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Opportunities and challenges of digital fabrication applied to field work in biological projects

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Abstract: This article documents the use of digital fabrication technologies throughout the stages of developing a prototype designed for field use. The device was developed to collect data on the feeding patterns of hummingbirds in the Cerro de la Muerte area in the Talamanca mountain range of Costa Rica, considering the importance of these birds as pollinating agents. This design and development process, carried out in a Fabrication Laboratory, focuses on digital fabrication prototyping, with multiple iterations and modifications. Through the development stages of the device, the opportunities and challenges of applying digital fabrication to a project with biological impact are illustrated, along with insights on how to better approach future projects of this nature.
Keywords: *Digital fabrication, Fab labs, Field work, Hummingbirds, Prototyping.*

1. Introduction

In 2020, a collaboration between the Costa Rican biologist Emanuel Brenes and the Kä Träre Fabrication Laboratory was established, in order to develop a prototype that would make use of digital fabrication technologies to capture data relevant to the feeding patterns of hummingbirds in the Talamanca mountain range, specifically in the Cerro de la Muerte area, as well as the interaction between these birds and the different types of flowers on which they feed. The purpose of the research was to analyze these data, compare the recorded patterns of hummingbird visitation, and thus determine if there is a symbiotic advantage for flowers and hummingbirds, determined by the morphology of the latter - the length of the hummingbirds' beaks versus the depth of the flowers. We also sought to investigate the potential effects of climate change on these important pollinators.

This article seeks to document the ideation process, fabrication and field testing of the proposed device, the different iterations of prototypes that the team developed, as well as to analyze the potential of digital fabrication technologies as efficient, accessible and less expensive means of prototyping, particularly for conservation efforts and innovative projects. Additionally, the opportunities and obstacles that manifested themselves in the development of the prototype are documented, in particular with respect to the limitations given by the atmospheric conditions to which the device was exposed, as well as the considerations required to develop a prototype that will be used mainly in the study of wildlife.

2. Background

2.1. Regarding Fab Labs

The Kä Träre Fabrication Lab is a research space of Costa Rica's distance learning state university, Universidad Estatal a Distancia. As a Fabrication Laboratory (Fab Lab, as this type of laboratory is commonly abbreviated), it has a series of technologies such as Arduino boards, laser cutters, filament 3D printers, resin stereolithography printers, CNC cutters, among others. These are known as digital fabrication technologies, and since their emergence they have positioned themselves as key tools in the development of prototypes. "...digital fabrication is characterized by the use of convenient techniques

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that facilitate the rapid creation of tangible prototypes, using CAD and CAM tools" [1]. CAD stands for Computer-Aided Design, or computer-aided design, while CAM stands for Computer-Aided Manufacturing, or computer-aided manufacturing. Digital manufacturing is referred to when the entire manufacturing process, whether additive or subtractive, is performed primarily by machines following a digital design.

Although digital fabrication tools can actually be used to create almost anything, it is more common to find fabrication processes applied to areas such as product design, engineering and architecture; compared to other fields such as ecological conservation and biology - areas that could also benefit from the openness and multidisciplinary nature of Fab Labs.

> "The Fab Lab project was created from an experimental course at MIT launched by Carqueijó, et al. [2] called "How to Make (Almost) Anything", whose intention was to bring together personal and digital fabrication, individual creativity, and group collaboration [2].

Since then, hundreds of Fab Labs have been created around the world, usually focused on the areas of engineering, programming, architecture and design. In recent years, uses of digital fabrication can be found in more and more areas, such as gastronomy, culture and medicine, among others.

The use of digital manufacturing technologies for prototyping, ideation, innovation and design processes is becoming increasingly common. This is due to multiple factors, one of which is the wide variety of materials available. Both 3D printing and laser cutting have a variety of material options that can be worked with. Laser cutting, for example, can be used on glass, wood, corrugated cardboard, acrylics and others. The variety of materials in 3D printing is even greater. "3D printing technology is capable to produce fully functional parts in a wide range of materials including ceramic, metallic, polymers and their combinations in form of hybrid, composites or functionally graded materials [3].

Another factor that greatly facilitates the prototyping process through digital fabrication is the ease of manufacturing multiple iterations of prototypes. The cost of 3D printing and laser cutting is relatively low. "3D printing is much more economical than subtractive manufacturing (where up to 90% materials can be lost in the manufacturing process)" [4]. Also, it should be noted that manufacturing times are much shorter with digital manufacturing compared to traditional manufacturing methods.

In addition to the advantages of digital fabrication, there are two advantages of Fab Labs themselves - the openness of these spaces, and the multidisciplinary approaches that occur in them to solve a problem. There is an international network of Fab Labs worldwide, composed of spaces that are characterized by the openness of knowledge, the search for accessibility and the constant development of innovation. These labs have multidisciplinary teams, usually engineers, programmers or architects, although there are many other cases that incorporate other disciplines. "Fab Lab is a prototyping platform for learning and innovation that provides important stimuli for local entrepreneurship and is based mainly on four key factors: openness, interdisciplinary collaboration, effectiveness, and transferability [2]. It is this openness and free exchange of ideas that empowers Fab Labs as agents of change and innovation.

2.2. Feeder Prototype Proposal

In the case of this prototype, it was generated based on a request from a biologist, who provided feedback and validation throughout the project. The development team was composed of an industrial engineer with emphasis on product design, two programmers and an animator. A prototype development strategy was employed, consisting of the fabrication of a device, which was tested in the field and subsequently modified based on feedback from the biologist.

The project proposal sought to use the advantages of digital fabrication to develop a hummingbird feeder, which would include an internal sensor equivalent to the anthers of a flower. This would allow measuring the biological efficiency of the interaction between these species. Additionally, it was proposed that it would also have a motion sensor, a timer, and a liquid meter. The feeder would be configurable with three flowers 3D printed in resin, corresponding to three flowers of different depths,

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commonly visited by hummingbirds in the Cerro de la Muerte area.: *Fuchsia microphylla*, *Macleania rupestris* and *Fuchsia splendens*.

3. Materials and Methods

The prototyping process for the hummingbird project was established with certain requirements and limitations. As mentioned, the initial proposal sought to have an internal sensor to the flower, equivalent to the distance usually found in the anthers of real flowers. Additionally, since the feeder would be visited by hummingbirds, it was necessary to ensure that the materials used were safe for the birds. It was therefore proposed to create an initial prototype that would be fabricated using three different technologies: fused material deposition printing, stereolithography printing on photosensitive resin, and electronic components such as Arduino boards and motion sensors.

Fused material deposition, or FDM, printing is one of the most common, affordable and accessible 3D printing technologies on the market. Consequently, it is also the most widely used technology in prototyping and design processes, thanks to the ease of performing multiple different iterations at relatively low cost. Solomon, et al. [5] define FDM as a material addition technique to produce physical parts directly from their digital data model. This type of printing was used to produce large parts in initial prototypes, for example, compartments to contain and protect electronic components.

The next technology, called stereolithography printing, consists of the solidification of a photosensitive resin, layer by layer, from a focused laser. This type of technology allows a higher level of precision than FDM printing, as well as the printing of objects with very thin or thin parts. Therefore, stereolithography printing was used to manufacture the models that required this precision, for example, the flower models and the nectar tank models.

An important detail that had to be taken into consideration for the development of the device is the environment in which this project was to be carried out, i.e., the atmospheric conditions of the study area. In this case, the field work was carried out in the Cerro de la Muerte area, in the Talamanca mountain range in southeastern Costa Rica. This is an area characterized by a cold climate, dense vegetation corresponding to the Costa Rican cloud forest, and a high level of humidity often present in the form of fog or precipitation. In a study they conducted in the Cerro de la Muerte area and the páramos of the Talamanca mountain range, Ramírez-Fernández, et al. [6] describe the climate as follows:

"The mean annual precipitation is 2,500 mm, with a relatively dry period between December and April, with a mean annual temperature 11° C for the CMBS and 7.6° C for the paramo [7]. The temperature oscillates drastically during the day, particularly in the paramo (−5° to 35°) [6].

Likewise, the subjects of the study, which are the different species of hummingbirds found in this region, had to be taken into consideration. Hummingbirds are small birds that are characterized by moving their wings at a high speed, between 12 to 80 flaps per second. One of the main difficulties in developing this project was how to measure the amount of nectar that these birds consume, corresponding to just a few microliters at each visit to a flower, which they collect with their tongues.

"Given that the quantities of nectar concealed inside flowers are small (on the order of microliters), and the narrow floral corolla (petals) limits the bill's ability to scoop, capturing mouthfuls of nectar with just the bill is not aplausible solution for avian

nectarivores [8].

This data is key, since one of the objectives of the prototype was to determine whether long-billed hummingbirds are able to acquire more nectar (and therefore more energy) from a flower such as *Fuchsia splendens*, which is of deep size, compared to a small flower such as *Fuchsia microphylla*. Additionally, we sought to catalog visitation times per hummingbird, both time of day and duration of visit, through motion sensors. A longer visitation time of a hummingbird represents greater pollination by the flower, which would mean that both species would benefit more from this interaction. Multiple tests of different sensors were necessary to perform the data captures, including:

- Hydrostatic level sensors.
- Motion sensors.
- Optical sensors (Laser recognition of received light).

3.1. Prototype Development

Throughout the project four prototypes were developed, each with its own particular characteristics and materials. This section details each stage of development of the device, the equipment and materials used and adds some details that led to the consideration of developing a new version for the next test.

3.2. First Prototype

The first prototype consisted of a device composed of two tanks, a compartment with electronics, a fluid pump, two sensors and a liquid meter. The biggest challenge in its development was to solve the issue of the anther sensor, as it presented two major problems. One was scale, as the internal space of the flowers is extremely small, only about 2 mm in diameter, making it difficult for any sensor to be present. Additionally, that same space was needed to provide a simulation of nectar (sugar water) to hummingbirds visiting the prototype. Therefore, the use of an internal sensor was discarded, replacing it with two sensors, one for motion and one for light, which essentially served the same function: to determine the presence of a hummingbird and to document the amount of time the hummingbird was feeding on the flower. In the case of the tanks, the smaller scale tank supplied nectar to the hummingbird, while the larger scale tank had a liquid meter. This was installed in order to measure how much liquid each hummingbird drank during a visit; for clarity, see Figure 1.

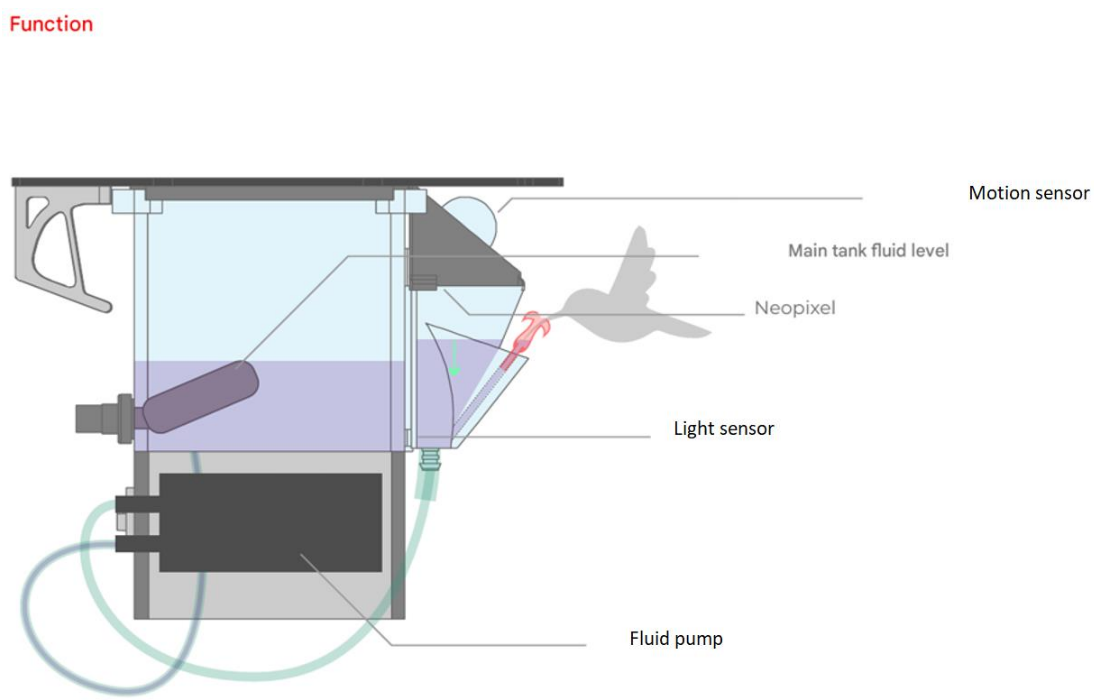

Figure 1.
Diagram of the first feeder prototype.
Source: Developed by Sandoval-Poveda and Tabash-Pérez [9].

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For the construction of this prototype, the following were used:

- Laser cutting for the tank roof. The equipment used was a Redsail M500 laser cutter, with 3mm thick red acrylic.
- FDM printing for the protective compartment of the electronic components. An Ultimaker 3 printer was used, with black PLA material.
- Electronic components such as sensors, Arduino boards and SD cards for data collection.
- Stereolithographic printing in photosensitive resin for the tanks and flowers. The equipment used was a FormLabs Form2 printer, with transparent resin for the tanks and white resin for the flowers. These were then painted with non-toxic acrylics.

The digital flower models were created from scratch using two 3D modeling programs, ZBrush and Blender. Photographs taken in the field by the biologist were used as reference. Figure 2 shows screenshots of the three 3D models. The assembly of the components is illustrated in Figure 3.

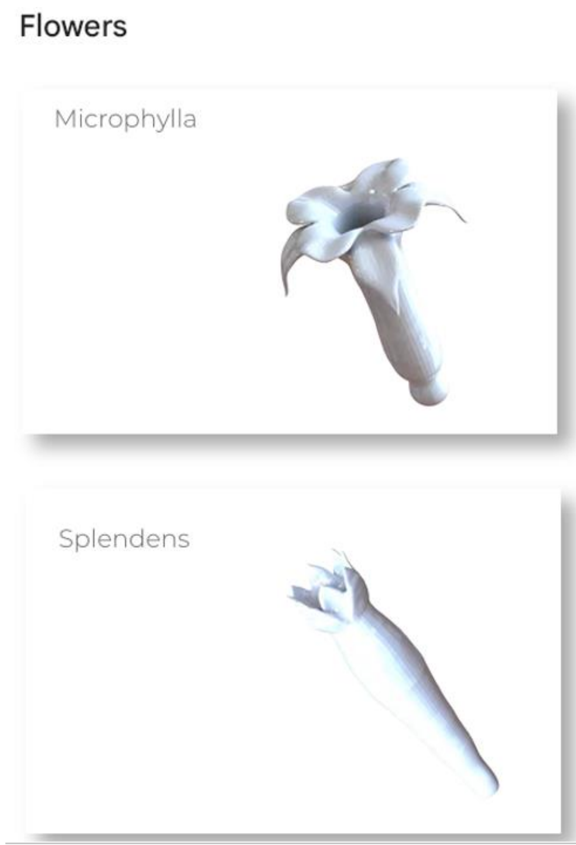

Figure 2.
3D models of Fuchsia microphylla, Macleania rupestris and Fuchsia splendens.
Source: Developed by Sandoval-Poveda and Tabash-Pérez [9].

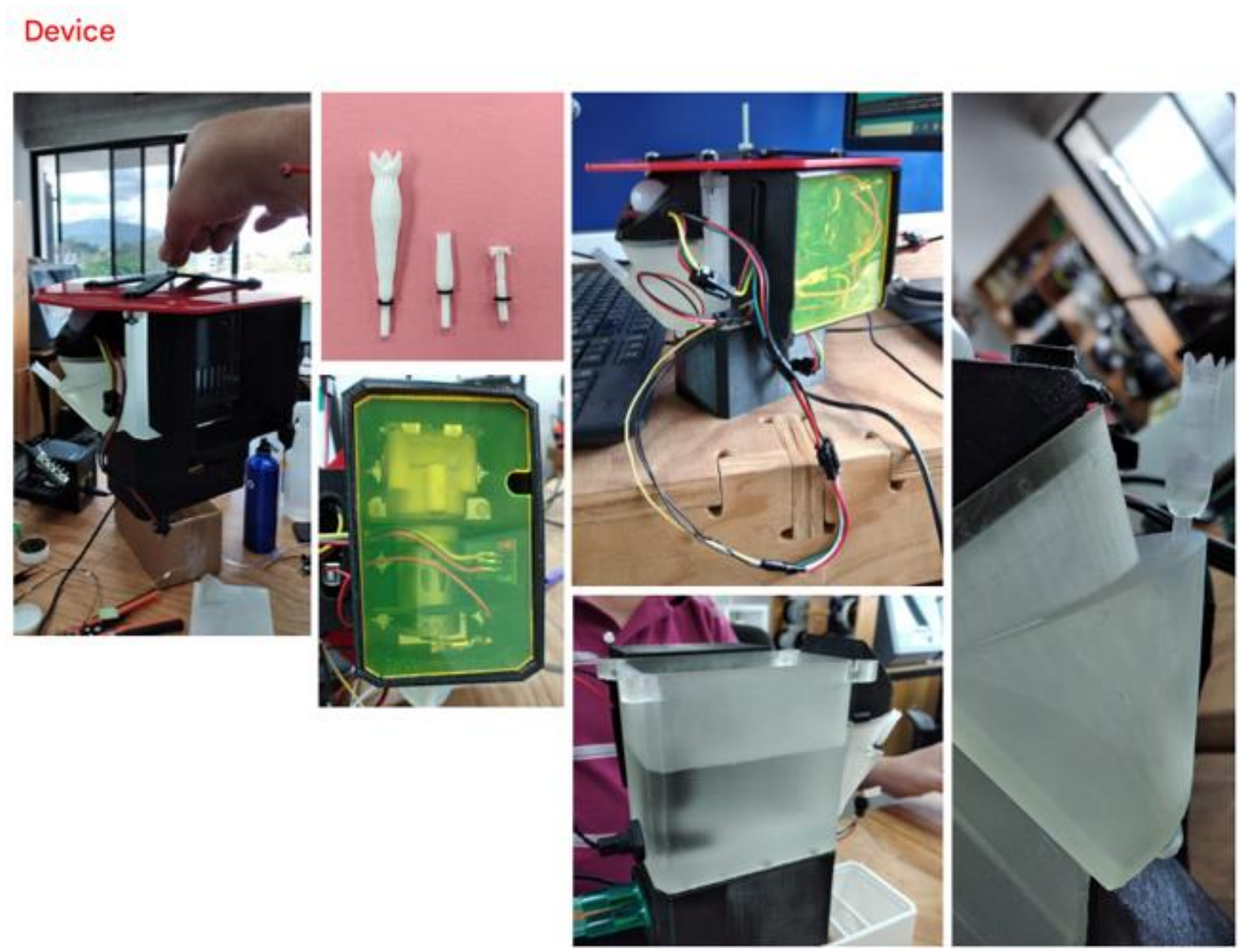

Figure 3.
Assembly of the first prototype feeder.
Source: photographs and collage by Sandoval-Poveda and Tabash-Pérez [9].

Two members of the digital fabrication team had the opportunity to visit, together with the biologist, the Cerro de la Muerte area to make the first field tests of the device. This visit was of utmost importance for the development of the rest of the project, as it gave the team first-hand experience not only of the subject of study (the hummingbirds), but also of the particular atmospheric conditions of this project and how they would affect the prototype.

In fact, field tests showed certain errors in the first prototype. One of the most important was the use of the color red for the fabrication of the protective roof of the device. Being a striking color similar to the flowers', the hummingbirds showed more interest in the roof than in the manufactured flowers. Another change that was required in the roof of the device was an increase in its size, since the climate of the area (particularly the high level of precipitation) had not been taken into account in the original design and a higher level of protection was required for the device.

This first prototype also showed high power consumption, as it constantly recorded all sensor data, regardless of the presence of a hummingbird. Therefore, an on/off button was proposed for a 1.2 version, so that the biologist could control when he wanted to capture data on the device. A clock display was also installed that would activate when it detected activity.

The most important problem arose with respect to the sensor that was acquired to measure the level of nectar, which, despite being specialized for measuring liquids, was incapable of measuring the very small quantities consumed by hummingbirds in a single visit, since, depending on the case, these quantities can only be measured in microliters (μL). Additionally, the sensor rusted very easily. This rust problem was originally attributed to the effect of the atmospheric conditions in the Cerro de la Muerte area on the device.

For version 1.2 of the device, black acrylic was used for the new roof, and a new sensor was proposed, in this case, fabricated in the laboratory. The protective compartment of the sensor was fabricated using resin printing (using the Form 2 printer, with transparent resin), which had internal electronic components. Six sensors were distributed in the compartment at different elevation points, so that when they came into contact with the nectar they would activate and indicate the level. The sensors are illustrated in Figure 4.

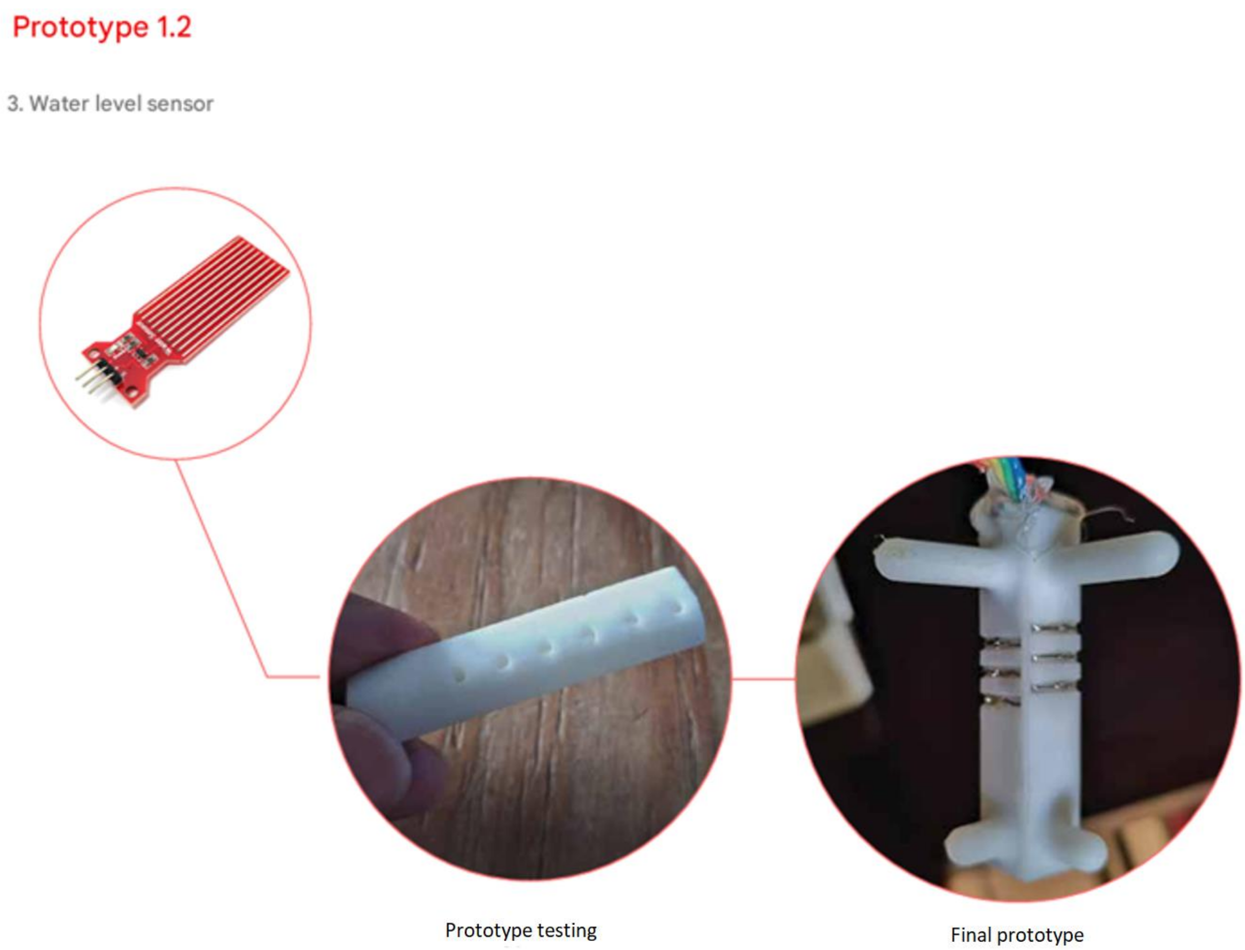

Figure 4.
Fabricated sensor.
Source: Figure by Sandoval-Poveda and Tabash-Pérez [9].

3.3. Second Prototype

After changes were made to version 1.2 of the device, it was turned over to the biologist for further field testing. These tests yielded multiple problems with the device, primarily with the liquid pump that transferred the nectar from the large tank to the small tank. This problem was directly linked to the electricity required by the device. Once more, these problems in the electronics were hypothesized to be the effect of atmospheric conditions.

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Taking into account the lessons learned from the first device, the idea was to create a second prototype, reducing the number of electronic components and with a single tank. Figure 5 illustrates the design proposal for the second device.

Figure 5.
Proposal for the design of the second prototype feeder.
Source: Screen capture by Sandoval-Poveda and Tabash-Pérez [9].

In the second prototype, tank refilling was performed mechanically with a syringe, activated by the device's light sensor. It was proposed that the tank would automatically refill after a period of inactivity by activating the syringe until an opaque sphere inside the tank activated the light sensor. This would theoretically solve the problem of measuring the nectar consumed, since in order to refill the tank to a maximum filling point, the syringe would have to be compressed a specific measurable distance, equivalent to a specific amount of liquid transferred. This distance would be recorded by the device, and could then be converted to the amount of liquid delivered. Figure 6 plots the filling process.

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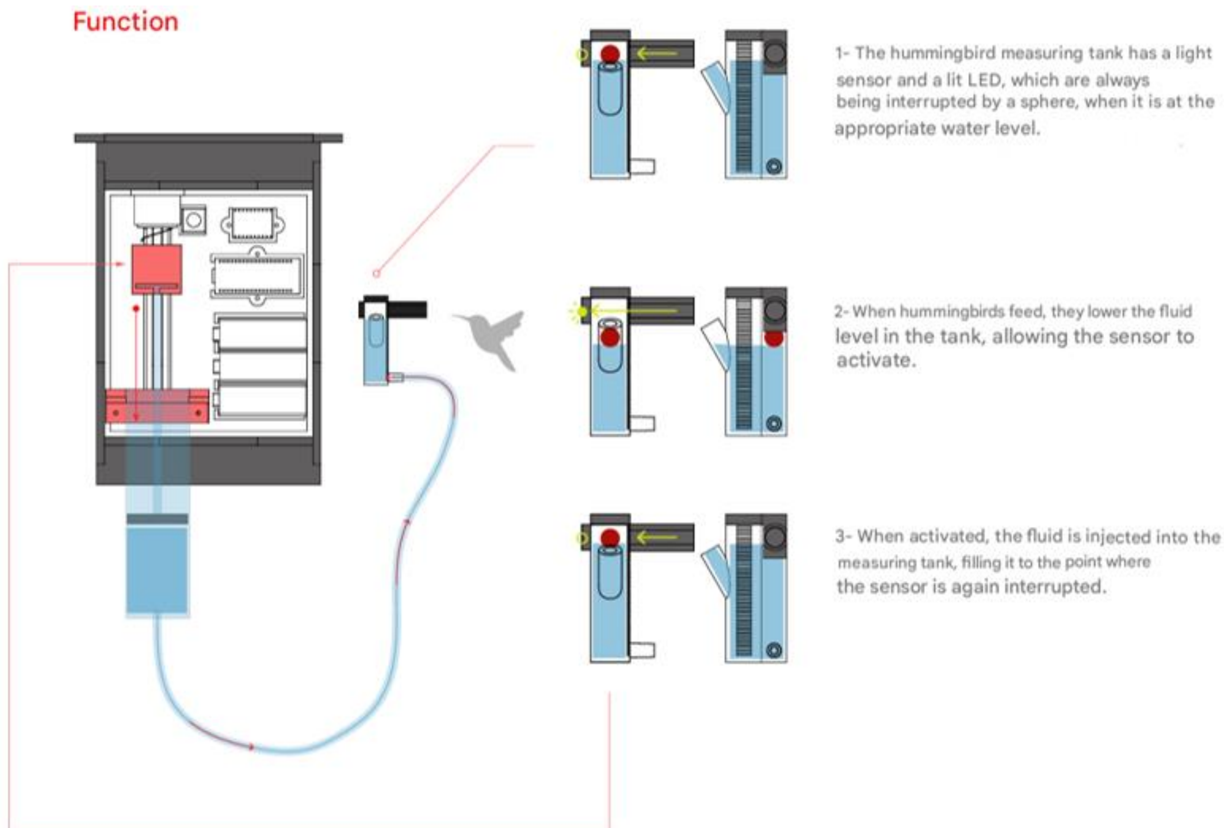

Figure 6.
Feeder tank refilling process, second prototype.
Source: Figure by Sandoval-Poveda and Tabash-Pérez [9].

For the construction of the second prototype, the following were used:

- Stereolithographic printing on photosensitive resin for the tank. Form 2 from FormLabs and transparent resin were used.
- FDM Printing for the overlays. Ultimaker 3 with black PLA was used.
- Sensors and electronics for the filling mechanism.

The development of the second prototype had multiple complications. The tank filling electronics did not perform as expected. Additionally, the electronics continued to rust easily. This, coupled with the departure of the programmer who had been working on earlier versions of the device, resulted in the second prototype not being as successful as expected.

3.4. Third Prototype

In the absence of a programmer, it was necessary to rethink the device with a third prototype proposal. This focused on solving the problem of the tank. It was decided to eliminate the electronic component for filling, using a single tank with measurements corresponding to the liquid present, and a base that could be configured with the previous flowers. Figure 7 illustrates the proposed design of the third prototype.

Figure 7.
Proposed design of the third prototype.
Source: Figure by Sandoval-Poveda and Tabash-Pérez [9].

This design used a screw-type connection between the vertical tank and the base. To manufacture it, only photosensitive resin printing was used, specifically with transparent resin. The main advantage of this proposal was that the lack of electronic components would avoid the problems that had occurred in past prototypes.

However, this third prototype, although functional, only provided data on the amount consumed, and was very inaccurate, which was not what was expected for the project proposal. This third prototype was not manufactured and at this point it was considered to close the project.

3.5. Fourth Prototype

Towards the end of 2022, a new programmer joined the Kä Träre Fab Lab team, and was integrated into the hummingbird project. This breathed new life into the project, and development of the fourth prototype began, taking inspiration from the previous two prototypes and improving on the learnings from those stages.

As for the design of the device, the general design of prototype 2 was retained, consisting of a measurement tank and an adjacent compartment with sensors and other electronic components. A short-presence optical laser sensor was added for hummingbird beak detection. This sensor was capable of detecting changes in the topology of the visiting bird's beak, which would facilitate the determination of the hummingbird species. Additionally, an interface was created for easy collection and graphing of the captured data. Figure 8 shows a diagram of the design of the fourth prototype.

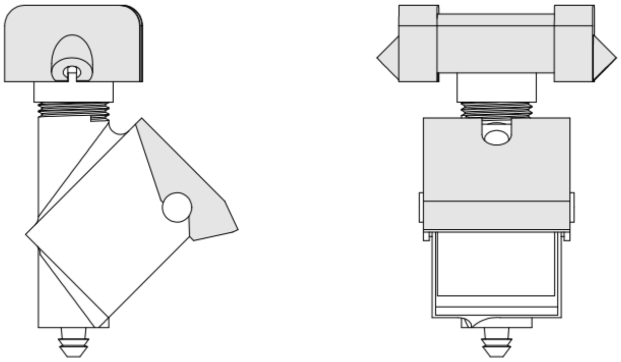

Figure 8.
Proposed design of the fourth prototype.
Source: Figure by Sandoval-Poveda and Tabash-Pérez [9].

Originally, the programmer proposed to use sensors to detect small fluctuations in the electrical resistance of sugar water to measure the levels of nectar consumed by hummingbirds through copper wires. Tests with this approach found that the copper wires oxidize very quickly. This revealed the real root cause of the problems in the electronics - the rapid oxidation of the components was due to the combination of electricity and the contact of the components with sugar water. This nectar-like solution, by a process similar to electrolysis, accelerates the oxidation process of electronic components.

Although this proposed technique for measuring nectar levels is functional, it was decided not to use it because of the desire to avoid any harm to the hummingbirds that might be exposed to the particles emitted by this oxidation process.

For the construction of this prototype, these technologies were used:

- FDM printing for the caps and connectors of the electronic components. Ultimaker 3 printer was used, with black PLA material.
- Electronic components such as sensors, Arduino boards and SD cards for data collection.
- Stereolithographic printing on photosensitive resin for the tanks. The printer used was a Form 3B+ printer from FormLabs, with transparent resin.

One of the main improvements of this prototype was the creation of a monitoring and control application by the programmer, which allows the user to control the refilling of the device's tank, turn it on and off, as well as directly access and visualize the captured data in a clearer way.

4. Results

A fourth and final prototype was manufactured and delivered for field testing. The device has two parts: a nectar storage tank, and a dispenser where the hummingbirds come to feed. When the tank is to be filled for the first time, the liquid is introduced through the dispenser. With the monitoring and control application, the device can be set in two different configurations: one for filling the tank, and one for dispensing nectar. Additionally, there is a control board, which gives operation to the system, captures data after a set amount of time (determined by the user through the application), and communicates with the device through wifi. In addition to the above, this device allows the user to monitor environmental data, for example, humidity and temperature, and to make comparisons with the frequency and level of hummingbird visits to the device.

The device is a state machine. This means that there is a condition, which can vary according to other conditions that the machine has. There are three states:

- The IDLE (paused) state, where the user can perform parameter settings and make adjustments to the calibration of the sensors.

- The ACTIVE state, which activates a TOF (Time of Flight) sensor that cycles to determine if there has been an arrival of a hummingbird at the device. If the TOF distance is less than the user-determined threshold, an arrival is recorded and the device is held in standby until the subject moves away. Subsequently, the dispenser is refilled and the microliters required for that action are calculated, determining how much nectar was consumed. The corresponding data capture is done and returns to sensor activation. In this state the user can receive real-time data, adjust the liquid in the dispenser, and start or stop data recording.
- The REFILL state performs an automatic filling of the storage tank, with the liquid that the user manually introduces into the device through the dispenser.

Figure 9 illustrates the three components of the fourth prototype: the storage tank, the dispensing tank and the receptacle for the flowers. The operating algorithm of the device is described in Figure 10.

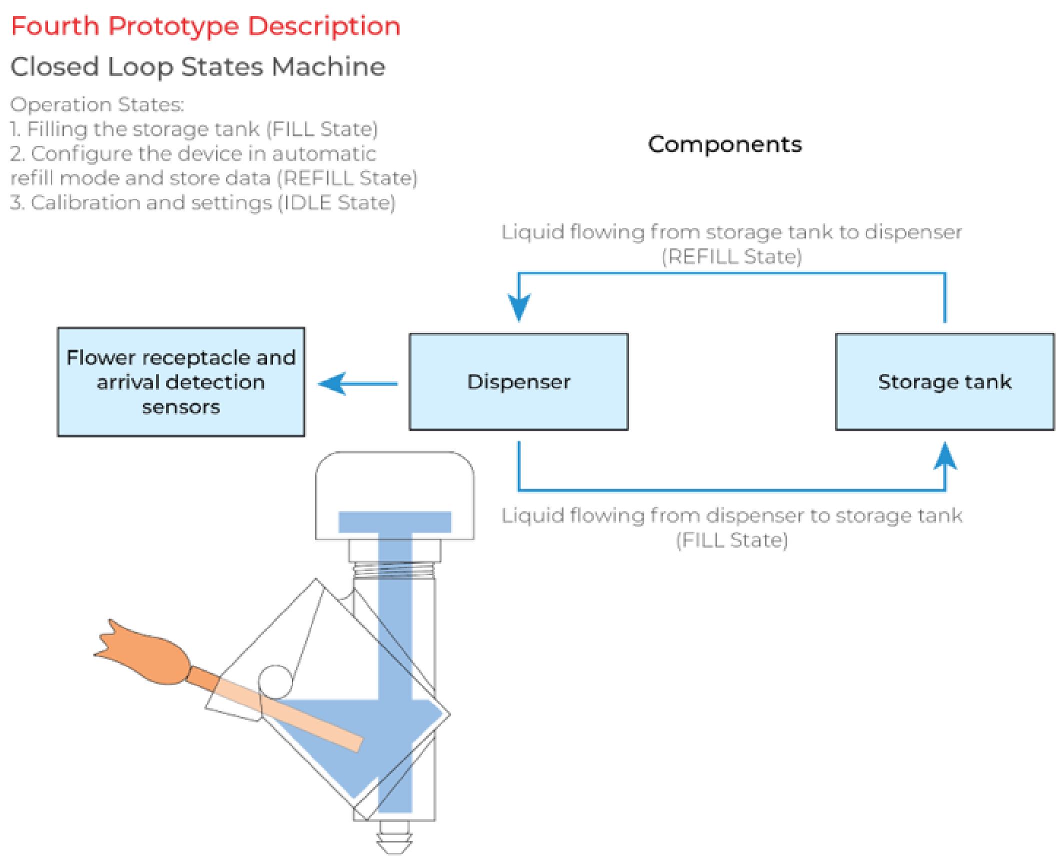

Figure 9.
Components of the fourth prototype.
Source: Figure by Ewel, et al. [10].

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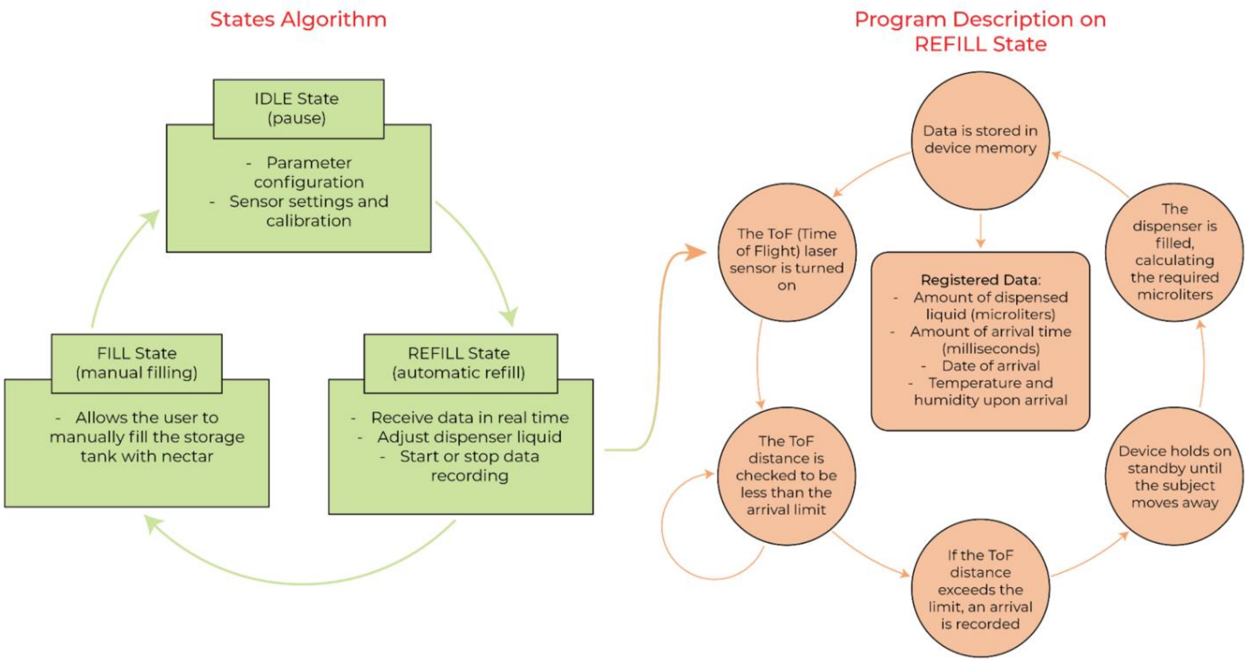

Figure 10.
Description of the state algorithm used in the fourth prototype.
Source: Figure by Ewel, et al. [10].

5. Conclusions

Four iterations of the hummingbird feeder device were created, each responding to feedback from field tests conducted by the biologist.

Given that resources were exhausted, both in terms of investigator time and materials, it was necessary to conclude the project at the end of the fourth prototype. The latter, although successful in terms of ease of installation and use, as well as data collection and monitoring, did not allow the field data collection expected by the biologist, specifically due to new energy-related complications caused by atmospheric conditions.

In spite of the fact that neither the objectives nor the expected results were achieved, this is considered a learning experience for all those involved, providing situations and results documented so that in the future, if other research of this type is carried out, the factors that were or were not successful as far as the prototype is concerned can be considered.

5.1. Opportunities

- Digital manufacturing has all the potential for the development of data capture devices in the field, however it is necessary that their development goes hand in hand with specialists in the area, not just the manufacturing team.
- The development of devices for practical applications generates ideal scenarios for learning digital fabrication equipment, both in potential applications and in the testing, use and effectiveness of materials.

5.2. Challenges

- One of the main difficulties for the development of this prototype was a lack of clarity in the communication between the biologist and the laboratory team. Despite multiple meetings and exchange of information in both directions, some characteristics of the study subjects, in this case hummingbirds, as well as the conditions to which this device would be exposed, were not

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clearly explained at the beginning of the process, but gradually as part of the feedback from the field tests. This meant that the first prototypes did not have the desired impact, a situation that could have been avoided with clearer communication.

- Digital fabrication spaces are usually located in urban sites, with very controlled atmospheric situations compared to field test locations. To manufacture devices intended for biological projects, it is essential to prototype and validate at the site where the study will take place.

Finally, some recommendations are proposed for those who wish to venture into digital fabrication for field testing, and for fabricators who are going to develop a project together with teams of professionals outside these specialties:

- It is recommended that a different prototyping methodology be used, one in which the biology team that is going to perform the field tests is fully involved in the fabrication process. There are scopes and limitations within the area of digital fabrication that the biologics team is not aware of, as well as features unique to the work of the biologics team that are unknown to a fabrication team. However, the development of this project revealed that these shortcomings may not be apparent to both parties and, therefore, the need to clarify things that may be obvious to specialists in one area, being key information, that members of the other team need, is not evident.
- Likewise, it is recommended that the fabrication team be more involved in field testing, and ideally that they be able to experience observing the species that are the subject of the study. The visit of the fabrication team to the study area resulted in multiple changes and improvements to the device. Therefore, it is recommended that these opportunities occur early in the design process, and that they be frequent, so that they can be used both to seek inspiration and to detect early and in a timely manner difficulties or limitations that are very difficult to foresee, such as temperatures, humidity and species external to the study, when manufacturing within the regulated spaces of the laboratories.

5.3. Statements and Acknowledgements

5.3.1. Data Availability Statement:

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

5.3.2. Ethics Statement:

This project did not involve any studies involving human participants. All stages of the prototype's development were approved by the biologist in charge of field research to ensure the wellbeing of the species of hummingbirds who were the subject of study.

5.3.3. Funding

The hummingbird research process was funded mainly by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, as well as additional funds supplied by Kä Träre Fab Lab, the Investigation Branch of UNED, and the School for Natural and Exact Sciences of UNED (ECEN). Prototype development was mostly funded by Kä Träre Fab Lab, both in investigator time and materials.

5.3.4. Author Contributions and Acknowledgements

The author of this article was also a participant in the project, as the 3D modeler of the printed flowers and offering feedback throughout the prototyping process. Special thanks to biologists [10] coordinator of Kä Träre Fab Lab, and to Farith Tabash Pérez and Harold Carvajal Álvarez, the product designer and programmer of the development team.

5.3.5. Conflict of Interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Copyright:

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