Satellite Swim Lane

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(Received March 1st, 2023)

To avoid our Payenkeu CubeSat becoming a potential danger for the other satellites revolving around our planet, we are planning a pool simulation to test the ignition of the ionic engine and the sail. To do this, we will immerse our CubeSat prototype in a swimming pool to make the final adjustments.
This crucial, low-cost test phase seems to us to be a vital step in the viability of our satellite. This step will prepare us to minimize the legal risks in case of loss of control in space.

Key Words: Payenkeu, Weightlessness simulation, Sail craft dynamics, Maneuvering, Legal risk issues

Abbreviation

LEO : Low Earth Orbit

Nomenclature

f	:	frequency (Hz)
L	:	characteristic linear dimension (m)
rpm	:	rotation per minute
Re	:	number of Reynolds
V	:	velocity ($m.s^{-1}$)
x,y,z	:	axis
α	:	attenuation ($dB.m^{-1}$)
σ	:	conductivity ($mhos.m^{-1}$)
ρ	:	density of the fluid ($kg.m^{-3}$)
μ	:	dynamic viscosity of the fluid (Pa.s)

1. Introduction

On November 4, 2022, France and Spain partially closed their airspace, following the uncontrolled fall of the central stage of a Chinese rocket [1]. The rocket hit the Earth in the middle of the Pacific Ocean. Such events are rare for the moment, but the risk inevitably increases with the development of space flights.

If space was restricted to the great industrial powers such as the United States or the USSR at the beginning of the space conquest, the number of space agencies has increased since the development of micro-satellites. While the launcher technology remains under the control of the great powers, satellites have become affordable for many actors: small nations, "third world" countries, universities, and even small companies... As for CubeSats, limited to low earth orbits (LEO) until recently, the development of solar sail propulsion opens the door to the solar system, and even to the Universe. New questions emerge in terms of responsibility: the trajectory of any new satellite must respect the space environment already in place.

This study is part of a race organized by the International Astronautical Federation, whose rules, set in 1991, are inspired by the novel The Wind of the Sun (Arthur C. Clarke, 1972). The rules of this race are fixed by the International Astronautical Federation in 1991 with a starting line at 50.000 kms sphere and the end with a picture of the center of the far side of the Moon.

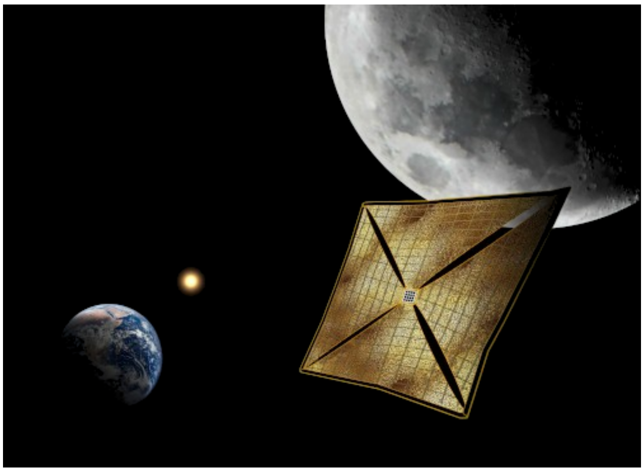

Figure 1

During its flight, our Payenkeu CubeSat will navigate only with its sail. The deployment of its sails will be one of the most delicate phases. Before this, we intend to use ionic engines which will first stabilize the satellite, and then give it sufficient rotational speed to deploy its sails. During this sensitive maneuver, a loss of control during this maneuver could have serious consequences.

2. Description

Our final CubeSat is divided in 2 parts: Propulsion / thruster and the sail craft. The propulsion will be done with ionic

engines and will be replaced by propellers for the prototype, as well as the sail will be emulated with a fishing net.
The dimensions of the Payenkeu CubeSat are: 200mm x 200mm x 300mm. The prototype is done with 3D printers.

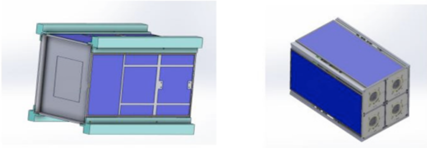

Figure 2

3. Organization of the steps of the flight.

We have to find a partner to embed our CubeSat in a rocket. This rocket will eject our CubeSat on an orbit with is detailed in §4.1. This is the point where our system will switch on.
First of all, we will power on our ionic engines to stabilize the trajectory to get out of the LEO.
When the trajectory is stabilized, we can open the sail covers and we make the satellite rotate on himself, let him conserve a clean trajectory. In this phase, we need to move the ionic engines to impulse a rotative movement. Now we can split the thruster from the sail craft.
This step is crucial and is the aim of this work.
Now, the sail craft can deploy its sail and at the same time, the thruster records the deployment, send the movie to the sail craft (with a Wi-Fi link). You can notice that only the sail craft is communicating with the Earth.
The sail craft can fly alone to the Moon, with its own system onboard in charge to handle the trajectory, the position in space and optimization of the sun exposure.

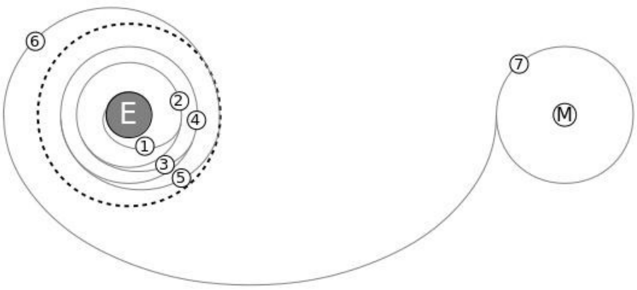

Figure 3

The upside picture describes the different steps of the Payenkeu flight.

1. The satellite is in the rocket and leaves the Earth to reach the launch orbit
2. One time the rocket is on the right orbit (predetermined), the system of ejection is activated.
3. The communication with the Earth is effective. Now the stabilized satellite has to elevate itself (from low orbit).
4. When the satellite is positioned at 50.000 kms, the thruster and the sail craft will separate. At this time, the sails will be deployed.
5. The sail craft can now flight with its sails, from the starting line (fixed at 50.000 kms)
6. Using a spiral trajectory around the Earth, the sail will flight to the Moon. [This step is not printed on the picture].
7. When the sail craft turn around the Moon, the aim of the challenge is to take a picture of the hidden face of the Moon… and send it to the Earth!

4. Technical risks & Injuries: consequences

The major risks are described in the “CubeSat Design Specification” [2]. There are some solutions proposed by scientists but here, our approach is new, due to a sail usage.

The CubeSat Technology is well known for fixed orbits, close from their ejection. At this time, the collision risk is limited; almost null.
Indeed, all the flying items on one circle orbit flight at the same speed.
They are all motionless in a coordinate system for each satellite on the same orbit. As they seem motionless between each other, they cannot collide.
Unlike usual satellites equipped with engines dedicated to maintained the altitude, our Payenkeu CubeSat is a sail craft, remote controlled from Earth. You notice that the engines are used until less than 50.000 kms before they are trashed.
As the sail craft, Payenkeu will fly through all the orbits from the first LEO to 400.000 kms which is the Earth-to-Moon distance.
Due to the rotations of the CubeSat and the Earth, there will be some periods where the communications will be interrupted.
Using a photonic propulsion, the sail craft will accelerate very slowly, and the sail orientation will be done very slowly. We plan the flight will be done in more than one year, with slow responsiveness.

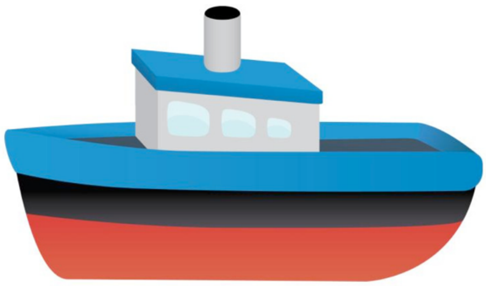

Figure 4

The Payenkeu CubeSat is designed without detection sensors (to detect other dead bodies). Using a sail to navigate, the craft is also not designed to change its trajectory quickly enough to avoid another known satellite.

In this case, turning around orbits occupied by others items, there is a risk of possible collision.

Considering that all active satellites are known we intend to incorporate these elements in the Payenkeu flight (main board computer). In one side, the power of computing is incredible,

in the other side, the mechanical is not really responsive, reactive. To avoid collision, the flight will be split in multiples arcs (of a spiral), computed without known active satellites. We don't want to send in space a "bato fou" [3] [mad boat]! We don't want to open a juridic case with other companies / countries!
The financial risk is so important to dispense the realization of tests on Earth before the launching. Don't forget that the risks will carry on more than one year!

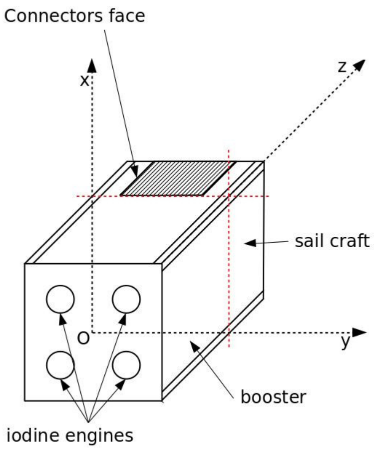

Figure 5

In this figure, we basically represent the Payenkeu CubeSat to better understand how it will work.

4.1. Partner choice

More than this, the ejection orbit involves some designs for our CubeSat. The design of our CubeSat is mostly dependent of the future altitude of ejection.

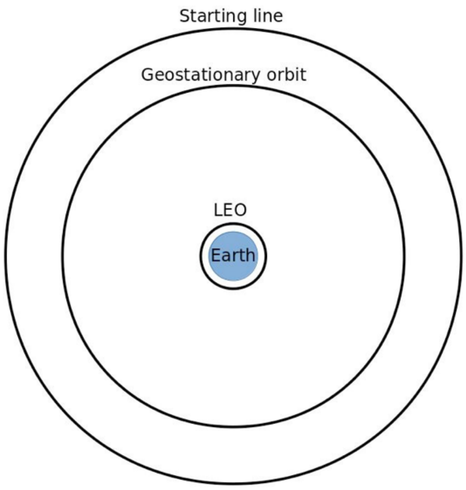

Figure 6

Here, we will study 3 cases: low orbits (LEO), geostationary orbit and orbit around 50.000 km from Earth.
For all of these cases, the first aim of our satellite, is to go to the starting line of the race (50.000 kms).

- Using a light rocket used by a new space agency, we can benefit of a low-cost launch. The Payenkeu CubeSat is used as a test payload. With the risk indeed by the kind of launching. The other problem will be to risk involved by the flight in a dense space. We can easily say that there will be more risk of collision.
- Attached to *another* geostationary satellite for the launch, we will handle the unlink. At this time, the distance to join the 50.000 kms from Earth involve less risks than the first case. This kind of launching is possible with some agencies. But since the constellation comings, the program for geostationary satellite becomes obsolescent. By this way, the cost increases.
- Using a heavy rocket, we can pretend to be ejected around 50.000 km from Earth. In this case, we avoid to travel through all the satellite around the Earth. It seems to be the better solution…. If the cost is free! (Which is not the case)

In this case, it's better to evaluate the launching cost, included with the insurance policy cost. The partner choice will be done with these criteria.

4.2. Stabilization of the package (thruster & sail craft)

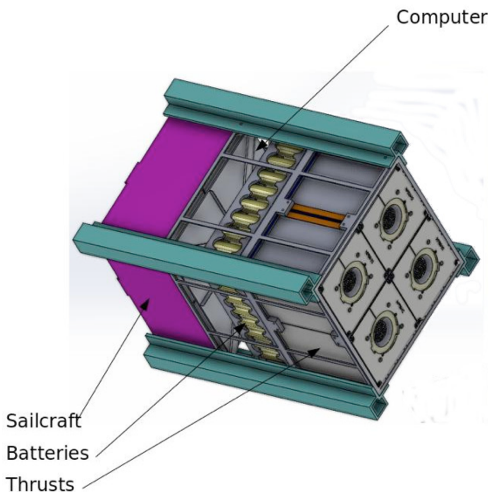

Figure 7

Just ejected from the rocket, the package will inherit unpredictable and randomized pulses. At this moment, the CubeSat is autonomous. It has to successfully handle the different movements to stabilize the flight.
This phase is very sensible unless the rest of the mission is compromised.
The 2 parts are working as a one package. The sail is still inside the box.
For the half of an hour, we have to do nothing. It's the rule for each ejected satellite.
After this timer, our package gets out the roof and deploy the antennas and the measurement tools.
A quarter of an hour later, it can send its state (all right, we hope!) to the Earth station.
As the communications are handled by the sail craft, our

satellite can receive orders.
The first one will be to start the thruster sequence to stabilize the package.
In our configuration, the mainboard inside the sail craft handles the flight and transmit to the booster board which pilot the 4 ionic engines. For this, the communication will be assumed with a Wi-Fi link.
The aim of this phase is to eliminate the spin and therefor align itself on the trajectory given by the launcher.
To do this, the 4 thrusters are parallels to the z axis and oriented on z-. Using a pair of thrusters, we can rotate the package on x or y axis. The thruster has a motion sensor which return the angular and linear accelerations. This kind of thruster are handled by an embed board from which we can drive it. Our “thruster” package includes a board which pilot the 4 motors. A specialized battery (12V / 20 Ah, more information in 4.7) is also included to make this system autonomous.
At the end of this phase, the package will have a zero rotation for the x and y axis. The z axis is aligned to the trajectory. It may be a z rotation.

4.3. Flight in the LEO / Flight to exit the LEO

The ground station drives the flight to the Payenkeu CubeSat. Communications are also a strategic aspect of this project.
Even more, the communications are relayed from the main board (in the sail craft) to the booster board with sail covers a Wi-Fi communication “in space”.
Each relay of the system communication can generate some errors, some loss…
This step is a crucial one, according to the altitude, the sail can be used… as a sail or as a parachute! This last case is a very dangerous one, because the CubeSat can go back to Earth.
As we said, this zone is very dense, the craft have to move quickly (to avoid obstacles).
The sail craft needs to be thrusted to a higher orbit before we can deploy the sail. One advantage of the thruster is that its reactivity is much better than that of the sail. As a sailboat, which uses its own engine to get out the port and uses its sail when it is out.

4.4. Opening the sail covers, rotation of the package

The sail covers are solar panels. We will open them at 90° by releasing a spring. This operation involves a modification of the kinetic satellite movement. At the same time, to prepare the rotation of the satellite, we need to move the ionic engines. The gravity center is therefore modified.
The satellite has now a new spin. To drive it, we need to integrate this predictable modification to avoid a loss of control.

4.5. Separating & deploying the sail

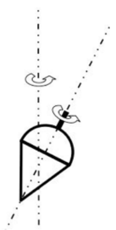

Figure 8

From Earth, we send the command to free the sails.
We imagine that the main problem of the sail covers are the frictions, and more spin (or an under-control spin). The risk in this case is the sail covers risks to hurt the sail.

4.6. End of life for the thruster

When the split is done, the thruster records the operation and sends it, with a Wi-Fi link, to the sail craft. It needs to have enough power to realize this. It should also have enough fuel to move by itself. It’s our decision, now, to decide what to do with this thruster, this junk.
The main risk is to jam the space with one more waste and later cruise another satellite.
If we chose to send it to destroy it by itself during the entrance into the atmosphere, it risks to cruise another waste or worse, an operational satellite.

4.7. Generic consideration about power

The thruster needs to own his battery (to work in a standalone situation); and there will be one battery for two sails and 2 solar panels. All of this battery needs to be supervised by a control system.
Those batteries are involved in the control of the flight.
Any problem on these strategic items, the CubeSat can have a bad orientation and the flight can be compromised.

4.8. Risk about collisions

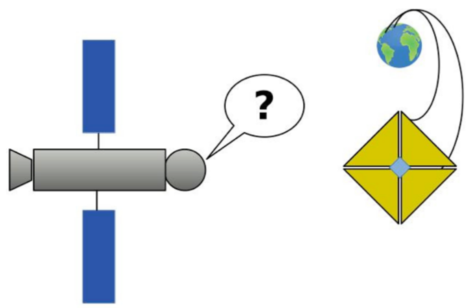

Figure 9

During all the flight, the eventuality of collision is a possibility. Considering that the craft will change a lot a time of its orbit, it is necessary to anticipate this.
Especially on low orbit, the number of known satellites is high. This period of the flight will generate a high risk.

5. Solutions

5.1. Partner choice

We focus the launching of our CubeSat on a low cost one. In this case, the insurance can be close to zero. The loss of our CubeSat is not dramatic.
As the launching cost depends from the ejection point, the highest it is, the more expensive it is.
For all these reasons, the best choice is based on a low-cost launching, low orbit.

5.2. Stabilization of the package (thruster & sail craft)

We make the choice to anticipate all this phase, in a swimming pool to reproduce inertial and slow movements, in a similar space environment.
The weight of final Payenkeu will be 9 kg and the volume will

be 12 L. Some parts of the prototype will be closed (waterproof) and some other open to the water. This configuration then behaves as something like weightlessness, in a swimming pool.

In the water, it is obvious that the ionic will not work. To have something the most similar of this item, we will use propellers with the same impulsive command system.

This equipment works with a delay and an impulse.

The usage of the ionic engine is limited by its total impulse (capacity of the tank).

This behavior will be simulated by a micro-controller (each propeller owns its controller which totalize the impulses).

This test will qualify the booster board dedicated to handling the flight and almost the balancing of the Payenkeu.

To simulate the flight in space, on a LEO orbit (200 km), the expected speed of the CubeSat is 7700 $m.s^{-1}$. In a pool, the mock-up needs the have the same Reynolds' number. This number depends from the fluid density, the object dimensions and its speed (in the fluid). As the dimension of the mock-up and the CubeSat are the same, we need to adjust the speed in water to obtain the same Reynolds' number as we the CubeSat is at the real orbit (200 kilometers).

$$\mathrm{Re} = \frac{\rho V L}{\mu}$$

Figure 10 : Definition of Reynolds number [5)]

In this case, the maximum speed should be 0.08 $m.s^{-1}$.

In the swimming pool, this speed from the departure to 0.08 $m.s^{-1}$ is equivalent to 3 minutes of the propellers acceleration (simulating the ionic engines). During this time, the mock-up will move 8 meters.

Considering the mock-up has the following dimensions, when it is deployed: 0.8m x 0.8m x 0.3m.

In a French public swimming pool, the classic swim lane dimensions are 25m x (more than 1.2m) x (almost) 2m; which are exactly what is needed to realize our move tests.

Parts of the mock-up will be waterproof, of course!

5.3. Flight in the LEO / Flight to exit the LEO

In the swimming pool, we will used a LoRa link [5)] at 868 MHz to communicate with the mock-up.

Attenuation of radio waves in water (and, in fact, in any conducting medium) increases both with increase in conductivity and increase in frequency. It can be calculated from the following formula:

$$\alpha = 0.0173\sqrt{f\sigma}$$ [6)]

Electromagnetic absorption by water

In a swimming pool, σ is between 2.5 and 3 mS/cm. As the used depth, the attenuation will be present. We can expect that the communication will be sufficient for our tests.

In a random starting position, we will test the mock-up which have to position itself to swim in the lane (TEST 1).

This sequence will reveal the efficiency and reactivity of the system.

5.4. Opening the sail covers, rotation of the package

For the same reasons explain in §5.2, the rotate speed will be less than 10 rpm.

Propellers & sail covers move exactly as the final CubeSat. Note that, for the prototype, the sail covers have no solar panels. This phase will evaluate the driving program of our Payenkeu satellite.

In the next reality, the rotation when we open the sail covers, have to be in front of the sun. In the swimming pool, the sun is replaced by the surface of water.

The sensors used will be optical. More precisely, we will use light sensors.

The mock-up should have to set its position to vertical and rotate in a uniform circular movement (TEST 2).

Figure 11

5.5. Separating & deploying the sail

In the swimming pool, we will study the behavior of each part during the split.

For the (TEST 3), the new beginning position is the pool bottom. The mock-up will rotate on itself to 10 rpm maximum with open sail covers. The sail craft part is ejected with a spring. This phase will evaluate: the separation, the split video, the deployment of our net and the communication system (Wi-Fi and LoRa). In this case (underwater), we know that the Wi-Fi attenuation is higher than in space.

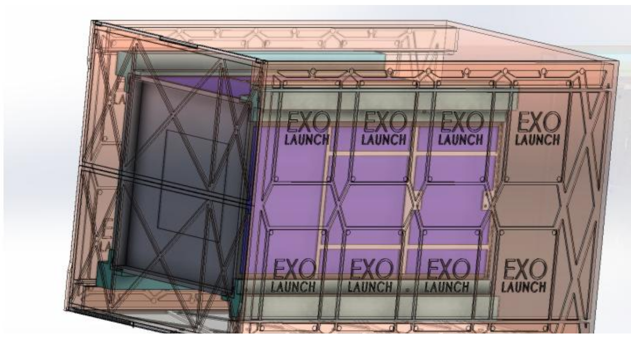

Figure 12

One way of this next study is to find the best velocity for this phase; and maybe find other solutions.

5.6. End of life for the thruster

This part of the flight cannot be simulated in the swimming pool. In this case, we will speak about generalities.

The end of life will depend from the rocket ejection (low orbit or high altitude).

It seems that the choice of the end of life will be one of this:

The first one, we can send the thruster to the Earth for an organic destruction (without communication) when it comes in the atmosphere. Due to its light density, we expect that it well be entirely destroyed. In this case it seems that the only risk is the unvoluntary interception of another satellite. To avoid this, it will be needed to calculate a clean window to realize this down operation. It can be done before the splitting, on Earth. If the ejection orbit is low, this case is the only one.

The second solution consists to put the thruster in the space junk fixed at 36 300 kilometers. This solution can only be used if the ejection orbit is close or higher than this altitude.

5.7. Generic consideration about power

For the mock-up, we choose to use a sea-battery (waterproof) based on lithium for the thruster. The mock-up will also be used to test the future energy board of the sail craft.

This board should be in charge to monitor the battery load, the panel production and the consumption.

This board is currently in development.

5.8. Risk about collisions

This risk is very difficult to anticipate because our sail craft has no sensors for detecting flying objects.

In this case, the CubeSat has to incorporate a flying controller.

In this controller, an optimized database with the flying objects that can interfere with the CubeSat trajectory is uploaded and upgraded depending of its position.

These positions are extracted from the international, open source, of known flying objects.

From the Earth, the board receives orders to handle the trajectory commands and compares to its internal database to generate the best flying curve (including the avoidance trajectory).

To evaluate this behavior, we will put some obstacles (buoys with ballast) in the swimming pool and indicate them to the pilot controller. Now we can check that our prototype will avoid them.

This step will validate the pilot with engines.

6. Conclusion

In this paper, we have declined the aim of our CubeSat; its trajectory and all the risky phases. We analyzed the risks and propose some solutions to realize them in a swimming pool to evaluate and adjust our mock-up.

We choose to create a simulator which is a stand-alone project, not too complex, to create a space environment simulation, incorporating some hazards.

One point of view, is that our construct approach is done by constraints (physical, legacy and financial).

Now we are ready to finalize our mock-up. As our tests have not yet been completed, we have listed the main points to implement for the prototype.

In a later step, a Payankeu-Alpha satellite will be launched from a rocket into LEO at approximately 200 kms with the main purpose: deploying the sail. We will compare the reality of a flight in space to the results of our "flight" in a swimming pool. The tests are expected to be done for the next year.

Acknowledgments

We would like to thank Jean-Claude Lan-King-Chak for his help to print the 3D items and all the persons which participate for the mock-up realization.

This project is sustained by the U3P association [7] mostly for its shared experience.

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