easy to implement the algorithm. It used the magnetic compass to provide the Roll angle kept at 90° , normal to the ground surface at this point; valves are injecting gas in a configuration showed in figure 18.

The Pitch is set at 90° , also normal to the ground surface at this point. The valves are injecting gas in a configuration showed in figure 19. Hence, the Yaw correction since is locket to 0° , no corrections are required in this sense but they can be tested orienting the gimbal support pointing the Yaw rotation normal to the North.



Figure 18 – Static test. A torque for rotations in Roll

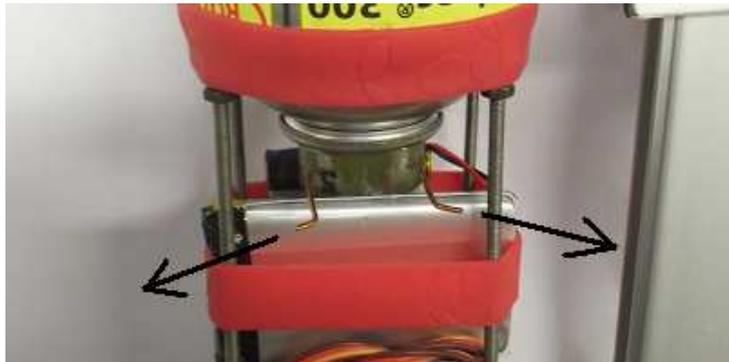


Figure 19 – Static test. A moment for rotations in Pitch

6.4.2 Results

Due to the lack of time, we were not able to implement the radio-link between the launcher and the simulator in order to perform the hardware-in-the-loop before we printed this work.

Any case, in the early tests, we have observed that the liquefied butane changes the center of gravity a little. The vector control algorithm should take into account this fact in a real flight. It was calculated that the WikiLauncher center of gravity in configuration 1 is displaced 270 mm forward when stage1 is burned; crossing the nozzles and generating a gimbal-lock situation.

CHAPTER 7. CONCLUSIONS

This chapter presents the general conclusions, the system conclusions and the environmental impact study.

7.1 General conclusions

- The main objective was achieved: To build a prototype (Called the system) of a simplex vector control device for the WikiLauncher based on the idea of to use the butane bottle neck as a cast for composite material (Styrene).
- The achieved implementation is better than the previous in terms of mass and simplicity.
- Secondary objective was not achieved: A real flight to test the performances of the system. The difficulty of to perform a real flight is huge; some static tests were done instead.

7.2 System conclusions

- System requirements were achieved. Mass assembly is 85 grams while the previous prototype was 91 grams. The system fits in a diameter of 55 mm.
- The spiral system design demonstrated that works fine to develop a functional prototype in a few weeks.
- High level requirements were achieved. Rotary valve concept does not guarantee the sealing. A main valve is required that will work for pulse control instead of progressive control.
- Computational Fluid Dynamic showed that the maximum allowed angle of attack at 8 Mach is 4 degrees before the shockwave touches the tail and creates instability.
- The WikiLauncher in configuration of light stage1 (Config. 1) has a problem with the center of gravity that is too close to the nozzles. The arm to create a moment in Pitch and Yaw is small and there is not enough moment to make sure the vector control is stable. We propose to change the Butane bottle for a smaller one in order to displace the center of gravity.
- The low-cost manufacturing process based on to use the bottle neck as the cast, performing four lateral drills for the four parallel shafts looks like worked fine but a fifth servo is mandatory due to the rotary valve cannot achieve the sealing.
- During the early static flight test, we have observed that the liquefied butane changes the center of gravity a little. The vector control algorithm should take into account this fact.
- Cold gas quantity should be tested in a real flight.

7.3 Future work

Even the Computational Flow Dynamic simulations were performed with Solid Works, the use of ANSYS 13 is recommended because it will produce better and more detailed results like dynamic analysis, modal study and harmonic study.

Due to the lack of time, the hardware-on-the-loop test should be improved in order to complete the static test.

A real flight to test the vector control subsystem is mandatory to validate the static test.

7.4 Environmental impact

The use of solid propellant is nasty but using this type of launcher based on a rocket is a significant reduction of contamination if a conventional launch provider is used. Reusable orbits at a very Low Earth Orbit are an important reduction of space Junk. In any moment safety regulations were observed by any WikiSat team member.

The author proposes a local reforest action consisting in the tree plantation of few trees in the program⁸ "Bosque de los Amigos de la UPC en Cornellà de Llobregat".

⁸ <http://www.upc.edu/saladeprensa/al-dia/mes-noticias/2011/se-inaugura-el-bosque-de-los-amigos-de-la-upc-en-cornella-de-lobregat>

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ANEXES

TÍTOL DEL TFC: Millores en un sistema de control vectorial per a una mini-llançadora basat en materials compostos

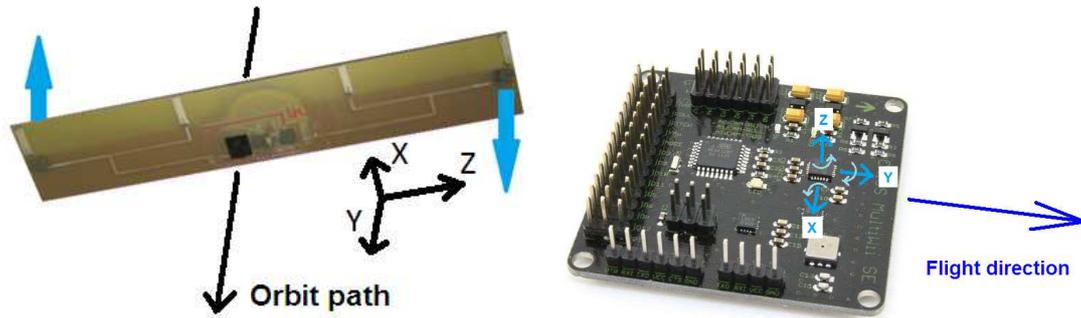
TITULACIÓ: Enginyeria Tècnica Aeronàutica, especialitat Aeronavegació

AUTOR: Alí Beizae

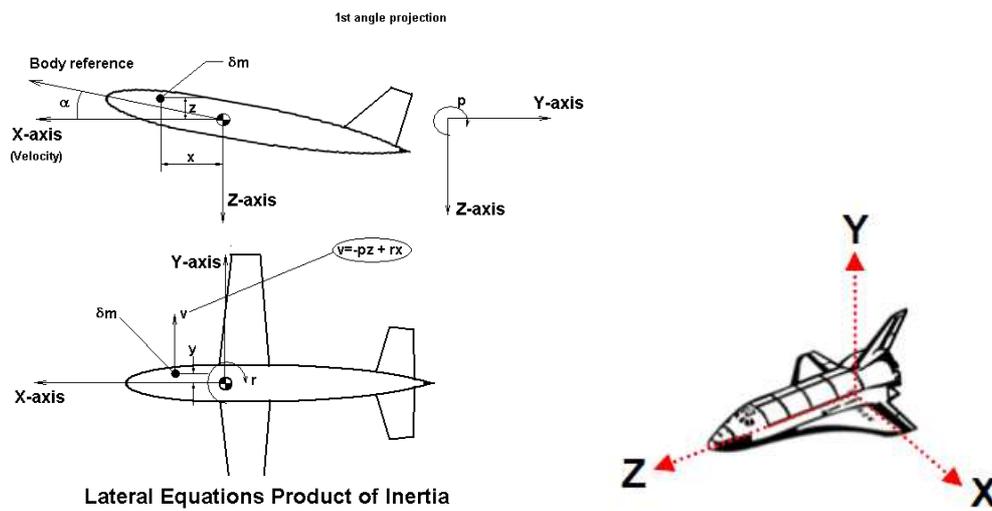
DIRECTOR: Joshua Tristancho Martínez

DATA: 26 de Juny de 2013

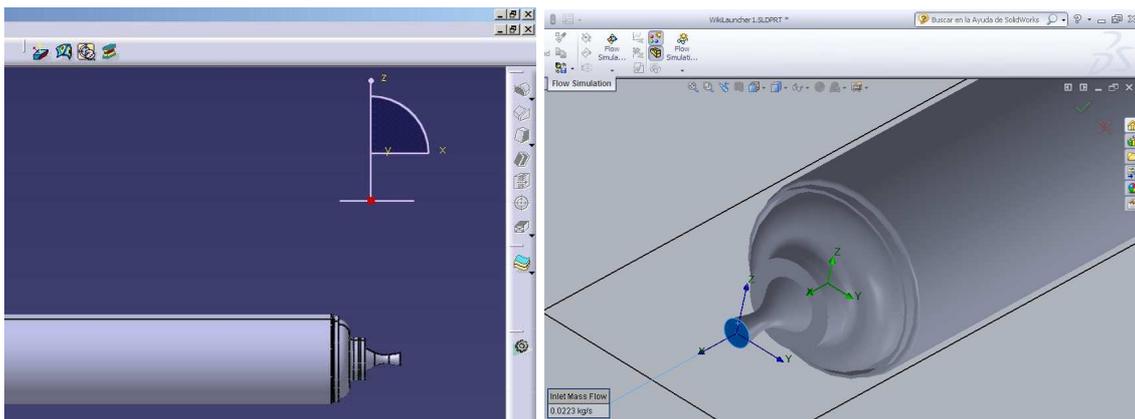
Annexes. Reference systems and its applications



Reference system of the Arduino installed in the WikiSat (a) and in the WikiLauncher (b)



Reference system in Aeronautics. Source: Wikipedia (a) and Moon2.0 simulator (b)



Reference system in CATIA (a) and Solid Works for CFDs (b)

Annexes. CFD simulation Supersonic solver. Alpha=0°

WikiLauncher configuration: Config1
Flight phase: When engine is turned off

Atmosphere conditions

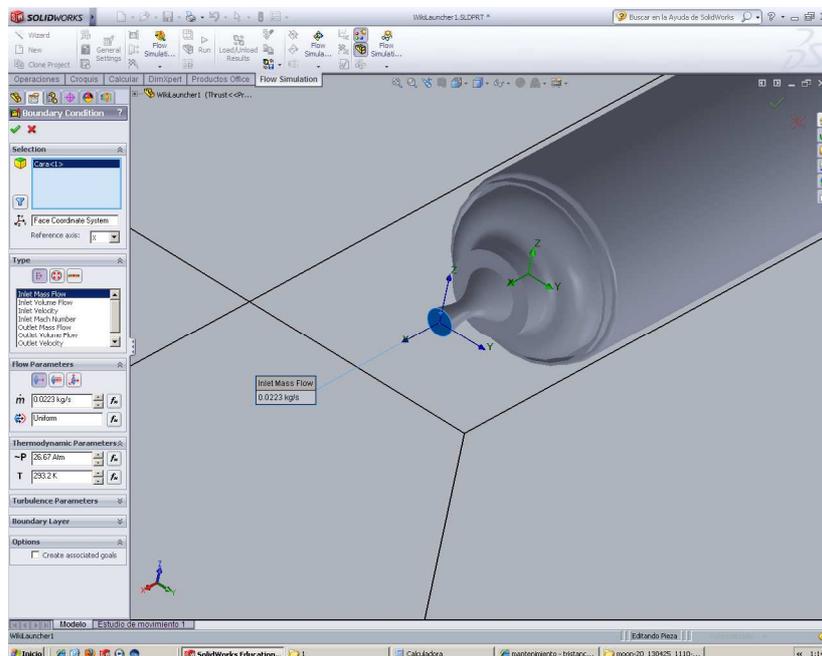
Temp=247.85K
Pressure=14.64 mPa
g=9.485 m/s²
Altitude=104.619 km

Kinetics

DeltaV: 3,604 m/s
Launcher total velocity: 2860 m/s (Mach 8.3)
Angle of attack: 0°
Drag: 4.8 mm/s² (dry mass=400 grams; $F_{\text{drag}}=0.00192 \text{ Nw}$)
Max G during the burn: 11g
Flight time: 1m 16s

Nozzle modeling

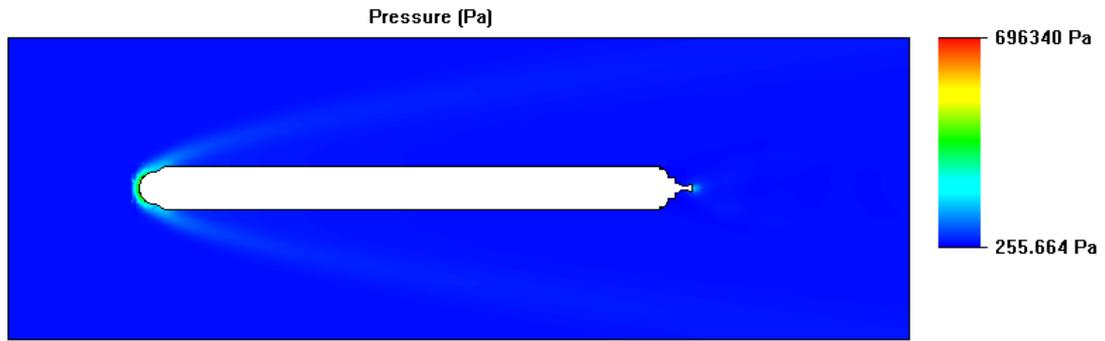
Temp=970K
Pressure: 10,129.5 Pa
mass flow= 0.0217 kg/s
Area = D8mm (50.3 mm²)



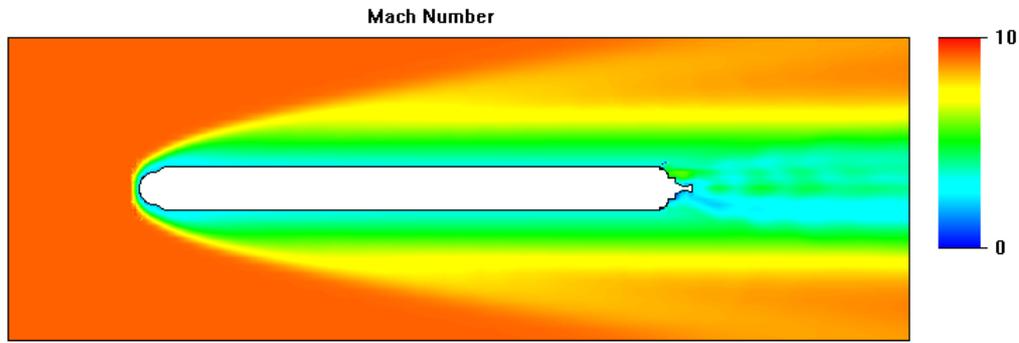
CFD

Fluid cells: 262,124 (Mark 3)
Iterations: 1,000
CPU time: >1,000 seconds
Parameters: Pressure, Mach Number and Temperature

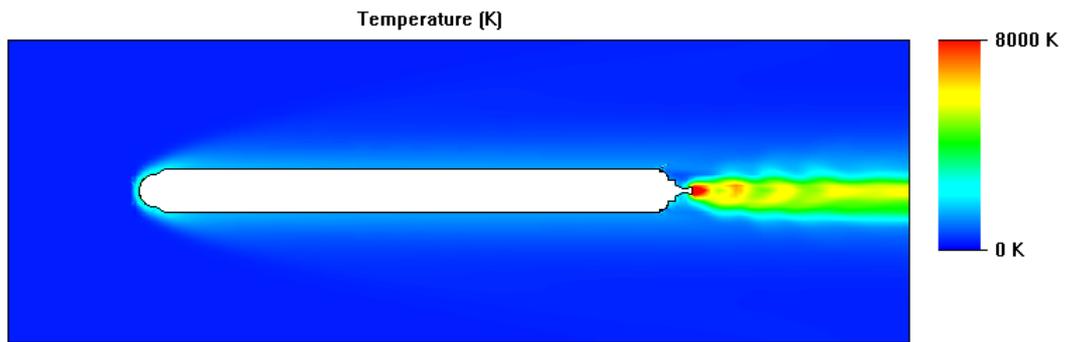
Alpha=0°



Min=255.664 Pa Max=696340 Pa
Iteration = 800



Min=0 Max=9.41953
Iteration = 800



Min=228.986 K Max=15690.5 K
Iteration = 800

Annexes. CFD simulation Supersonic solver. Alpha=5°

WikiLauncher configuration: Config1

Moment of the flight: When engine is turned off

Atmosphere conditions

Temp=247.85K

Pressure=14.64 mPa

g=9.485 m/s²

Altitude=104.619 km

Kinetics

DeltaV: 3604 m/s

Launcher total velocity: 2,860 m/s (Mach 8.3)

Angle of attack: 5°

V_x=2,849 m/s

V_y=249 m/s

Max G during the burn: 11g

Flight time: 1m 16s

Nozzle modeling

Temp=970K

Pressure: 10,129.5 Pa

mass flow= 0.0217 kg/s

Area = D8mm (50.3 mm²)

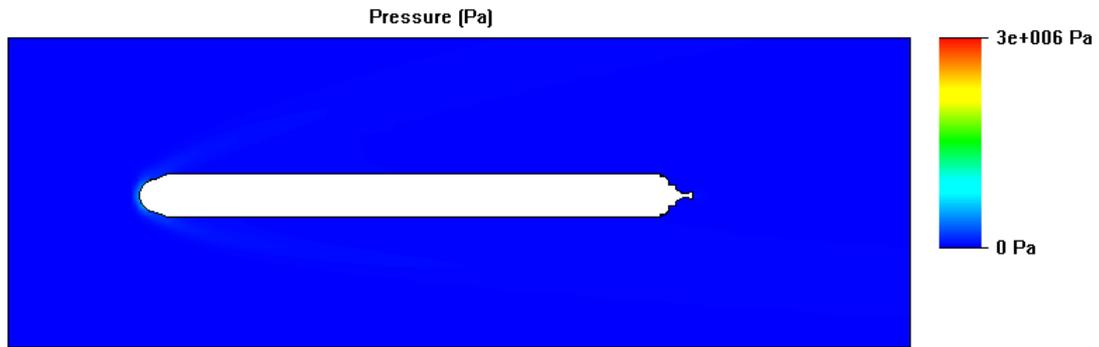
CFD

Fluid cells: 262,124 (Mark 3)

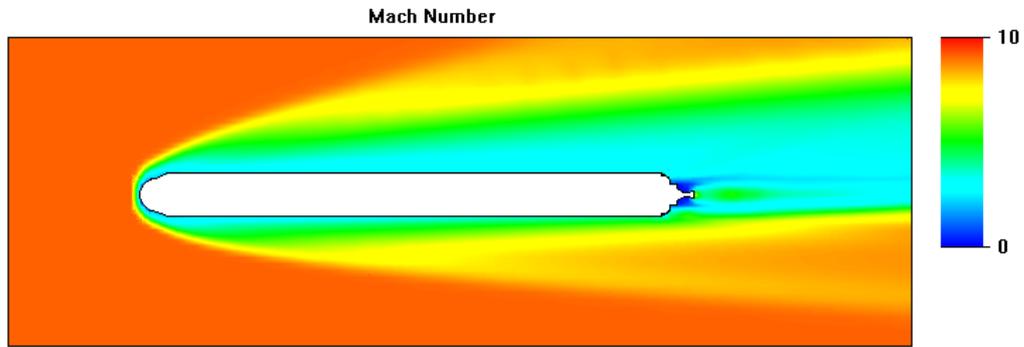
Iterations: 1,000

CPU time: >1,000 seconds

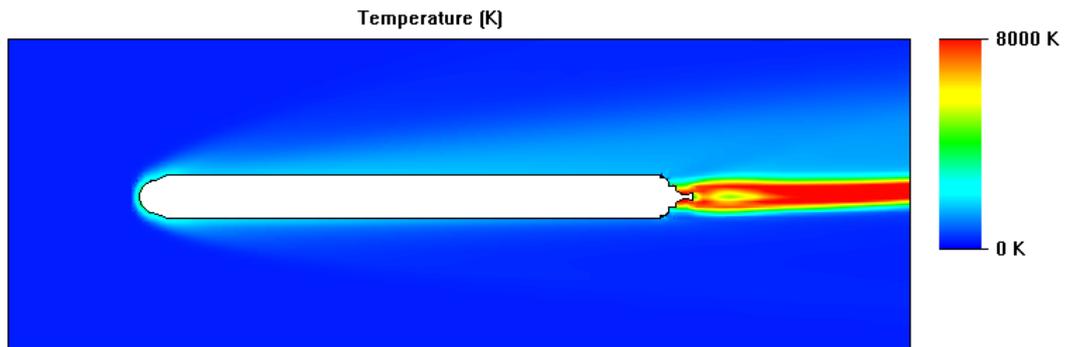
Alpha=5°



Min=172.478 Pa Max=812212 Pa
Iteration = 1000



Min=0 Max=17.4651
Iteration = 1000



Min=224.805 K Max=12191.6 K
Iteration = 1000

Annexes. CFD simulation Supersonic solver. Alpha=10°

WikiLauncher configuration: Config1

Moment of the flight: When engine is turned off

Atmosphere conditions

Temp=247.85K

Pressure=14.64 mPa

g=9.485 m/s²

Altitude=104.619 km

Kinetics

DeltaV: 3,604 m/s

Launcher total velocity: 2,860 m/s (Mach 8.3)

Angle of attack: 10°

V_x=2,817 m/s

V_y=497 m/s

Max G during the burn: 11g

Flight time: 1m 16s

Nozzle modeling

Temp=970K

Pressure: 10,129.5 Pa

mass flow= 0.0217 kg/s

Area = D8mm (50.3 mm²)

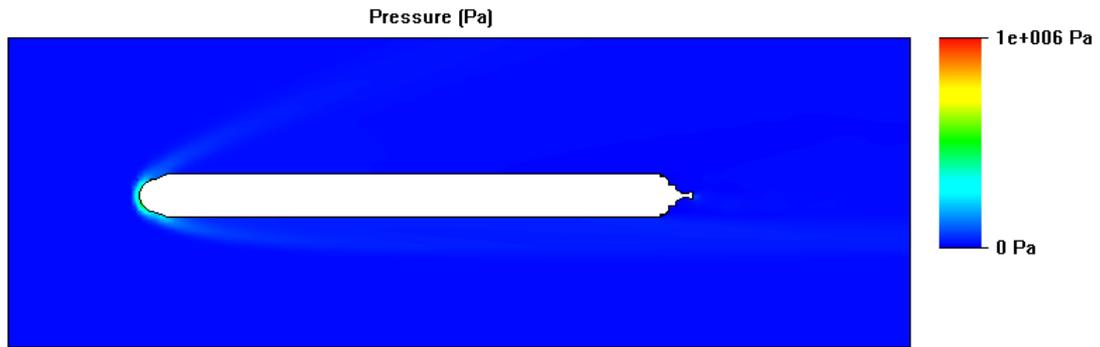
CFD

Fluid cells: 262,124 (Mark 3)

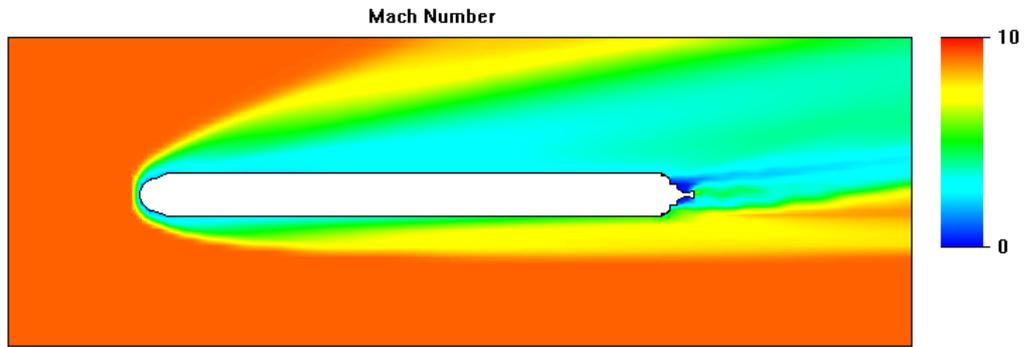
Iterations: 1,000

CPU time: >1,000 seconds

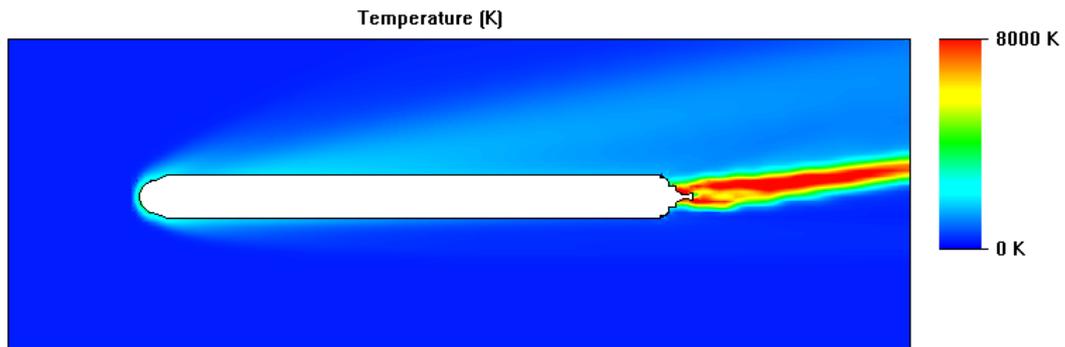
Alpha=10°



Min=171.853 Pa Max=878904 Pa
Iteration = 1000



Min=0 Max=20.7255
Iteration = 1000



Min=233.344 K Max=29992 K
Iteration = 1000

Annexes. CFD simulation. Vector control flow. Pitch

Estimated total flow $258 \text{ g} / 60 \text{ s} = 4.3 \text{ g/s}$

Each nozzle will flow at 2 g/s

Pressure: $7 \text{ Atm} = 709,275 \text{ Pa}$

Temperature: 293.2 K

Nozzle configuration: Two consecutive closer nozzles

Distance between nozzles: 21.9 mm

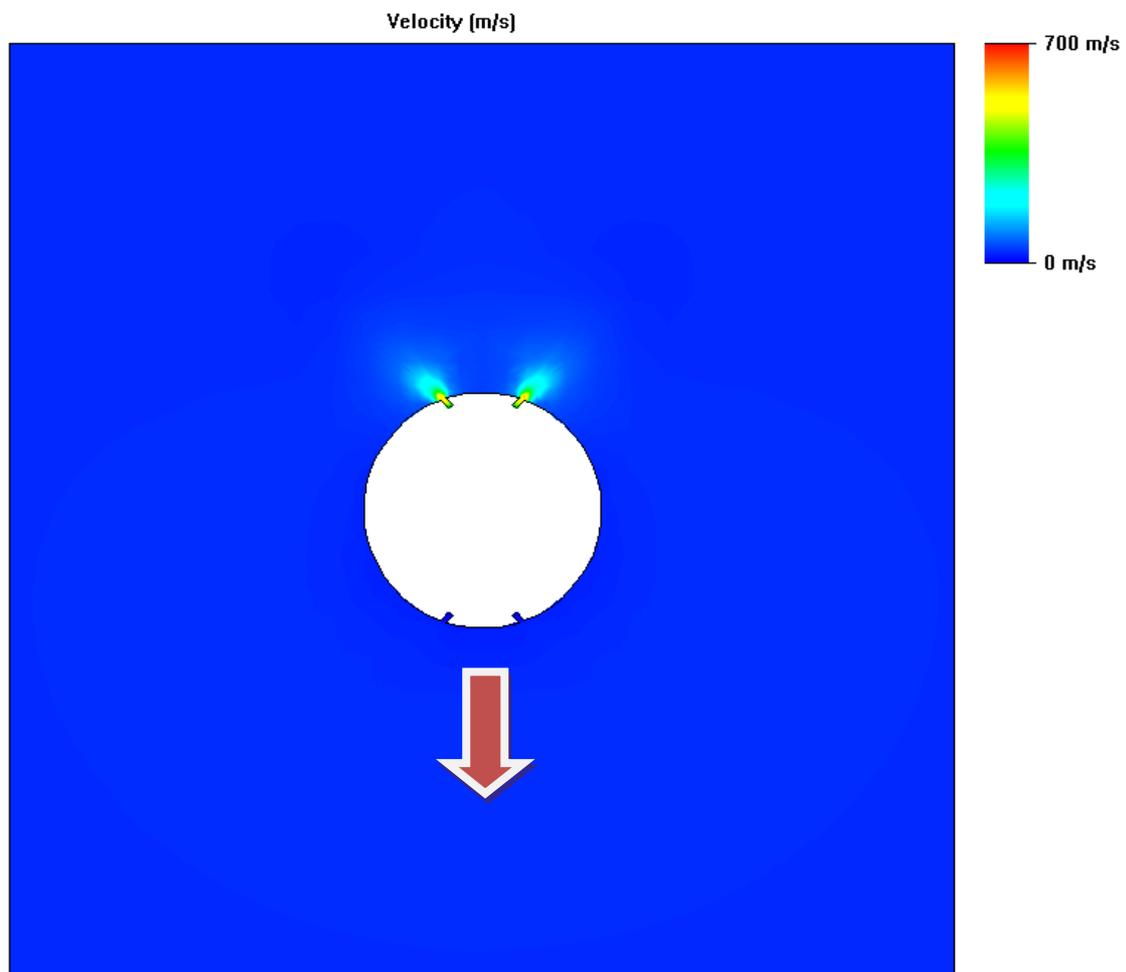
WikiLauncher effect: Launcher pitch rotation

CFD

Fluid cells: 262,124 (Mark 3)

Iterations: >100

CPU time: $>1,000$ seconds



Min=0 m/s Max=611.3 m/s

Iteration = 50

Annexes. CFD simulation. Vector control flow. Yaw

Estimated total flow $258 \text{ g} / 60 \text{ s} = 4.3 \text{ g/s}$

Each nozzle will flow at 2 g/s

Pressure: $7 \text{ Atm} = 709,275 \text{ Pa}$

Temperature: 293.2 K

Nozzle configuration: Two consecutive far nozzles

Distance between nozzles: 63.8 mm

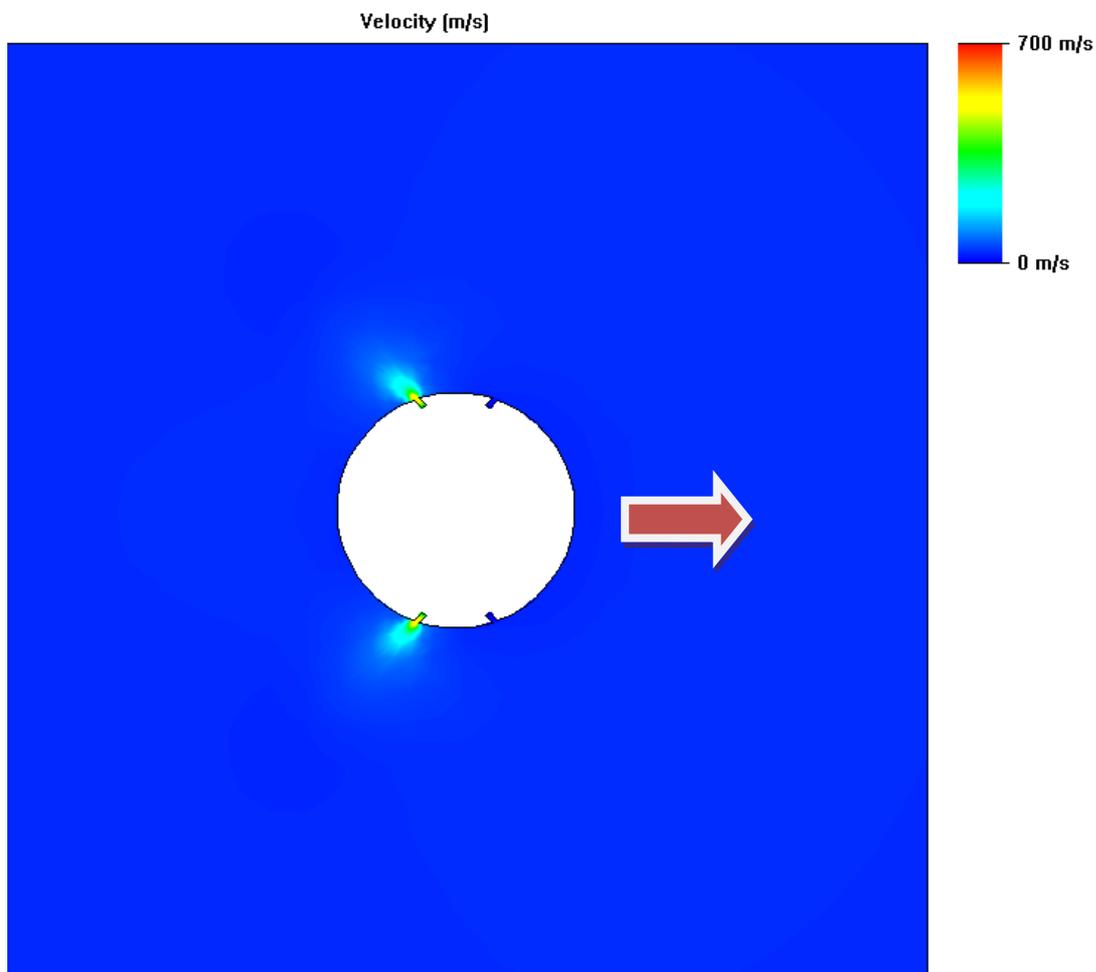
WikiLauncher effect: Launcher Yaw rotation

CFD

Fluid cells: 262,124 (Mark 3)

Iterations: >100

CPU time: $>1,000$ seconds



n=0 m/s Max=609.564 m/s
ration = 50

Annexes. CFD simulation. Vector control flow. Roll

Estimated total flow $258 \text{ g} / 60 \text{ s} = 4.3 \text{ g/s}$

Each nozzle will flow at 2 g/s

Pressure: $7 \text{ Atm} = 709,275 \text{ Pa}$

Temperature: 293.2 K

Nozzle configuration: Two alternative nozzles

Nozzle arm: 12.7 mm respect to the center of gravity

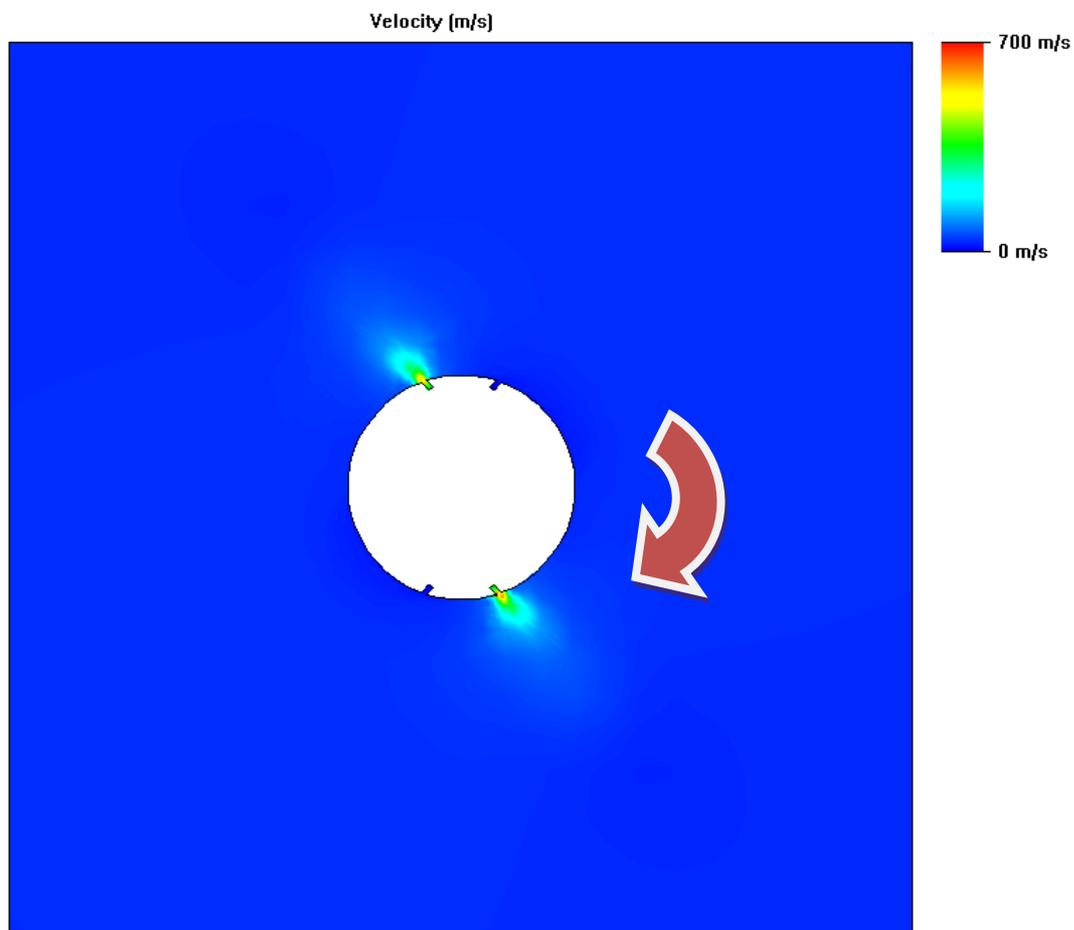
WikiLauncher effect: Launcher Roll rotation around the flight direction. Also it is the spinner angular rotation vector provided to the last stage.

CFD

Fluid cells: 262,124 (Mark 3)

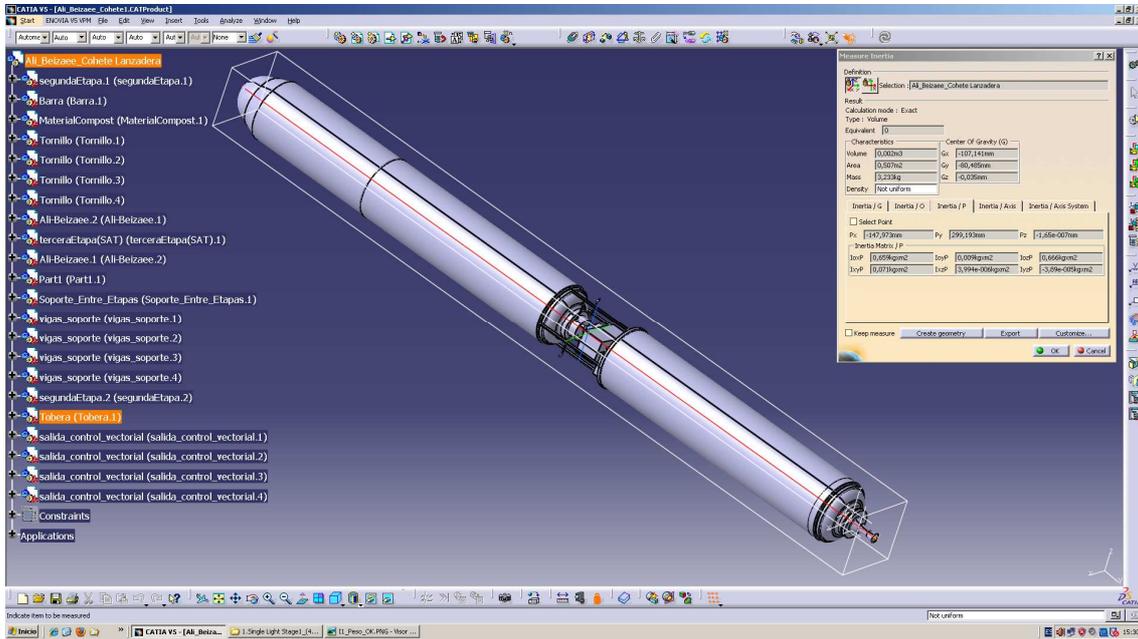
Iterations: >100

CPU time: $>1,000$ seconds

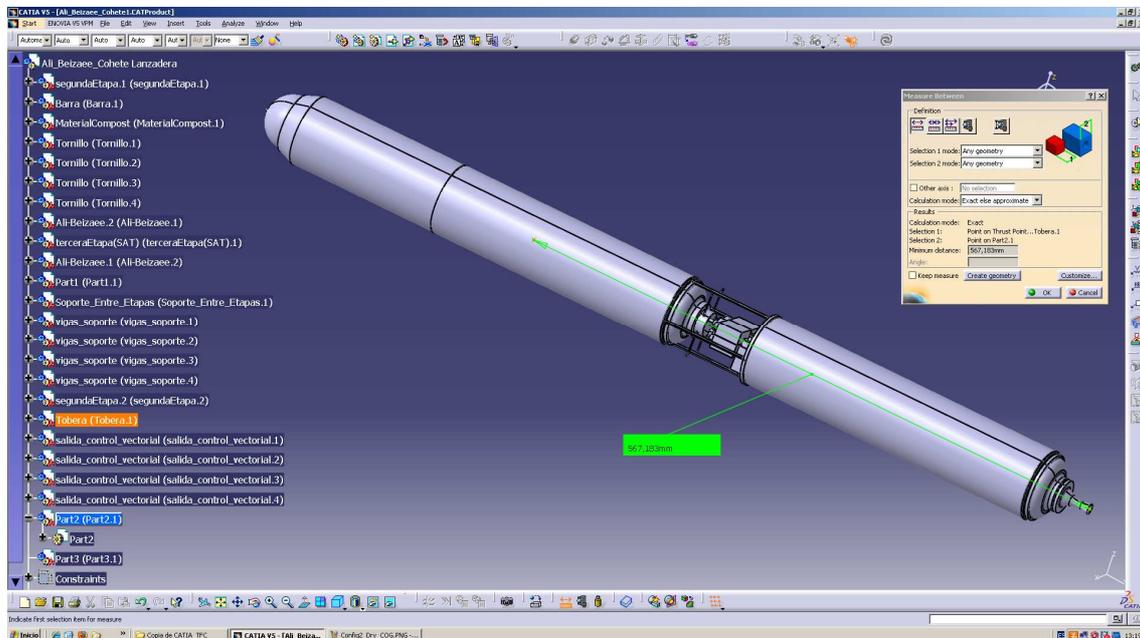


Annexes. WikiLauncher configuration 1

Center of Gravity (297 mm) in Configuration 1 Wet. Mass 3.233 kg

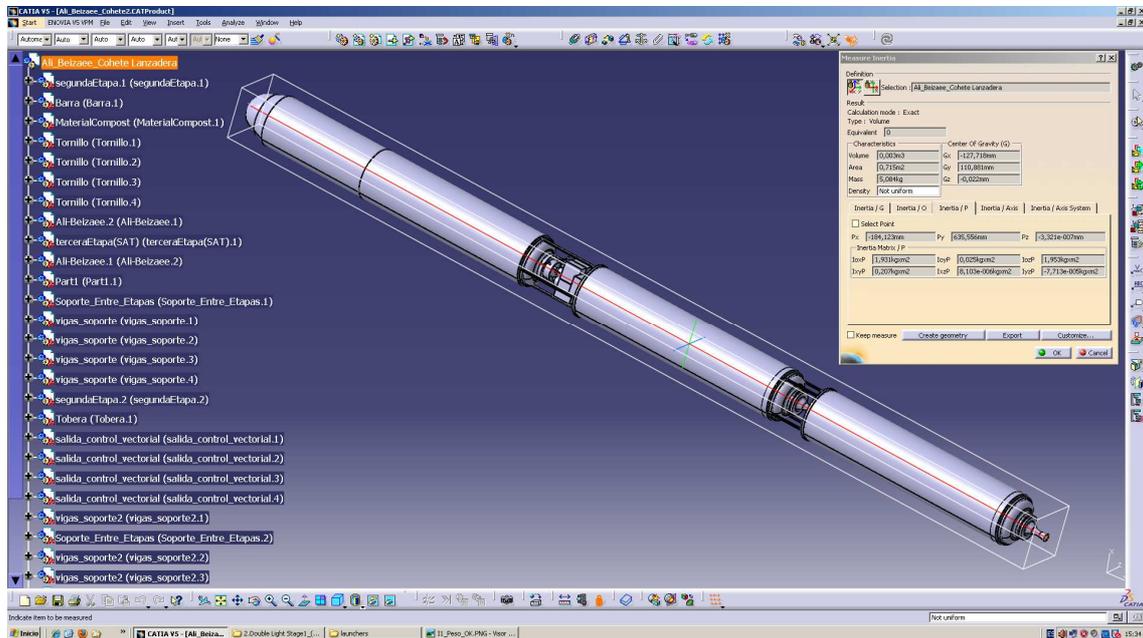


Center of Gravity (567 mm) in Configuration 1 Dry. Mass 1.633 kg



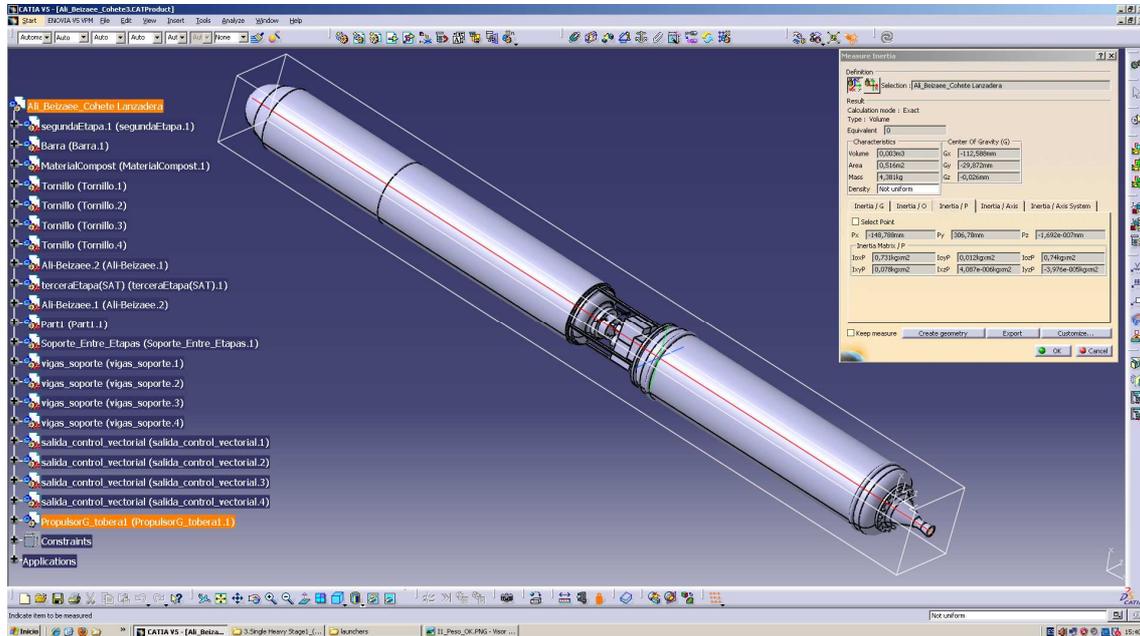
Annexes. WikiLauncher configuration 2

Center of Gravity (461 mm) in Configuration 2 Wet. Mass 5.084 kg



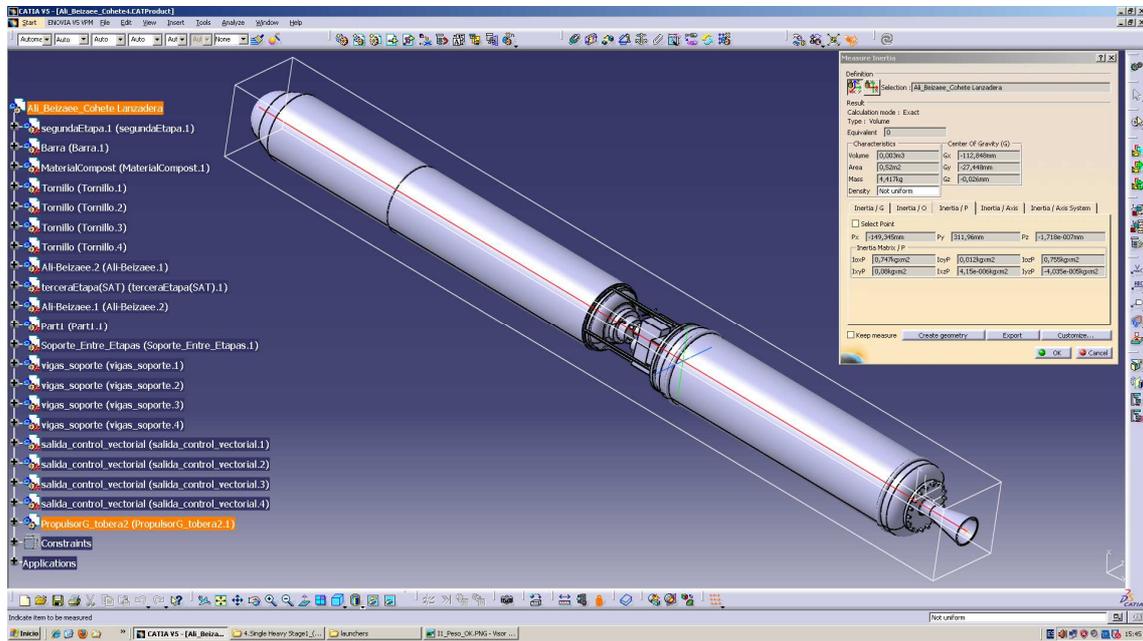
Annexes. WikiLauncher configuration 3

Center of Gravity (341 mm) in Configuration 3 Wet. Mass 4.381 kg



Annexes. WikiLauncher configuration 4

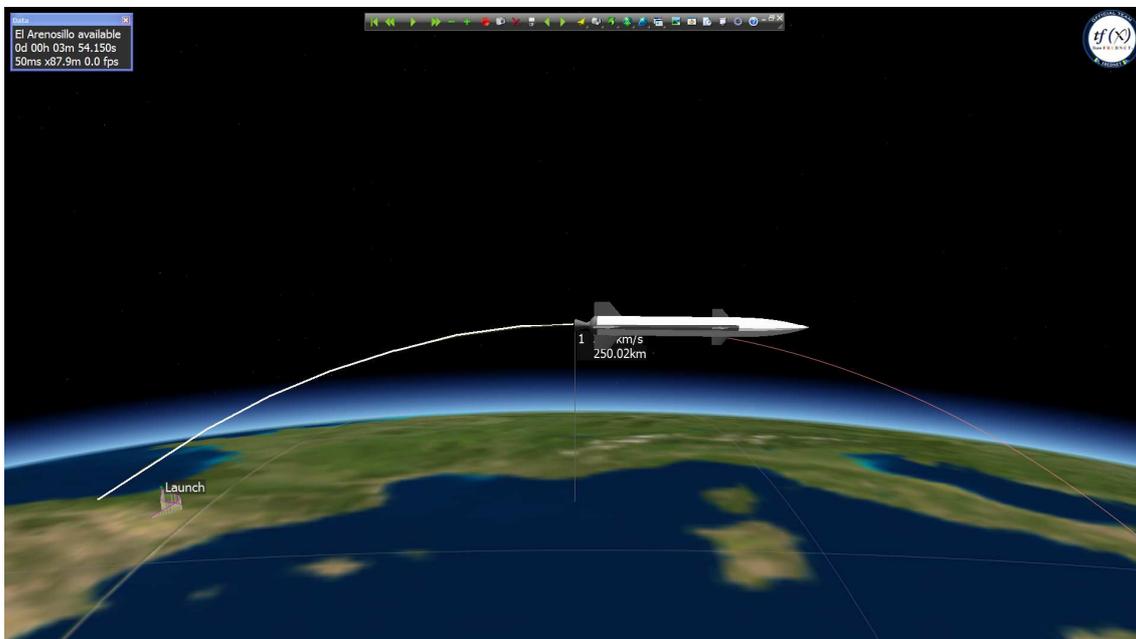
Center of Gravity (339 mm) in Configuration 4 Wet. Mass 4.417 kg



Annexes. Trajectory simulation

The WikiSat team proposes the use of a Rockoon that is a combination between a balloon and a rocket.

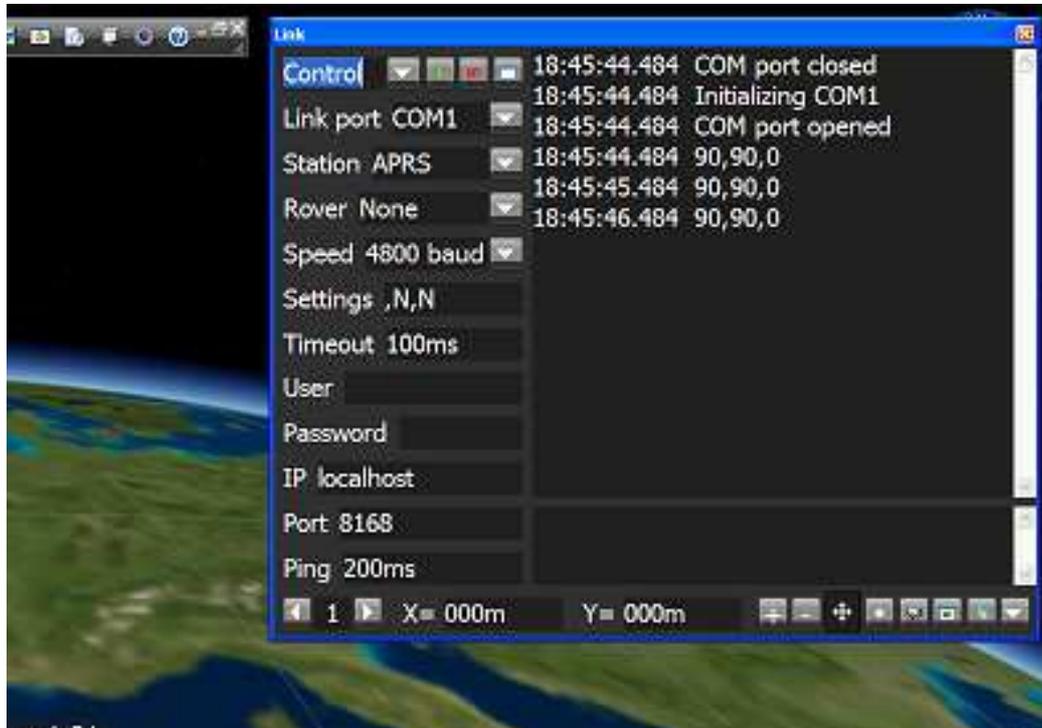
The rocket is called WikiLauncher. This launcher starts from 32 km in the stratosphere bursting the balloon. The launcher should have at least two stages depending on the payload mass. The first stage is responsible of reaching a 250 km orbit (Below the International Space Station that has a 350 km altitude orbit above the Sea Level). The last stage is responsible to achieve the orbital speed of 7.6 km/s. Depending on the WikiLauncher configuration it can have more than two stages but all of them except for the last stage will be used to achieve the apogee. Satellites are injected in orbit only 4 hours after the balloon release. The payload mass is about 100 grams (Up to six femto-satellites) while the launcher mass is less than 10 kg and less than 2 meters of length.



The trajectory is mainly a parabolic flight. After of them, there is a correction maneuver before the apogee. A spinning maneuver is also required before to ignite the last stage. For this reason, the vector control subsystem should be located before the last stage. The vector control system shall to correct the rocket attitude during the unstable phases of the flight. The correction maneuver consists of to point towards the correct direction and to turn around it to provide a minimum spin to the last stage. After the last jettison, this module should be discarded with the previous stage. The last stage increases the speed until the orbital velocity is achieved. After then, satellites can be released. The previous figure was extracted from a Disaster Management mission trajectory simulation presented by Tristancho in [4]. The Vector control will work only when engine is burning and during the correction maneuver. The rest of the time is in idle.

The Link panel (F9) of the Moon2.0 simulator was configured in order to communicate with the Arduino computer in the launcher as showed in the following figure. The external link mode is set to "Control" mode. The link port is

set to the available COM (COM1 in the example) port at “4800 bauds” and settings “8,1,N,N”. The hardware-in-the-loop option is activated selecting the option “Launch Trajectory” which means that, when running the trajectory simulation, the Arduino will control the Rocket. The attitude control is done by changing the Pitch, Roll and Yaw angles. In this case, Yaw is locked to 0° and Pitch is kept at 90° while Roll is maintained at 90° as well.



Annexes. Roberto's vector control implementation

Previous implementation mass was 136 grams for the Roberto's prototype [6]. This version presented too much complexity for a Low-cost application.



Annexes. Brass implementation

Previous implementation mass was 91 grams for the Brass's prototype based on the idea of a butane bottle but too heavy and expensive for a low-cost application.



Annexes. Ali's implementation

The final implementation is 85 grams for the composite material based manifold. This mass includes the Arduino computer and the LiPoly batteries. This version was simplified to the maximum using micro-valves based on the rotary concept.

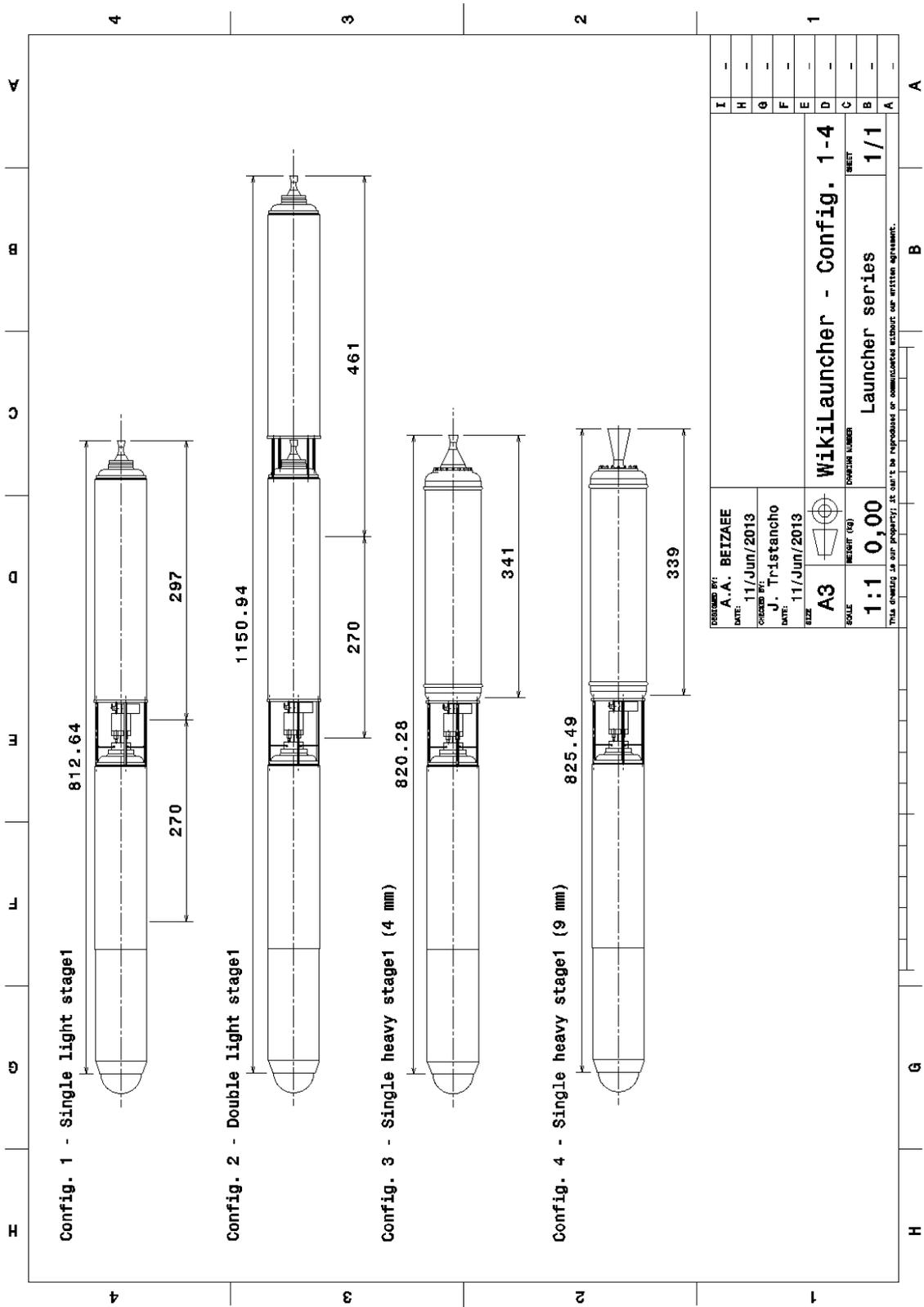


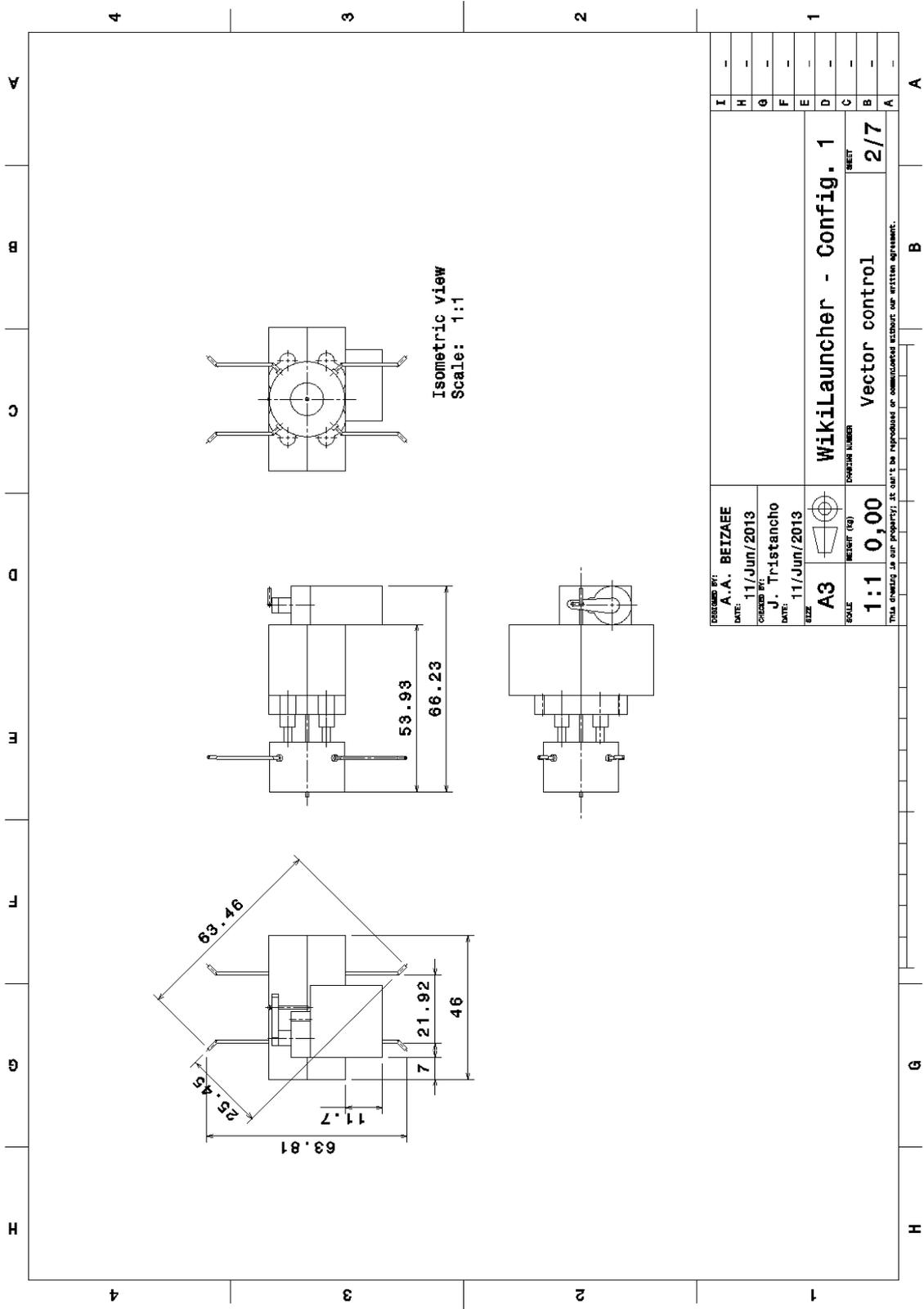
Annexes. WikiLauncher drawings

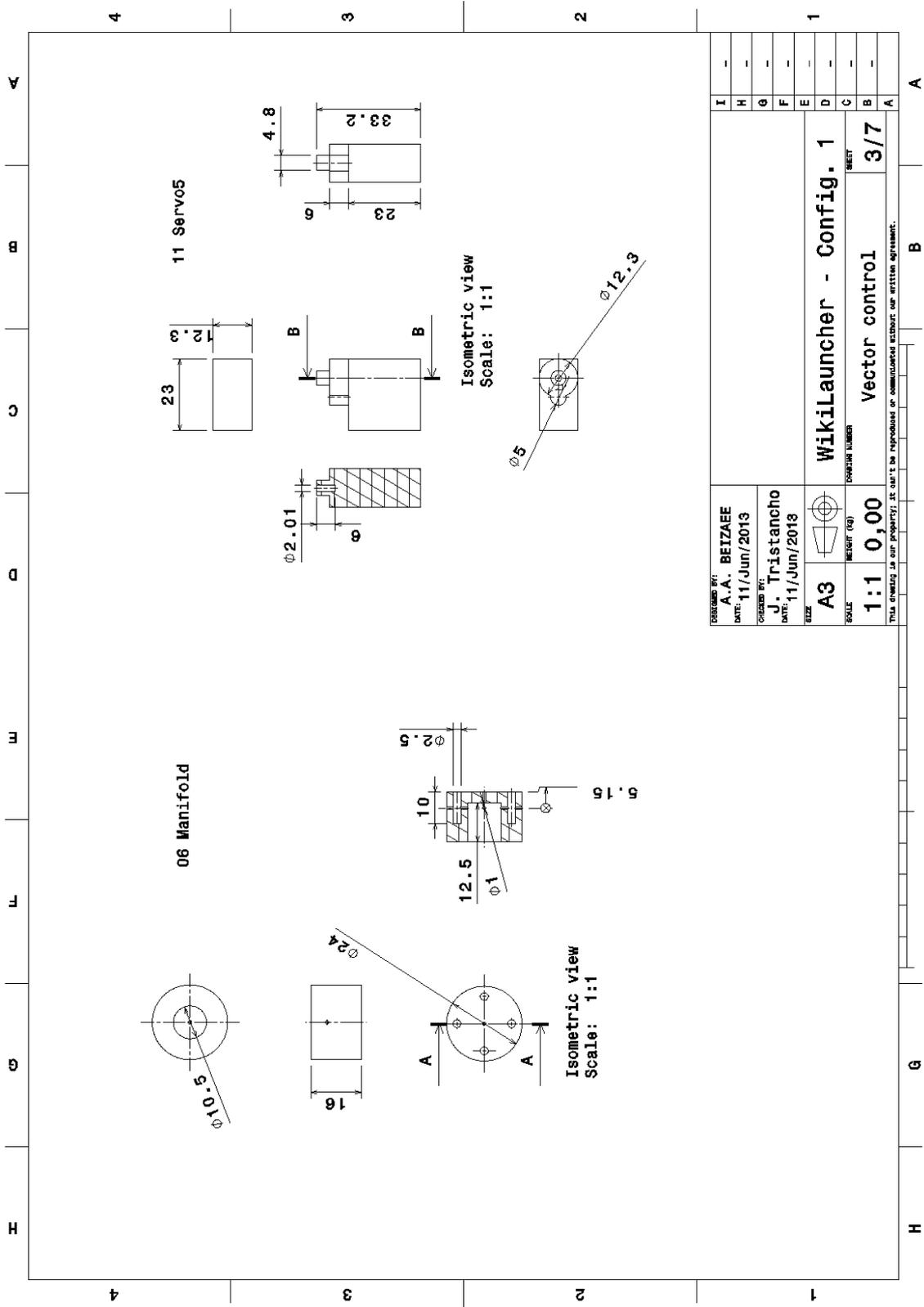
DRAWINGS SUMMARY

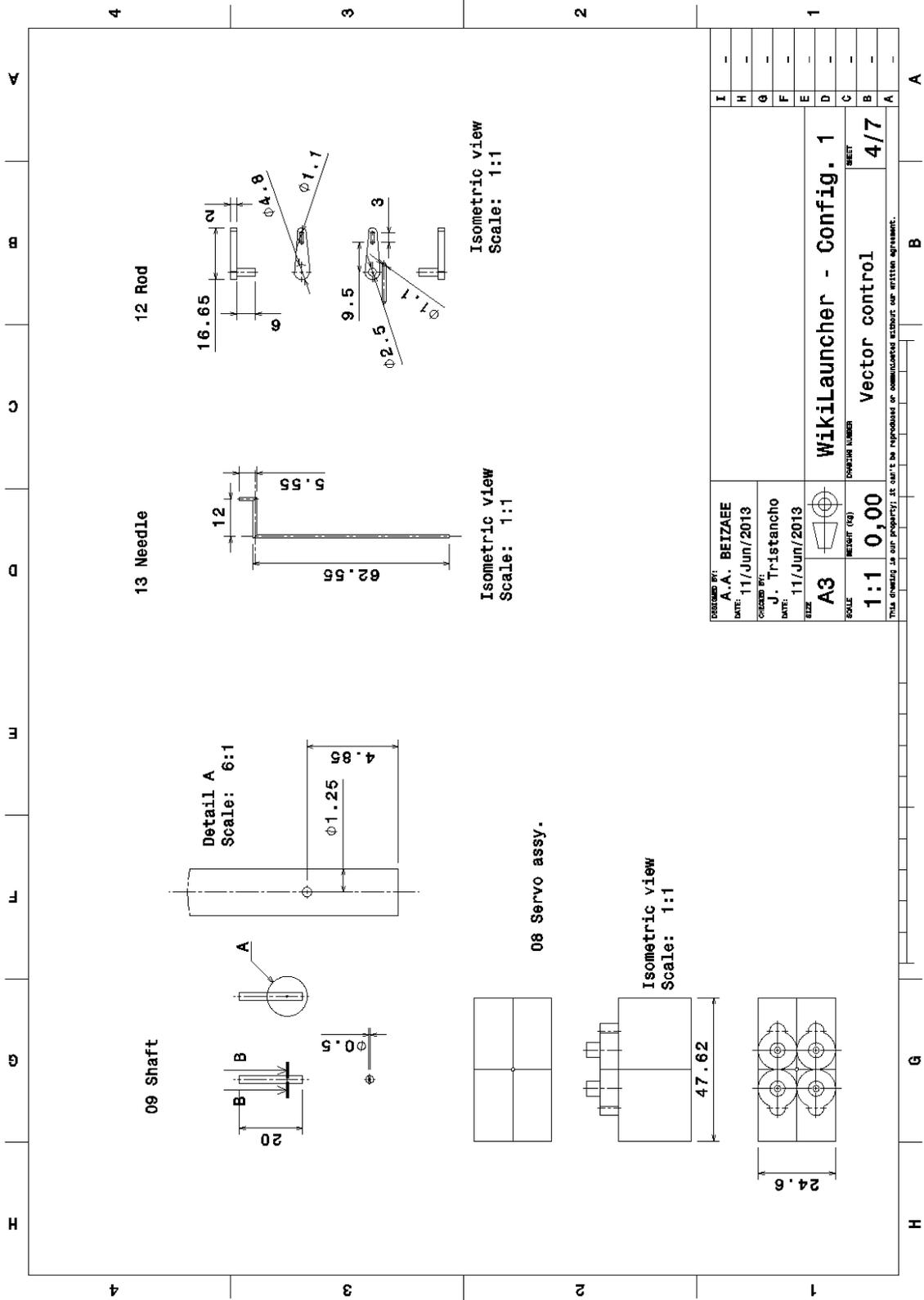
1x WikiLauncher configuration
1x Payload subsystem
7x Vector control subsystem
5x Propulsion subsystem

Annexes. WikiLauncher configurations summary

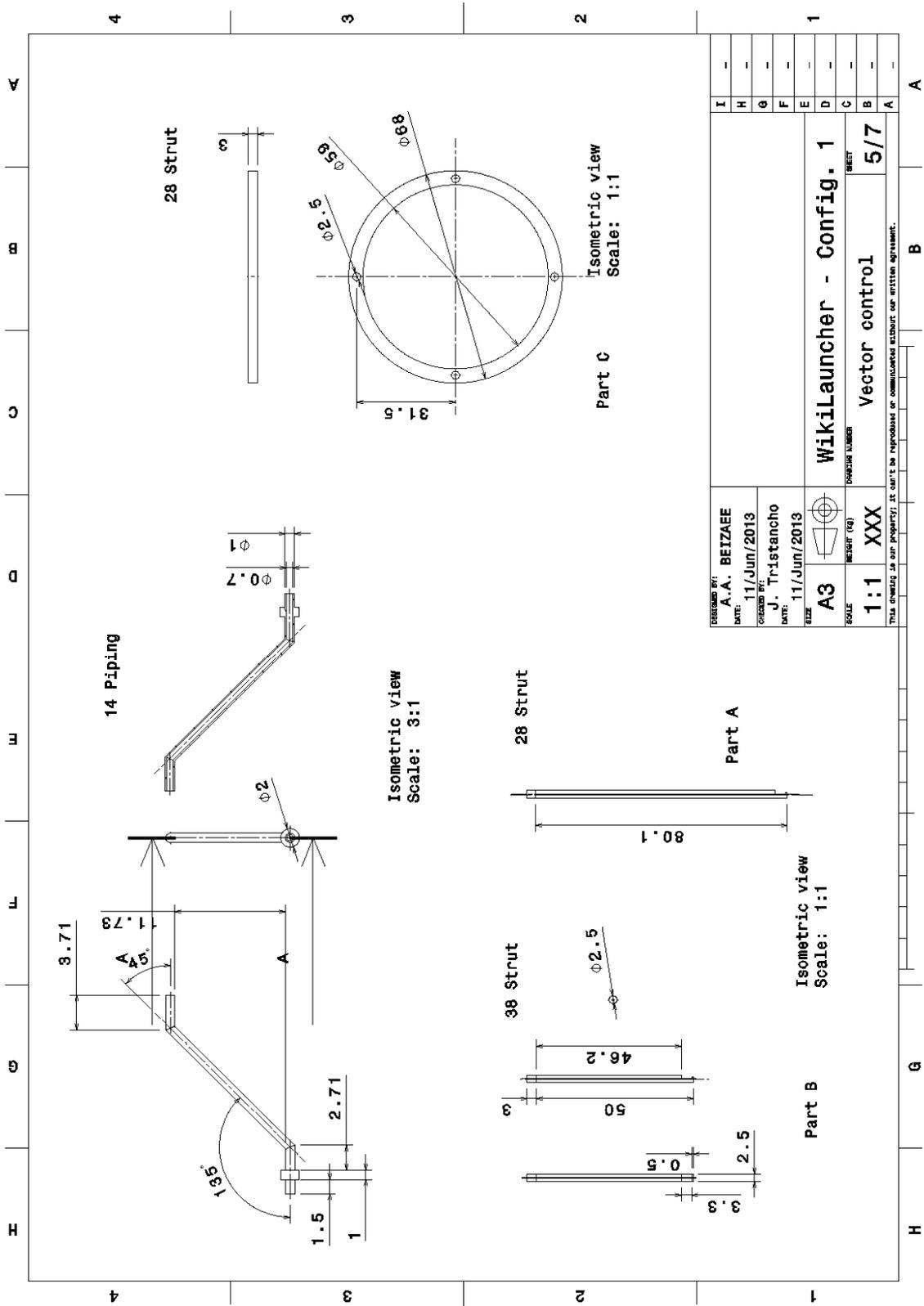


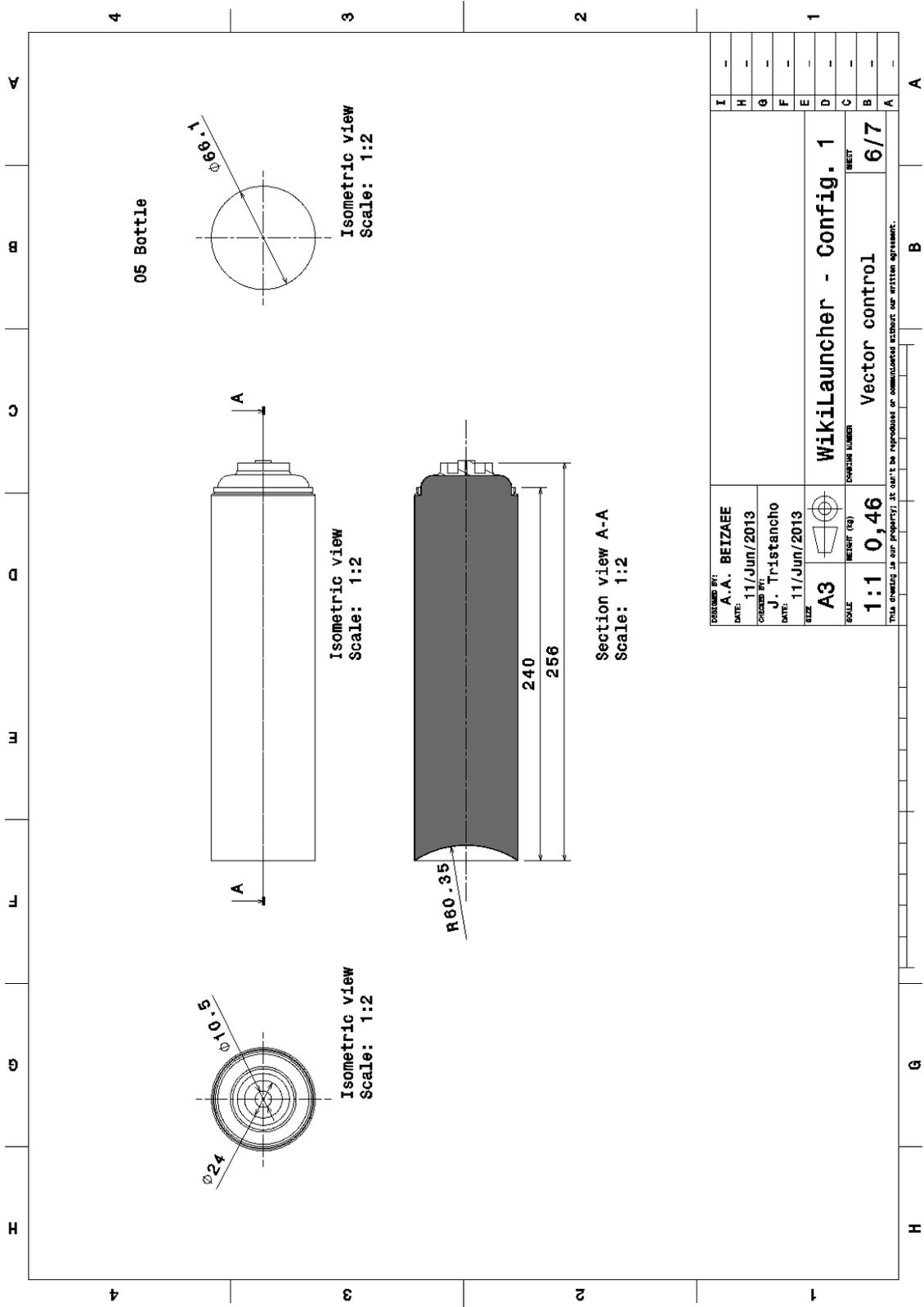


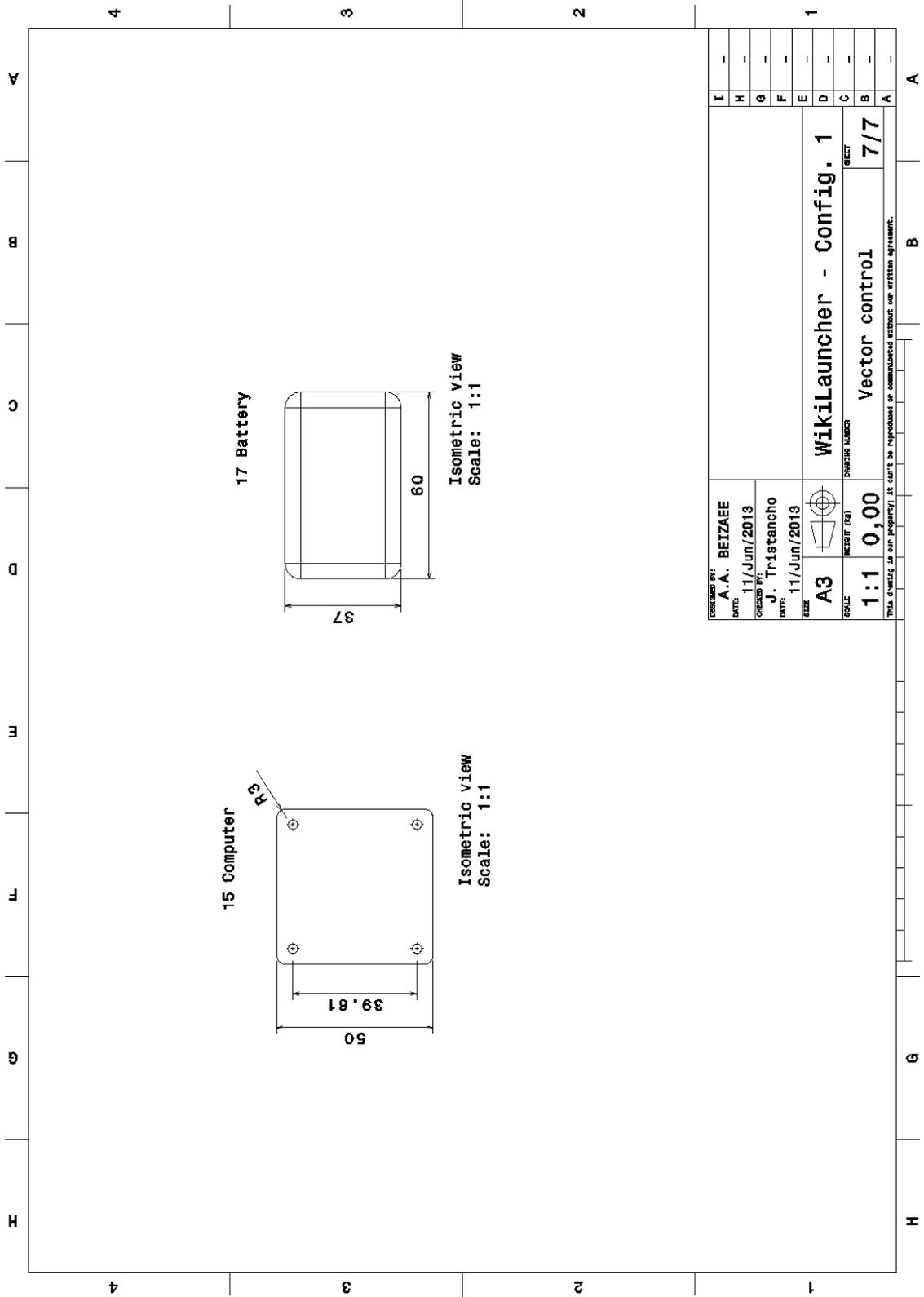




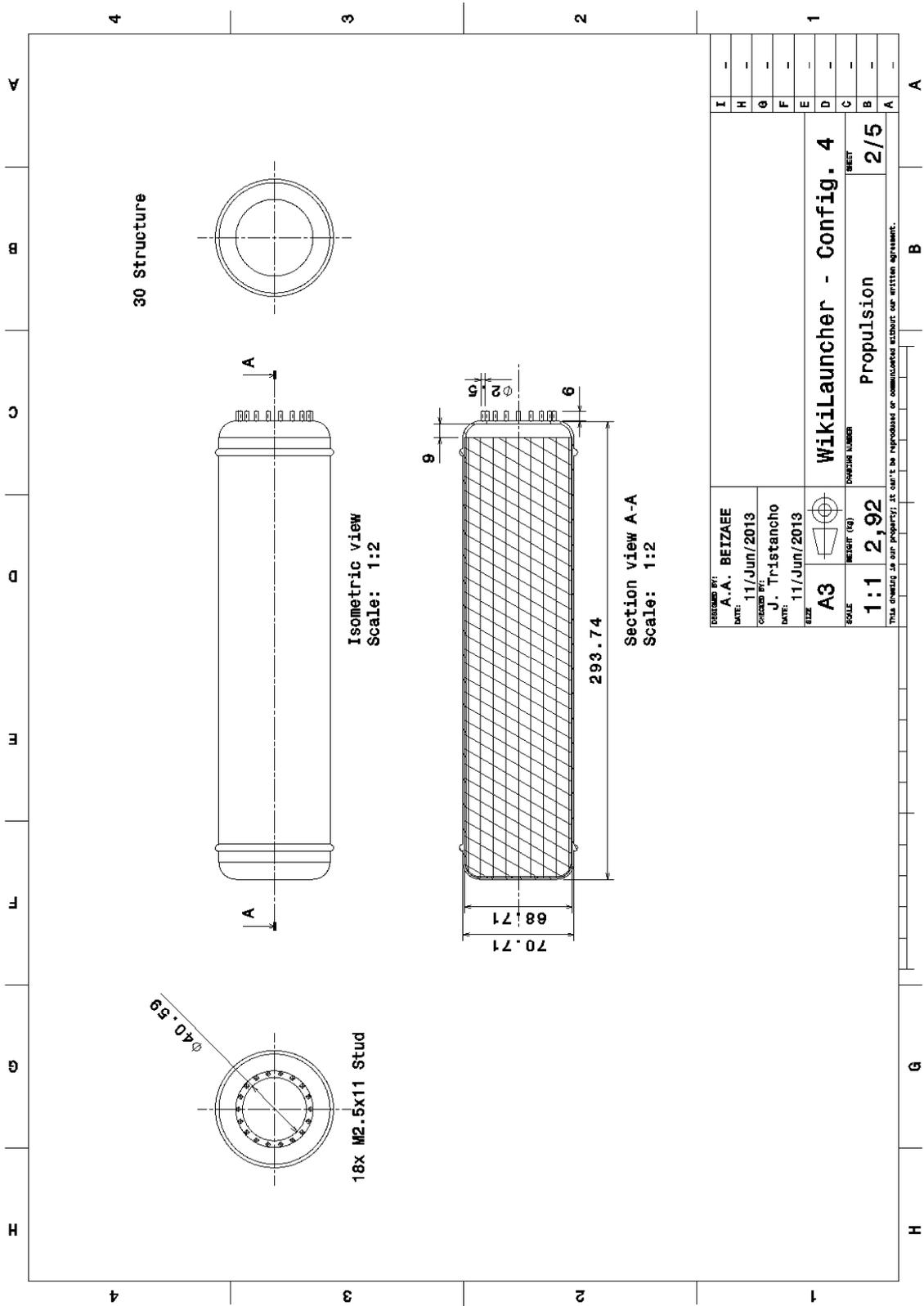
DESIGNED BY: A.A. BEIZAE	DATE: 11/Jun/2013	ORDERED BY: J. Tristanchio	DATE: 11/Jun/2013	SIZE: A3	SCALE: 1:1	WEIGHT (KG): 0,00	DRAWING NUMBER: WikiLauncher - Config. 1	SHEET: 4/7
THIS DRAWING IS OUR PROPERTY; IT CAN'T BE REPRODUCED OR COMMUNICATED WITHOUT OUR WRITTEN AGREEMENT.								



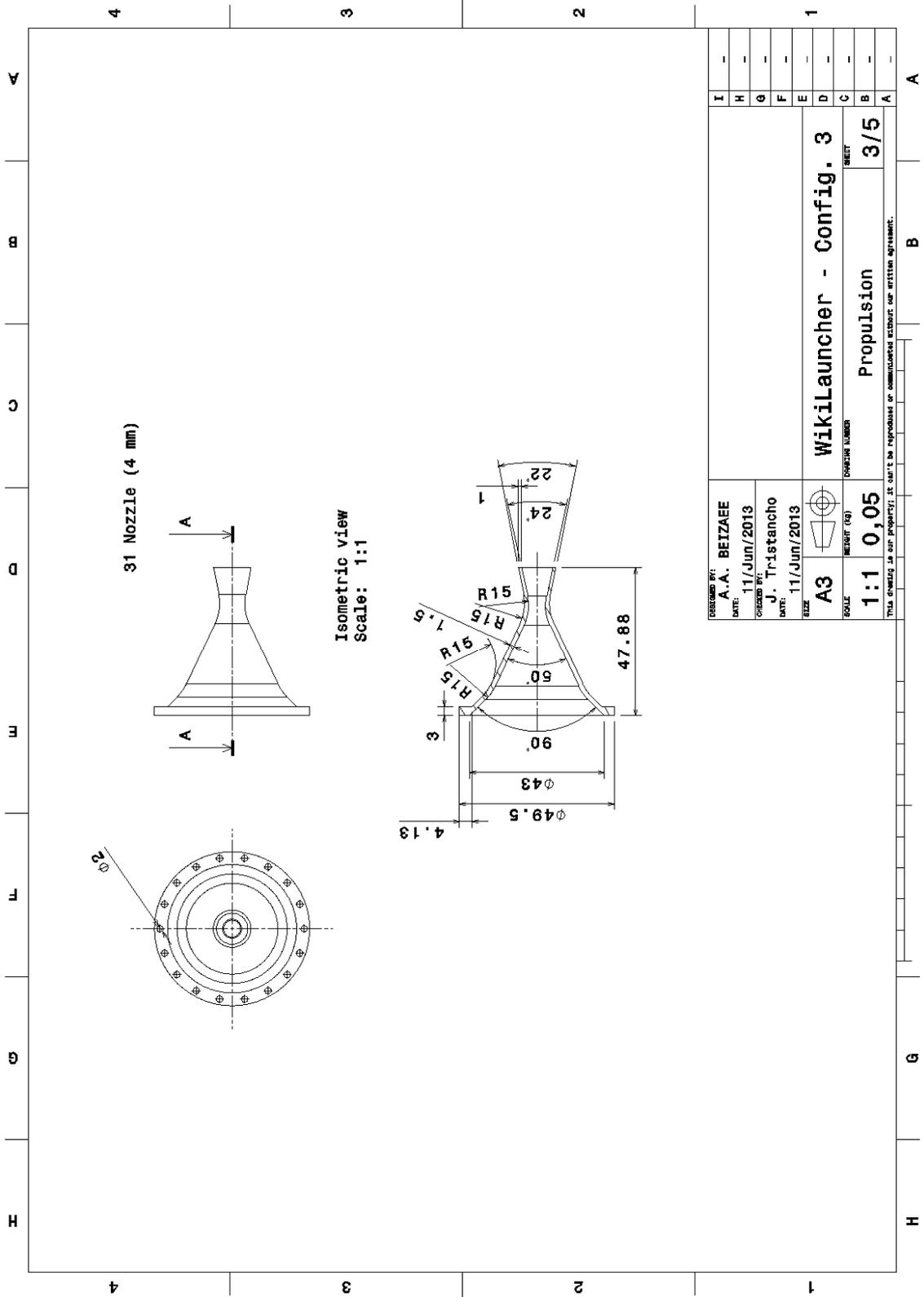




DESIGNED BY: A.A. BEIZAE	DATE: 11/Jun/2013	ORDERED BY: J. Tristanchio	DATE: 11/Jun/2013	SIZE: A3	SCALE: 1:1	WEIGHT (KG): 0,00	DRAWING NUMBER: WikiLauncher - Config. 1	SHEET: 7/7
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