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# Design of a device to slow the motion and vertical descent of a water rocket inspired by tropical seeds from Costa Rica

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## Abstract

The project design is framed in the project: "C1461 Mobile Laboratory of Action and Thought in Biomimetic Arts" in which an interdisciplinary group of researchers and students from the Universidad de Costa Rica collaborated in multiple iterations to develop an innovative way to solve design challenges in aerospace engineering and, embed in rocketry, functions that emulate adaptations observed in nature. After taking Costa Rican South Pacific seeds as mentors through biomimicry thinking, the development of the main deliverable of the project, which consists of a design and proof of a parachute system based on the principle of flying seeds was fulfilled. Several experimental steps were developed: 1. the conceptual design, 2. material selection, 3. design optimization, 4. prototyping, 5. testing and evaluation in the laboratory, 6. testing and evaluation in the field, 7. final report and design, and 8. demonstration and divulgation of the results. In this scientific article, we elaborate on all these stages with special emphasis on the evaluation stage in the laboratory and the field test. It is important to highlight that the project is rooted in a highly vulnerable area of Costa Rica where the researchers intentionally evoke an inclusive call as an inspiration to potentiate people's involvement and curiosity in the scientific and technological development of our country.

**Keywords:** Biomimicry, flying seeds, *Cedrela odorata*, biodiversity, biodesign, aeronautics

### Acronyms/Abbreviations

GIA: Aerospace Engineering Group (Grupo de Ingeniería Aeroespacial)
UCR: University of Costa Rica (Universidad de Costa Rica)
LAB: Mobile Laboratory of Action and Thought in Biomimetic Arts
CNC: Computer Numerical Control
PLA: Polylactic Acid
FDM: Fused Deposition Modelling
MVP: Minimum Viable Product
CAM: Computer Aided Manufacturing
EIM: Mechanical Engineering School (Escuela de Ingeniería Mecánica)

## 1. Introduction

Universidad de Costa Rica promotes the generation of interdisciplinary research projects, in this line, support was given to the project: C1461 "LAB-Mobile Laboratory of Action and Thought in Biomimetic Arts" inscribed in the UCR South Campus, winner of the Seed Fund 2021-2022 awarded by the Vice-Rectory of Research of the UCR.


Fig 1. *Cedrela odorata*'s open fruit.

People from different areas of knowledge participated in this project: biology, musical arts, design, and the GIA with people mainly from engineering participating. The aim of this project is to develop prototypes with which a response or solution based on the biomimetic tool can be given to any need. Since one of the strengths of the GIA is working with water rockets, we proposed the possibility of rethinking the design of a device to slow the motion and vertical descent of a water rocket inspired by tropical seeds from Costa Rica. In [1], you can see the entire conceptual and theoretical development of the biomimetic tool application to the device that we propose.

The design process included several stages and group discussions until the final deliverable was reached, which will be the one we will work on within this document.

The design consists of several parts to consider: the body that covers the bottle, parachute, and opening system.

In this work, the analysis on the biological adaptation and descent of the flying seed and the principal considerations for its selection, will be presented. Subsequently, a section will be developed on the materiality with which the prototype was proposed, being this a fundamental aspect in the application of the biomimetic tool since environmentally friendly materials were crucial. Additionally, a section will be developed corresponding to the prototyping and testing process. It is also of great interest to show the experimental results obtained from the studies carried out mainly in the boundary layer wind tunnel and from the field tests carried out with the final prototype. At the end of this paper, the results obtained and recommendations to continue the work and get future robust results will be presented.

## 2. Material and methods

In this section of the document, we will present how the process of design, prototype, and test of field test were realised.

### *2.1 Mentor Selection*

Biomimicry design method was used in order to create design ideas for a new parachute device. The step by step of this methodology and the theoretical aspects are described in [1]. However, the main results obtained by applying this method are mentioned hereafter.

In biomimicry thinking a mentor is a natural element that brings us inspiration. It could be an organism or a group of organisms and its adaptations and functionality guide our design approaches and lead us in how to resolve a certain design challenge. In this investigation flying seeds of Costa Rica were chosen as mentors. We considered ten flying seeds and studied their aerodynamic and deploy mechanisms in order to identify possible solutions. Field trip collections and observations were also necessary to learn more about those mechanisms and the ecosystem they belong to. We chose *Cedrela odorata* as the main mentor due to the shape similarity of its fruit with the fuselage of a rocket, its characteristics of flight and dispersion and its abundance in the area of interest. A picture of the fruit is shown in Fig. 1. The flying winged seeds of 2,5 cm to 5 cm of length, develop in small capsules which open through five valves with a central axis when their development and weather conditions are optimal, as shown in Fig.1.

### *2.2 Prototype Models, Design and Building*

The experimental process can be described as is shown in Fig. 2.

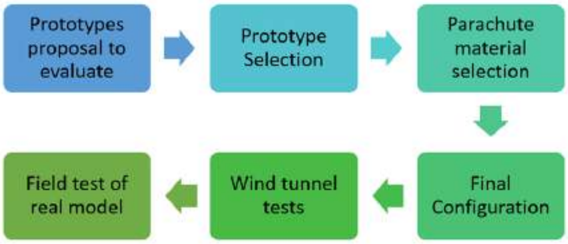

Fig. 2. Experimental process

We tried first to manufacture the prototype´s parachute support (wings) with recyclable or biodegradable materials. One of our first options was to try “balsa” wood, which is highly used for crafting. This material is highly rigid, and we could only find long sticks which made it difficult to give as a result our preferred curved shape as the one observed in Fig. 1. Bamboo was the second material tested. We tried manufacturing, with this material, the parachute's wings-fruit valves taking advantage of its cylindrical shape. A bamboo cane was cut into four pieces, each one meant to be the base or in other words, the pseudo valve with the structural integrity of the parachute´s wings. We marked the shape of each piece and then tried to cut the wing shape it was marked on. However, the bamboo pieces burst when pressured to cut. After trying to manually manufacture the wings with no success, we decided to move into a more controllable manufacturing process, 3D printing. This technique allows to design and print any shape with a biodegradable filament, making it faster and easier.

To build the first prototypes, it was necessary to base ourselves on 3 central axes to carry out the design process: 1. biomimetic component, 2. manufacturing process, 3. sustainability of materials. Based on a conventional water rocket construction model, we took as a proof of concept the use of a recycled bottle as a rocket pressurisation chamber and from there we built an enveloping structure to be able to couple each part of our systems.

Fig. 3 shows various design elements of the final proposal. To achieve this design, an iterative process was passed through 3 different prototypes, all of them were made focusing the manufacturing process on digital manufacturing using CNC machinery, more specifically, all its forms were designed to be made with FDM printing on material PLA, which is a polymer of the most used in 3D printing.

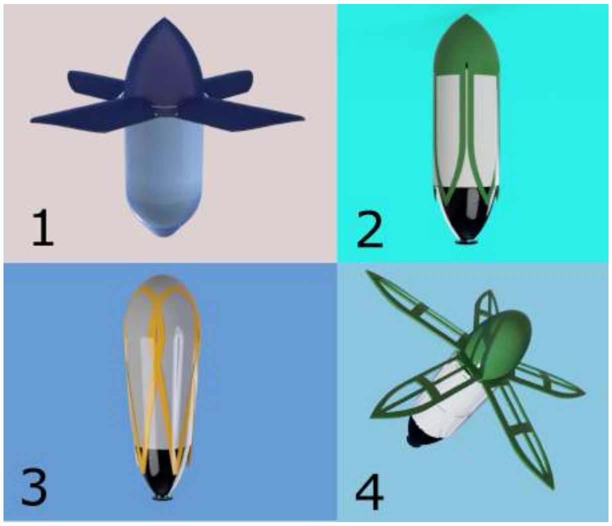

Fig. 3. Detail of the evolution of de design of the prototype

In Fig. 3 we can see the differences between each prototype until we reach the PMV that we selected as the model for manufacturing. These designs consist of four parts assembled together. The thin elongated structures mimic the valves of the fruit and the seed wings and are extremely important because the parachute will be attached to this structure, being the most critical in terms of mechanical stress. Using 3D printing as a manufacturing process, we obtain a material that is not isotropic, so it can behave in very different ways in the presence of localised mechanical stresses, this is because the adherence between 3D printing layers is not completely uniform and it depends on the state of calibration of the machine and the flow of material. Therefore, a stress analysis can provide us with an approximation of how the material will behave, however, it is not reliable enough.

In Fig. 4 we show the mechanism that was proposed for opening the valves-wings of the prototype.

These thin elongated structures represent a challenge when subjected to impact during landing by the fuselage, in addition to the fact that they have to withstand the drag force of the parachute, which has to be distributed in each of the wings. Fig. 5 shows the results of the static analysis, we proceeded to use CAM software to analyse the theoretical deformation that a wing would suffer due to the action of the wind current during its descent with a parachute. We simulate this with a load of 20 N distributed along the wing.

This simulation allowed us to have an approximate behaviour of the prototype. These results may differ from the practical tests, since 3D printing has a lower effective performance due to the adhesion between its layers such as explained before.

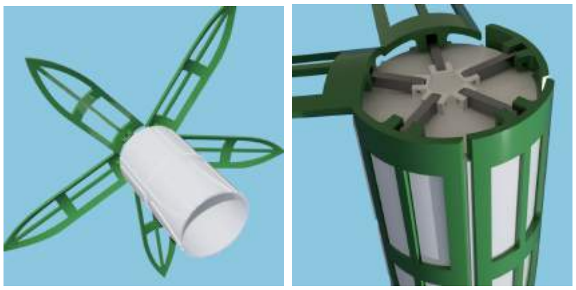

Fig. 4. Detail of the opening mechanism for the prototype

Table 1. Properties of 3D printed PLA.

| Properties | Value |
|---|---|
| Density | 1.14x10-6 kg/mm2 |
| Young's Modulus | 2.1GPa |
| Poisson's Ratio | 0.36 |
| Yield Strength | 26.94 MPa |
| Ultimate Tensile Strength | 28.1 MPa |

For a displacement of 13 millimetres it was necessary to reinforce the 3D printing material, so each of the wings was coated with polyester resin, the same widely used in manufacturing with composite fibres. This resin gives the material greater impact and deformation tolerance, making it more resistant to flight testing.

Once the parachute support prototype module came to a final design, a parachute itself was needed. Parachutes are one of the crucial elements in a flying mechanism. Most of them are made of fabric or polymers. However, our main goal was to adjust our design thinking to biomimicry-based design. In this case, we started by modelling the prototype parachute in plastic bags, which helped to corroborate and experiment with the parachute dimensions calculated before. Our main focus was to manage a design that sustained the prototype's integrity while landing. This also helped to better understand what strength, flexibility, and thickness our final parachute material needed to have. After experimenting with plastic materials, two biomaterials were explored, an agar-gelatin bioplastic and a cellulose biotextile.

There is currently a great deal of research in the fabrication of materiales called "bioplastics" which have similar properties as polymers made from oil but its degradation is easier and faster under natural conditions. In [2] we found some recipes to create these materials and helped with our purpose. We applied this information with different variations in order to explore alternatives for the material of the parachute. First, an agar-gelatine based bioplastic was built. The materials used to create the bioplastic were agar-agar, gelatin, glycerin and water.

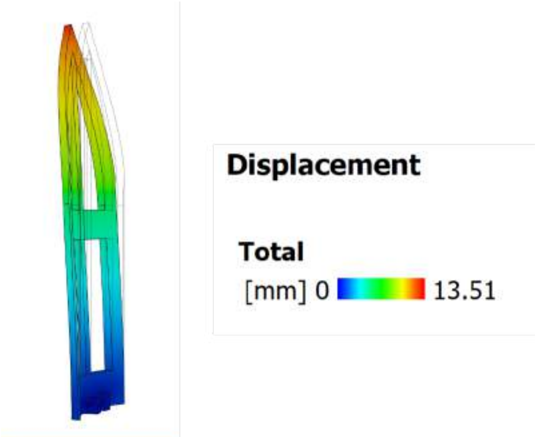

Fig. 5. Results of total displacement for each wing according to the simulation

Table 2. Total displacement resulted according to the simulation

| Total | 0 mm | 13.51 mm |
|---|---|---|
| X | -12.95 mm | 0.1975 mm |
| Y | - 3.797 mm | 0.06985 mm |
| Z | - 0.4346 mm | 0.4939 mm |

In parallel with the bioplastic development, a biotextile was tested. This material can be swed and dyed. It was manufactured by a costarican researcher, Sofia Ureña using sugar, tea, and SCOBY (Symbiotic Culture Of Bacteria and Yeast) (see Fig. 6). The results obtained from this processes are shown in further sections.

*2.3 Experimental Design and tests*

The first experimental phase was carried out in laboratory conditions for the selected prototype, both at scale and in real size. This experiment design included only the biotextile material since the bioplastic material still needed some improvements to be used as parachute material. The initial 3D printed parachute support tests were performed by a scale model, to find improvements in design with the minimum material waste possible.

Once the experiments were performed and disadvantages and advantages of the scale prototype could be seen, the real scale prototype could be redesigned and 3D printed. As for the parachute, it was set to use plastic and fabric before using the biotextile itself. This was thought to help waste the limited biotextile we had available and prove the diameter calculated in the next section was reliable to lower the prototype velocity.

Fig. 6. Biotextile manufactured by Sofia Ureña

This laboratory stage was designed to place both scale prototypes inside the EIM wind tunnel. This machine is a prisma with wooden edges and transparent polymer enclosures on both lateral and upper sides (see Fig. 7). The main technical specifications of this equipment are shown in Table 3 and Table 4. Based on the wind operation curve, 1000 RPM is the minimum velocity we could operate in. That led experiments to be performed at a theoretical speed of 10 m/s (These calculus would be shown in section 3. Theory and calculus).

Table 3. Wind tunnel motor specifications [3]

| | Value |
|---|---|
| Power | 29.8 kW (40 HP) |
| Frequency | 60 Hz |
| Amp | 92.6 / 42 A |
| RPM | 1770 |
| Service Factor | 1.15 |

Table 4. Performance specifications for the fan of the wind tunnel [3]

| | units | Value |
|---|---|---|
| Volumetric flow | $cfm$ | 47 520 |
| Operating SP | $in\,WC$ | 1200 |
| RPM | | 1423 |
| Tip speed | RPM | 12294 |
| Speed | $v$ | 4.26 m/s |
| Outlet area | sq.ft | 11.27 |
| Gas type | | Standard air |
| Total efficiency | % | 49.22 |

Fig. 7. EIM wind tunnel used for laboratory tests

Once the best prototype, its configuration and parachute material had been selected, a second experiment phase was performed. A field test was designed and carried out dropping the water rocket with the device´s wings open to determine its behaviour during landing. The launch was established from the fifth floor of a parking building at the university. Results of both experimental phases would be developed in the coming 4. Results section.

## 3. Theory and calculation

During the descent when the parachute is deployed, the forces acting on the rocket are its weight and the frictional air force known as drag, shown in the diagram of Fig. 8.

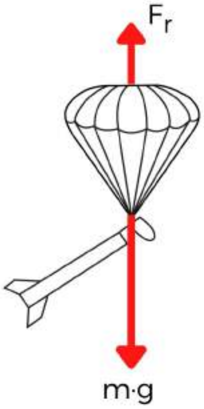

Fig. 8. Free-Body Diagram of the rocket during the descent. [4]

Applying Newton's second law the following equations that describe the movement of the model are obtained.

$$ma = - mg + kv^2 \quad (1)$$

Where m is the mass of the rocket, g is the acceleration of gravity, v is the velocity of the rocket in a specific descent time and k is a proportionality constant associated with the geometric properties of the parachute, as shown in equation (2).

$$k = \frac{\rho A C_d}{2} \quad (2)$$

Where ρ is the density of air at 25 °C, $A$ is the front area exposed to air, $C_d$ is the drag coefficient related to the shape of the parachute.

In table 5 approximate values of drag coefficients for several types of objects are shown. For this application, a flat semi-hemisphere type is selected since the shape produced in the prototype resembles.

Table 5. Approximate drag coefficients for several objects.[4]

| Object shape | $C_d$ |
|---|---|
| Rigid circular disk | 1.2 |
| Hemisphere | 0.8 |
| Flat semi-hemisphere | 0.75 |
| Sphere | 0.4 |
| Glider | 0.06 |

Reducing the rocket's rate of descent is necessary to ensure both the safety of people and wildlife on the perimeter and the integrity of the rocket's reusable components. According to [3] a descent speed that can be considered safe for a model rocket will be between 3.35 m/s and 4.26 m/s.

Once the parachute is open the speed will be gradually reduced until a constant velocity is reached. This happens when the weight of the rocket and the drag force are equal. Therefore, the acceleration is zero and the equation (1) becomes:

$$mg = kv^2 \quad (3)$$

Then, applying (2) and solve for A:

$$A = \frac{2mg}{\rho C_d v^2} \quad (4)$$

Solving equation (4) with the values of table 6, the minimum area for a specific speed, weight and shape of parachute is given.

Table 6. Data for parachute size calculations

| Variable | | Value |
|---|---|---|
| Mass | $m$ | 1 kg |
| Acceleration | $g$ | 9.78 m/s² |
| Density | $\rho$ | 1.223 kg/m³ |
| Drag coefficient | $C_d$ | 0.75 |
| Speed | $v$ | 4.26 m/s |
| Area | $A$ | 1.175 m² |

As mentioned before, the defining parameter for wind tunnel tests is the wind speed. From the EIM, the minimum possible $v$ speed is related to 1000 RPM.

Clearing this variable from the tunnel operation curve (5) we can determine the experiments theoretical operation velocity as it follows:

$$RPM = 96.88v + 19.16 \qquad (5)$$

Redistributing and clearing $v$ we obtain equation (6):

$$v = \frac{RPM-19.16}{96.88} \qquad (6)$$

Substituting RPM=1000, we obtain the theoretical velocity value:

$$v = \frac{1000-19.16}{96.88} = 10.12\, m/s$$

## 4. Results and analysis

The main results obtained so far in this project will be presented next.

### 4.1 Prototype tests in wind tunnel

As a reference, we tested a traditional parachute in the wind tunnel as shown in Fig. 9, in order to compare our proposal with the regular one.

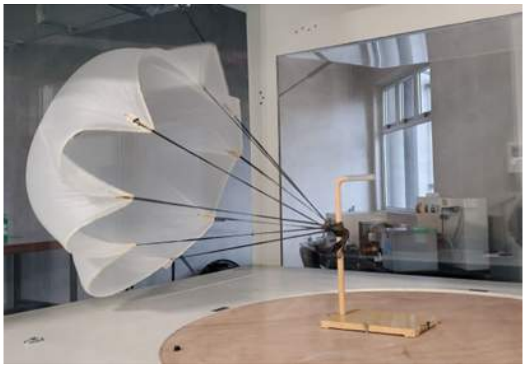

Fig. 9. Test of a traditional parachute in the wind tunnel

One of the most important results of this project is that we manage to produce our own bioplastic, from Agar, as explained above and shown in Fig. 11. Some important aspects when manufacturing bioplastic are the handling of the material during the drying stage, the necessity of keeping all surfaces and recipients disinfected and the importance of maintaining the proportions as indicated.

In Fig. 10 is shown why it is important to disinfect all equipment and areas in contact with bioplastic making. Once the bioplastic is contaminated it needs to be discarded.

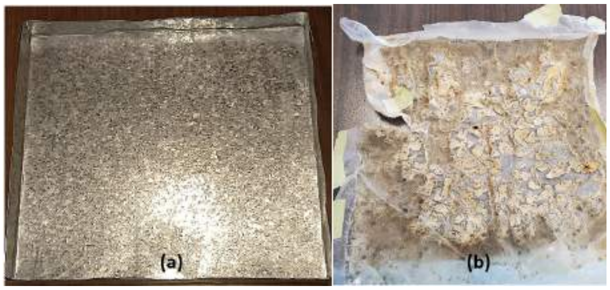

Fig. 10. (a) Functional bioplastic. (b) Contaminated bioplastic.

The thickness of the sheets can be modified by increasing the mixture amount or by smaller recipients. The specific thickness tested was not enough to allow mooring the bioplastic to the prototype´s wings. However, by adding a layer of wax paper, the material became more resistant and rigid. It was also possible to verify that this biodegradable plastic is an excellent option for the parachute since it reached the main functions to maintain buoyancy, has good durability, and is easy to handle as can be seen in Fig. 11 and Fig. 12. This material can be produced in the required size, and due to its easy handling it can be glued to generate larger pieces, as required. It is important to mention that this material was not tested in the tunnel since a big sheet has not been manufactured yet.

On the other hand, tests carried out with the biotextile showed that it is also a suitable material to be

Fig. 11. Agar-gelatine film produced

used. However, the manufacturing process of this material is more complicated and requires more time to obtain results of adequate quality and size as described previously. Contamination of the tea matrix when manufacturing is also something to consider. Besides that, it can generate little holes so it might be necessary to regenerate the material sporadically and repair it as a single piece of parachute. For example, the biotextile used for the real size model was repaired with other small pieces of biotextile (Fig. 13).

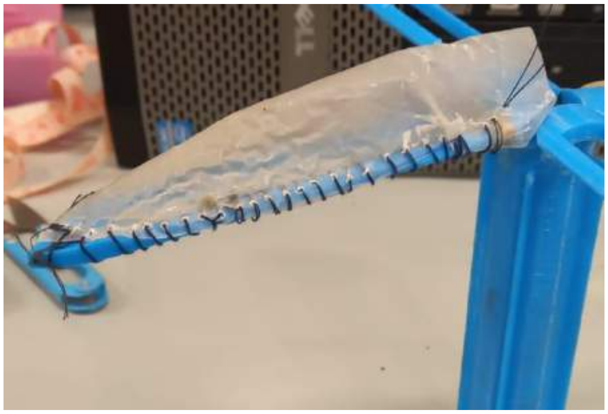

Fig. 12. Agar-gelatine-wax paper film stitched to scale opening mechanism model

Fig. 13. Patched biotextile parachute for real size model

In Fig. 14 it is shown the behaviour of this tea-based material during some tests in the wind tunnel. In this initial phase, the parachute had two sections: one little parachute for every wing and another parachute shape in between every wing. It was discovered that this parachute attachment was not ideal, since the drag force it generated needed to be higher.

The scale prototype experiments were key to better understand how the prototype develops while flying. Based on that, the prototype design was improved by adding some internal braces to every wind and by changing the parachute arrangement. These internal elements were added to provide more stability and prevent the wings from breaking when wind blows. The parachute took a circle shape and it was tied up to each wing´s end. The real size prototype with these modifications was placed on the wind tunnel to start experiments. As it shows in Fig. 16, a plastic bag was used as a parachute to first test how the new configuration performed.

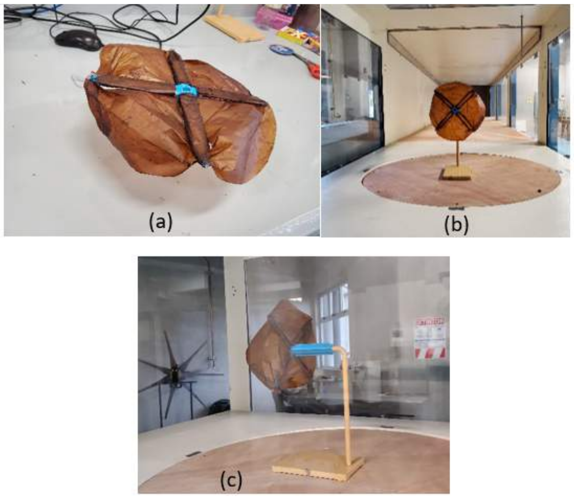

Fig. 14. (a)Biotextile parachute arrangement. (b)Biotextile scale prototype tested in the wind tunnel (top view). (c)Biotextile scale prototype tested in the wind tunnel (bottom view)

As shown in Fig. 15, with this configuration, the parachute behaves the same as traditional ones. After some tests, the real size blue prototype broke. For field tests, the prototype was re-printed with pink PLA and the biotextile parachute shown before in Fig. 14 was set up to fly outdoors. Field experiment results would be detailed next.

Fig. 15. Test with the real size prototype using a plastic parachute

### *4.2 Opening mechanism*

For the opening of the parachute we used a passive mechanism with activation due to the incidence of the wind. Initially, an electronic mechanism using servo motors and an altimeter was thought to deploy each of the wings during descent, but this idea was scrapped due to the weight of the telemetry and the complexity of the design.

The current design has five links pinned to each of the wings, thus constraining motion to one degree of rotational freedom along each pin axis as shown in Fig. 16. A rope attached to the fuselage and to the top of each wing maintains an opening stop on the mechanisms, in this way we can limit the "petals" to having an adjustment according to the size of the parachute.

Fig. 16. Opening mechanism with the wings, and parachute.

### *4.3 Prototype on site test*

To evaluate the performance of the parachute attached to the real size prototype, we decided to carry out "passive" tests of the device from a 5th-floor building. This means that no motors or mechanisms were used to open the prototype´s wing, they were just manually opened and free fall instead (Fig. 15(a)). These launches led to evaluating buoyancy and behaviour on constant changing wind flows.

Two field tests were carried out. On day one, we launched the prototype but its flight was not satisfactory. While landing, some wings crashed into the parking building and the wings broke when they impacted the floor´s concrete. On day two, the prototype was designed to land on the grass, to help minimize the arrival impact. This let the prototype fly twice, however, as shown in Fig. 17, the second test impact was so strong that the structure of the 3D printing system could not resist.

Fig. 17. (a) On site test of the prototype before landing. (b) Broken prototype after on site tests

## 5. Conclusions

Biomimicry has turned out to be a very interesting tool for developing projects related to aerospace engineering, mainly in countries like Costa Rica, which have great biodiversity and therefore have a large number of possible mentors who serve as inspiration for problem solving. or for design alternatives. At UCR, we believe that this line of research is a differentiator with respect to other research groups in aerospace engineering in our country and in the region.

There are alternative materials that can be used to follow biomimicry criteria, in our case we tested bioplastic and bio textiles, and both worked properly, according to what was expected. It is important to consider the production process of the material

The final design of the prototype depends directly on the available manufacturing process, due to the shape of its wings, 3D printing has significant disadvantages, the first of which is the resistance of the material, in each flight attempt of the prototype parts have been broken and making them again involves a high cost of time since the fuselage and wings have a duration of printing of approximately 39 hours, so in order to prototype more efficiently it is necessary to change the manufacturing process.

The experimentation must continue until a more robust prototype is obtained, and one that allows repetitive field tests. Another material must be selected for the manufacture of the prototype, however the parachute material may be any of the ones tested.

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