Do Robots Dream of Moss Fields?

An exploration of mutualism between robots and plants using MFCs and energy harvesting.

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Abstract

Nature has always been a fascination for humans. In robotics, various robots are inspired by nature in their shape and appearance, while some mimic its mechanisms and processes. This is taken even further with the integration of living plants. Exploring the way robots and plants can interact with each other. It seems however that the interaction is rarely beneficial for both parties. This paper proposes to explore plant-robot interaction based on the concept of mutualism. This exploration is done using Research Through Design (RtD) and focuses on the building of a working demonstration of plant-robot mutualism. Through this building, various insights are collected about the feasibility and notions needed to build mutualism. Those insights are reflected in a demonstration of mutualism comprised of a concept installation and a guide to replicate. Finally, this paper discusses lessons learned about mutualism, to offer tools for future exploration of plant-robot mutualism.

Keywords; Mutualism, Microbial Fuel Cells (MFCs), Energy Harvesting, Research Through Design (RtD), Design, Plant-Robot Interaction

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1. Introduction

When I started my project at the beginning of 2023, my topic focused on the impact of the material a robot is made of on human-robot interaction (HRI). This idea was born after the realization that most robots on the market are either made of plastic or metal, which is understandable from a security, durability and hygiene perspective. However, it makes the appearance of robots monotonous and doesn't seem to explore the potential of materials to convey new meanings and attract audiences. Material selection is crucial in product design and it can even be the start of a design process with methods such as Material Driven Design (MDD) [1]. This raises the question as to why this wouldn't be the case when choosing material for robots.

While digging through projects, I found several robots exploring new surface materials and broadening possibilities. On one side, they are hard-shelled robots, where it is easy to test various materials. By putting materials on top of the shell, it becomes possible to explore its impact and how it can help robots fit in specific settings or users. This is the case of PARO [2] a therapeutic robot covered in fur. Its objective is to help with the documentation of animal therapy in care facilities. Cuddlebits [3], a small zoomorphic robot able to recognise touch gestures, also uses fur as a surface material to create an affective response.

On the other side, new materials have been brought to robotics with the growth of soft robotics. Soft robotics is concerned with the design and fabrication of robots with physically flexible bodies and electronics. It opens a door for new and safer robot interactions. Soft robotics brings new robotics materials to the table such as fluids, elastomers and gels [4], not only to the outer part but also to the inner mechanisms. Examples of soft robots are Blossom [5], a robot kit that needs a knitted exterior, allowing for personalisation, or the tentacle-like robots made to grip various objects [6] This is taken further with the design of texture-changing skin [7] to explore new expressive non-verbal channels for social robots. All those projects testify to the interest and need to explore various materials in robotics. While the materials are novel, they still seem limited to specific types of materials. This leaves space to explore different materials out of the ordinary, closer to the natural world, such as wood or plants.

In the arts, it is possible to find pieces bringing together more surprising materials and robots. For example, Ken Rinaldo is an artist whose work focuses on developing hybrid ecologies with animals, algorithms, plants and bacterial culture. His work Autopoiesis [8] is a series of musical and robotic sculptures that interact with the public. The robotic sculptures are made out of wine wood, showcasing interest in different robotic materials. The use of wood is also found in the work of David Bowen's tele-present wind [9]. Tele-present wind is composed of motors and branches moving based on real-time direction and strength of the wind. While they cannot be considered robots, there is something robotic about the way they move. In both works, the combination of robot likeness and wood sticks makes for a novel visual experience, while conveying a warmth that is not present with plastic or metal robots. Those two projects highlight the fact that nature and robots side by side isn't new and has always been a point of interest.

Indeed, there seems to be something poetic about robots and nature, by the juxtaposition of life and man-made objects. Especially, when it comes to plants interacting with technology, since it puts forward the wish for technology and nature to exist in harmony. In the media countless examples can be found to confirm these interests, such as the overgrown guardians in Breath of The Wild [10] or the robots of Silent Running [11] helping save plant species. It is also the case in the arts, with projects involving robots, plants and their relationship to us. Squat by Thomas Shannon [12] is one the earliest examples of robotic art. It showcases a very minimal robotic installation controlled through the signals of a plant. This artwork made in 1966 already suggests a fascination for robots and their interaction with the world. This interaction can take other shapes, such as with the Telegarden by Ken Golberg [13], where a robot controlled remotely by humans tends to a garden. In this work, the robot acts as a caretaker for the plants, instead of using the plant as a sensory extension. Those projects show that the exploration of plant-robot interaction was already a subject of interest early on. The interaction explored could take many forms and focus on various relationships. Nowadays, plant-robot interaction is found on a grander scale with vertical farming. In vertical farming [14][15] robots are tasked to take care of plants as a way to optimize farming. Unlike Telegarden which explores new types of relationships where the humans take care of the plants through the robot, the robot is only a tool for us to be able to produce more. It shows a one-sided relationship, where the robot is at the service of plants and humans, but does not participate in more. This is also the case with UMOZ [16], a small robot covered in moss. UMOZ moves out of the sun according to the mosses' needs. While the connection between the plant and robot is physically closer, the relationship benefits only the plant, there is nothing in it for the robot.

All the cited examples bring together robots and plants in different ways, but it seems that the main interactions are limited to either the robot taking care of the plants or the plants acting as a sensory extension of the robot. Could there not be more to plant-robot interaction? Could plants and robots both offer utility to each other without the need for human intervention? Drawing from nature this relationship could be compared to a mutualistic interaction, where two species exchange benefits to survive.

Mutualism between robots and plants has yet to be explored. This leaves a gap to discover if such interaction is even possible and if so what shape would it take. Consequently, this paper sets out to explore the potential of robot mutualism and what it takes to realise it. This exploration is done through the building of a demonstration of mutualism between robots and plants. This exploration of mutualism is done to open a new discourse about interactions between technology and nature. Not in a way where technology is used to help us produce more and control nature, but as a way to mend our relationship with it. If robots can be powered by plants, it would allow the use of energy available in nature and limit the use of non-renewable energies. It could push forward new green technologies. Furthermore, it could open doors to discuss robots and their place in society. As of right now, research is focused on social robots and creating robots capable of fitting within human society, but what about fitting in human-less settings? All in an idea of technology and nature working together, blending in with each other, without the need for humans.

In this paper, I explore mutualism between robots and plants, through a discussion about the specifications of the relationship and then building on it to create a demonstration prototype. The final demonstration serves not only as a proof of concept but as a way to spark interest in the topic at hand. To do this, I first examine the interaction between robots and plants, as well as interactions found in nature (Related Work). Then, I restate my research aim (Research Aim) before reflecting on the possible shapes that robot-plant mutualism can take (The Shape of Plant-Robot Mutualism). Based on those reflections, I built a prototype of the demonstration of mutualism (Prototyping: Mutualism In Action). Finally, I share the finished demonstration with its chosen form (Result: Demonstration of Mutualism) and discuss my learnings about mutualism (Discussion).

2. Related Work

In this section, I discuss the various types of interaction found between robots and plants, before looking at the types of interaction found in nature. The objective of this section is to find what interactions between plants and robots are yet to be explored based on what nature offers.

2.1. Interaction between robots and plants

Various research and papers have explored possible and complex interactions between plants and robots. In this section, I discuss projects and papers examining collaboration and interaction between plants and robots. In the first part of this section, I discuss robots taking care of the plants, then plants used as sensors for robots and finally, plants used as fuel for robots.

2.1.1. Robots as caretakers

In robots as caretakers, projects can integrate plants as an integral part of their design, blending robotic technology and the realm of the living. UMOZ from Panasonic's Aug Lab [16] is a small walking robot covered in living moss. Its behavior is mapped on the moss's physical needs; if the moss enjoys the shade, it will stay away from the sun as much as possible. While UMOZ does not have any intended usefulness for humans, it does offer a healing presence. It wishes for humans to understand the moss's needs through the robot's behavior, to create a closer relationship between us and the moss. As stated by Takekoshi in his interview with Panasonic, "I wanted to create opportunities through design and technology to provide opportunities to learn about other living things and to suddenly change the perspective of the world" [17]. UMOZ is yet to be tested with the general public, but the vivid interest received on social media seems to show the potential of such a robot in the future. This project is an example of how robots care for plants, not only by acting based on their needs but by putting the plant's behaviour into light. BonsAI [18] by the TDK Corporation has similar features to UMOZ. BonsAI is a robot integrating a bonsai with a design that blends a robot and a tree. Together they form a robot plant pot. The robotic side takes care of the bonsai by following the sun, but also by asking to be watered since it can't on its own. Furthermore, BonsAI is designed to convey the plant's emotions through light and sound, but also interact with humans and offer a healing presence. HEXA [19] is also an example that combines plant and robot in its design. HEXA is a modular robot that was turned into a plant caretaker thanks to the integration of a plant at its centre and a light following module. Like the other two projects, it moves whilst following the sun. It can also interact with humans through gestures and responses. All of those examples show how robots can integrate plants into their design, which creates an interesting blend between robotics and nature. From those examples, it is clear that there is a wish to explore plant-robot interaction but also plants positive impact on humans.

While those examples blend in their design robots and plants together, they are not the only robots that take care of plants. An early work dealing with this is the Telegerden by Ken Goldberg [13]. Telegarden is an art installation that allows web users to view and interact with a remote garden. Users can plant, water and monitor the progress via an industrial robot arm. In this artwork, the robot and the garden are used as a “metaphor for care and feeling of the delicate social ecology of the net” [20]. It explores how humans can care for plants by giving instructions to a robot. The robot is solely there to follow the orders and take care of the plants.

This is also the case with automated vertical farms and gardens, except the human is not part of the equation or only remotely. Vertical farms wish to grow plants more sustainably and on smaller surfaces by taking farming upwards. Some high-tech vertical farms rely on robots and artificial intelligence to care for the plants, creating almost fully autonomous farms (SANANBIO [21], iFarm [14]). The same goes for automated gardens, such as FarmBot [15], which proposes an open-source robotic kit to take care of your plants. The robot does everything: planting seeds, watering them and taking the weeds out. In those cases, the robots are caretakers, fully separated from the plants themselves. They are created to solve specific food management and environmental problems. Some papers, such as the one from Sørensen et al. [22], offer technical guidelines for designing plant nursing robots. Showing the need and importance of developing robot caretakers.

Robots can tend to plants, but they are also used to manipulate the directional growth of plants. Wahby et al. [23] show how robots can be used to manipulate the direction of growth of plants through light stimuli. This is also done by Sareen et al. with Heliobots [24] which demonstrate robotic plant growth. However, unlike the previous paper, the robot lives on the stems of plants and guides them to grow into precise architectural shapes. In the project Flora Robotica, Heiko et al. [25] develop and investigate symbiotic relationships between robots and plants. This project is focused on creating a system where both robots and plants have equal roles. The robot controls the direction of growth of the plant, while the plant offers support and guides them through the growth. Finally, Instrument for Mediated Terrain [26] is an interactive sculpture where robot-like arms tend to moss gardens. The arms only activate when the audience comes closer to observe the gardens. This work asks participants to reflect on the life cycle in which humans, technology and nature meet. In this case, the robot does impact the growth of moss but reflects the impacts of humans on nature. It conveys a strong message.

While those projects bring robots and plants together, their interaction seems to be limited to the robot taking care of the plants. No direct benefits are drawn for the robot, it is a tool for humans to control the plants or extract benefits from them. It seems that overall, humans are the primary beneficiaries of this type of plant-robot interaction.

2.1.2. Plants as sensors

As seen previously, robots can use their sensors to take care of plants but some robots use plants as further extensions of themselves. Plants are sensitive beings that react and change based on their environment. Those reactions are used to expand upon the functionalities of robots, such as guiding their movements.

One of the earliest examples is the work "squat" by Thomas Shannon [12]. It is one of the first cybernetic interactive artworks. In the artwork, a robot is connected to a plant, which acts as the interactive interface. When the plant is touched, a voltage change happens, which triggers the robot to extend its legs. It will stop moving when the plant is touched again. This work puts in light the interplay between nature, machines and humans.

This play can also be found in the works of David Bowen who has realized various projects where plants are used to guide robots. In his work "plant drone" [27], a plant controls the direction of a drone. The drone reads the biological signals of the plant and moves accordingly, creating strange patterns in the sky. The control of robots through plants is also found in his work "plant machete" [28] where a robotic hand holding a machete moves according to the electrical noises of the plant. He considers the plant to act as the brain of the robot, controlling all movements.

The Cyborg Botany, part of the MIT Media Lab, group takes this further by exploring deep technological integration within plants [29]. They focus on finding ways to make plants respond to interactions by using their sensing and expressive abilities. For example, Planta Digitalis [30], where the plant is used as an antenna and motion tracker thanks to conductive wires placed inside the plant. Elowan [29] is particularly focused on plant-robot interaction. In this case, the robot uses the plant's electrical signals to drive itself towards the light. The plant acts as a sensor for the robot and through the connection, the robot can guide the plant to an accurate environment or react to the environment around it.

In this case, the robots tend to be the sole benefactor of the relationship. The plant is a tool for the robot to branch out its capabilities. It raises questions on how to balance this relationship. Can the robot be enhanced by nature while enhancing nature itself?

2.1.3. Plants as Fuel for Robots

Lastly, a category of robot-plant interaction is the use of plants, or more broadly biomass, as fuel for robots. The fuel allows for the robot to become energy-independent and explore the possibility of fully autonomous robots.

Gastrobot, which means "robot with a stomach", was coined by Wilkison [31]. It's a term that englobes robots powered by the digestion of various foods. This is done through the use of Microbial Fuel Cells (MFCs). The use of the stomach, or MFCs, allows the generation of energy to power the robots. Gastronome [31], later renamed CHEW-CHEW, is one of the first examples of robots capable of digesting foods. Through the digestion of food, it is capable of charging a battery and will move forward once it is completely charged. It is not fully independent since it needs to be manually fed sugar cubes to work.

Ecobot is another example of plants, or natural materials, being used to power a robot. Ieropoulos et al. focused on creating fully autonomous robots powered by MFCs [32, 33, 34]. This started with Ecobot-I [32] a robot capable of moving slowly at intervals thanks to the energy generated by MFCs. It was then developed more in detail with EcoBot-II [33], which pushes forward the first design and aims to raise the issue of creating fully energetically autonomous robots. The MFCs used here are made out of bacterial sludge cultures and fed with different substrates (sucrose, peach and flies). The power generated by the MFCs is used by the robot either to move forward, take temperature measurements or transmit measurements. In this project, the robot offers an adequate environment for the bacteria to grow, but it is not yet able to find and feed the substrate on its own. This is patched with Ecobot-III [34] which can collect food and water from its environment. Ecobot development pushes forward the development of autonomously powered robots, all at the detriment of the plants or biomass used. The biomas are reduced to waste and the robot does not give back to nature in any way.

This is not the case in various artworks focused on creating robots powered by nature to take care of nature. Nomadic Plants [35] by Gilberto Esparza, is work mixing a robotic system, an organic plant species, a set of microbial and photovoltaic fuel cells. This autonomous species has a metabolic cycle that can repair some of the ecological damage around it by recuperating the energy that it takes from the earth. It works in a way that upon encountering contaminated water, it will suck it up and store it in a group of microbial cells. The cells will generate electricity stored to power the robots while improving the collected water's quality for the plant it grows. In the same line of work, Caravel by Ivan Henriques [36], harvests electricity from bacteria and organic components in water. Carvel floats upon the water, using plants and filters to clean the water. This work also focuses on marrying technology and plants to help clean the environment, and make technology self-sufficient, all in the dream to help restore the earth's environment.

Those examples showcase how robots can use plants or more generally nature to power themselves. By using the energy of consuming plants robots become potentially autonomous, but most of the time to the detriment of nature. Only in the works of Caravel and Nomadic Plant does it cycle back to helping nature heal while taking from it. Even then, there are no direct benefits exchanged between the plants used and the robots, nature eventually benefits from it. It raises the question: is there not a way for the benefit to be almost instantaneous?

2.2. Interaction In Nature: Mutualism

Symbiosis is a term used to describe a relationship or interaction between two different organisms. The kind of symbiosis (parasitism, mutualism, commensalism and competition) depends on whether either or both organisms benefit from the relation. Those relations between organisms are essential parts of an ecosystem and can tell us a lot about an ecosystem's health.

Mutualism is defined as "an interaction between species that is beneficial to both" (p.315) [37]. The main benefit of mutualism for the species involved is the ability to survive. This ability is possible due to the exchange of benefits, such as nutrition, energy supply, protection from the environment and enemies, and finally transport - either from unsuitable environments or by dispersal of gametes [37]. An interaction isn't considered mutualistic if the species thrives as well without the other species. Mutualism is known in all kingdoms of organisms and mutualist's partners come from different kingdoms. Mutualism is "expected when it is valuable and when it is cheap and efficient" (p.316) [37]. We can classify mutualism between; direct mutualism in which two species interact physically, and indirect mutualism ("the enemy-of-my-enemy is my friend") in which species benefit from the other's presence but there is no direct contact (p.316) [37]. Direct mutualism usually involves exchanges of nutritional or energy benefits.

Mutualism found on Earth can be categorized into three types. The first one is known as resource-resource mutualism. In this mutualism, both parties provide each other with nutritional resources that are needed by the other [38]. Examples of this are lichens and mycorrhiza. Lichens is the relation between free-living algae and fungi, a relation that involves an exchange of carbons, nitrogen and other important nutrients. Mycorrhiza, on the other hand, is the association between the root of plants and fungi. In this case, the fungi help increase the plant's nutrient uptake while in return the plant supplies the fungi with the products of photosynthesis.

The second type is known as service-resource mutualism, in which one party provides resources whilst the second party gives a beneficial service to the first one [38]. An example of this is plant-pollinator mutualism, where the flower offers nutrients to the bees and the bees in return spread pollen with pollination.

Finally, the last and rarest is service-service mutualism. In this relationship, both parties provide beneficial services to each other [38]. This is the case with clownfish and anemones, in which the anemones provide shelter and food for the clownfish. In return, the clownfish provides nutrients for the plant and chases predators. Other examples are pistol shrimps and gobies who offer each other protection, the shrimp creates borrows while the gobies keep the shrimp alert of predators.

3. Research Aim

Multiple works deal with robot-plant interaction. As seen before, they can be split into distinct categories. First, the robot is a caretaker of the plant and watches over it. Second, the plant becomes a sensor for the robot. Finally, the plants can be used to generate electricity for the robot. In all cases, the relationship shown is one-sided in terms of benefits. Either the plant gains from the robot, as it is cared for and can grow optimally. Either the robots gain from the plant by extracting power from it or enhancing their abilities. Both rarely benefit from interacting with each other. However, from looking at interaction in nature between various species, there are instances where different species benefit from a relationship with each other. It is referred to as mutualism.

This paper proposes to explore plant-robot interaction based on the definition of mutualism. This exploration is concerned with the practical side of mutualism, focusing on what we can learn about plant-robot mutualism through the building of a working demonstration. The overarching question of the research is: What can we learn about plant-robot mutualism through its exploration?

The research aims to find if it is possible to build a working demonstration of plant-robot mutualism that is cheap and easy to replicate. As a result, I expect to present a working demonstration of mutualism as well as offer reflection points on what working with mutualism entails. Seeing that little work represents plant-robot mutualism, this research wants to offer a stepping stone for future projects on plant-robot mutualism. Furthermore, since there aren't many examples and things to build on, the demonstration focuses on being easily replicable. Which translates to the use of cheap and easy-to-find materials. This way, I want to encourage other people to explore plant-mutualism and pick it up.

This is done following the method of Research Through Design. Meaning that my research will be guided by a design process logic, with iterations and conceptual thinking, while being supported by scientific research (p.1378) [39]. RtD is an adequate choice since it includes a dimension of openness and looseness as said by Wilkie, Gaver, Hemment and Giannachi (2010, cited by Roggema [40]). This translates into the possibilities for multiple outcomes fitted to the question, as well as the wish to be open to everyone. The RtD used in the paper follows a DIY approach. The DIY approach translates by the use of easy-to-access materials and an at-home experimental setting. It fulfils the wish for this research to be accessible and easily replicable. Also, allows for a structure where knowledge is learned as the project evolves forward and problems arise.

Furthermore, this research paper will follow a DIY approach, meaning that everything will be done in a home setting with everyday life objects. This DIY approach makes this research possible with a small budget and limited knowledge. It also aligns with the wish of this research to be easy to reproduce and explore at home. By not requiring special materials and equipment it is accessible for most.

To answer and complete my research aim, I first reflect upon the modalities of this interaction and the possible shape it could take since mutualism is varied. Then, I move on to building the prototype of the demonstration. Finally, I develop the final shape of the demonstration of mutualism and reflect on the question in the discussion before concluding.

4. The Shape of Plant-Robot Mutualism

While mutualism exists in nature, it's important to define how it can be translated into plant-robot mutualism. In this section, I reflect and decide upon the shape of the mutualistic relationship. By shape, I refer to the benefits exchanged between the plant and the robots. What do they have to offer each other?

4.1. Plant Selection

The first decision was to select the plant species used for the relationship. It was important to narrow it down from the beginning to create a relationship tailored for the plant and put boundaries on the design.

Moss was selected as the plant. The first reason is that moss is common in the region this study happens in; the Netherlands. It makes its gathering easier. Furthermore, moss is a non-vascular plant [41], meaning it does not form roots, which makes a set-up with robots easier since there is no need to design around a root system. Moss is an interesting species as it can help indicate water and air pollution. They can also protect against erosion by retaining water. Those are interesting uses that could be explored in the mutualistic relationship. Finally, the use of moss also comes from its aesthetic value and appealing nature which can help captivate a broader audience. For example, in Japan moss is a central element of gardens and carries various meanings. It is a reflection of simplicity and humility. Moss offers a peaceful and soft surface that contrasts nicely with the usual materials used in robotics.

4.2. Defining the Exchange

Mutualism is based on an exchange of benefits between two different species. These benefits can be for example energy, nutrients or protection, as seen in the related works section.

To establish how it could be translated into an exchange between robots and plants, I listed the different needs of each part. For mosses, this is rather straightforward, they need sunlight but never strong direct sunlight, nutrients and water to survive. For robots, it's needed to think abstractly about them, like they are living beings with needs. The obvious answer is that they need electricity to function, it's their energy. Then, they might need to be protected from their environment; from the rain or other species. It could also be that they need to fit into a specific environment, which is the case for social robots fitting with human society.

On the flip side, there is also the question of what they could give to each other in this mutualistic relationship. Moss are non-vascular plants, to survive they capture the humidity found in the air, meaning that they could serve as a signal for humidity levels and air quality [41]. Also, they are great for air purification and hypothetically could be used as protection from environmental conditions. On the other hand, robots are modular and can be built for almost all scenarios. For example, they can monitor soil humidity and temperature, distribute water or even light the moss.

Based on the different possible benefits each could offer, I realized some sketches to diverge (figure 1). Those sketches helped transform ideas into form and reflect on their viability. It became clear that some ideas were impossible to realize in the time allowed for the thesis. Furthermore, I want to create something that realistically represents a mutualistic relationship between plant and robot. For that, sticking to a simple and obvious benefit exchange is key. It should be able to speak for itself and be straightforward. This is why I decided to focus my attention on the robot giving either water or sunlight to the plant, and the plant giving electricity to the robot.

Since the robot part is dependent on the electricity part, I decided to not make decisions on the benefit given. How much electricity I could create would impact the choice of hardware.

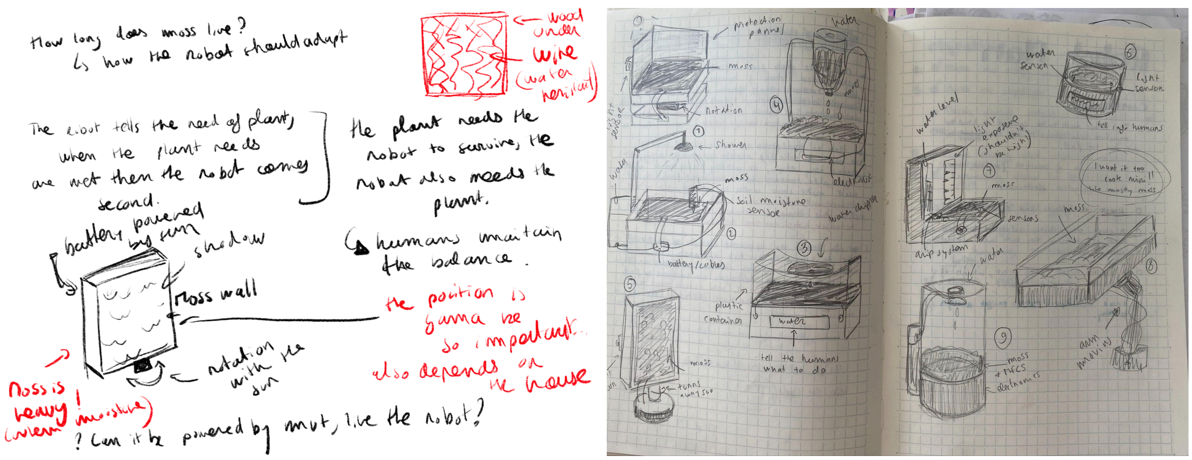


Figure 1: Examples of sketches and reflections on the concept.

5. The Plant Side of Mutualism: Generating Electricity From Moss

This section focuses on the technical parts of mutualism and answers the question of how mutualism can be achieved. In this part, I try to generate energy from moss with the exploration and construction of moss-powered Microbial Fuel Cells (MFCs). I explain what MFCs are and report the process of building voltage-efficient MFCs with off-the-shelf material.

5.1. What are bryoMFCs?

Microbial fuel cells (MFCs) are biochemical systems in which chemical energy is converted into electrical form by microbial activity. The electric current is generated by a simple phenomenon of driving electrons through a circuit [42]. MFCs are new ways to generate electricity that use organic materials such as mud or plants. They are considered green energies and could even help resolve problems of wastewater management [43]. The term MFCs englobes various types of MFCs based on the source of the organic matter. Some of those types are wastewater MFCs, mud MFCs and plant MFCs.

While MFCs can extract voltage from various sources, they present various challenges. The main one is that the voltage generated by MFCs is extremely low [43] which is a problem for everyday applications. The multiplication and scaling up of MFCs are necessary to generate higher voltages and power. However, scaling up MFCs is a complex exercise as it requires a balance of the chemical reactions between all parts at play [44]. Furthermore, power management systems (PMS), which harvest the energy from MFCs, are needed to make the energy generated usable [45].

For this research, the focus is on Plant MFCs, in which plants are part of the MFCs set up and participate in the bioelectrical reaction. Inside PMFCs, Bryophyte MFCs or bryoMFCs are a specific type of set-up. BryoMFCs are microbial fuel cells that use bryophytes (moss) to create electrical power. It differs from classic PMFCs since moss does not have roots, but rhizoids that stabilize them on the soil and prevent nutrient loss by erosion [46]. While they don't have roots, the process of generating electricity with bryoMFCs is similar to PMFCS. For simplification, I will explain how PMFCs function.

Generating electricity with PMFCs includes multiple chemical reactions. At its core, PMFCs use the plant root (rhizoids in the case of moss) release of organic compounds to fuel the bacteria found in the soil and on the roots themselves [46]. Those compounds, such as root exudates, secretion and gazes, are products of photosynthesis [47]. It's the oxidation of those compounds by bacteria that generates protons and electrons [47][48]. With the presence of electrodes, the anode and cathode, the protons and electrons can move. The anode, situated far from the cathode and the roots, is where the electrons go before moving to the cathode thanks to an external circuit [46] (Figure 2). The cathode, which is next to the roots and buried in the soil, receives the protons and electrons (Figure 2). At the cathode, the oxygen and other chemicals are reduced together with the protons and electrons to water and generate bioelectricity [46] (Figure 2).

The electrodes needed for the chemical reactions to take place are key components of MFCs. The voltage generated is dependent on the surface area of the electrode and the electrode material, especially the cathode which is the governing parameter of the biochemical reaction [44].

The soil in which the plan is buried is referred to as the supporting matrix of the PMFCs. While it is generally made out of soil, it can also be made with sediments. The supporting matrix can affect the PMFC's internal resistance [46].

While the components stay the same, there are multiple types of PMFCS set-up. The most common ones are single-chambered PMFCs where the anode and cathode are not separated by a membrane and double-chambered PMFCs where the anode and cathode are separated by a PEM (proton exchange membrane) or separator. The PEM prevents the diffusion of certain chemicals to the anode and allows protons to transfer to the cathode [46].

In research, the first mention of bryoMFC can be found in the First International PlantPower Symposium in Ghent, Belgium in 2011 [49]. In this project, they used a variety of moss referred to as *Dicranum montanum*. In a more recent study, Bombelli et al. [50] created a bryoMFC with a novel three-dimensional anodic matrix to enhance the physical contact between moss tissues and the anodic surface. They also compared the electrical output of bryoMFCs operated in sterile and non-sterile conditions. The paper proposes a new way to create bryoMFCs. For the set-up of the MFCs, they use platinum and carbon electrodes. In the end, they showed that the bryophytes *Physcomitrella paten*s can indeed be used in an MFC set-up to generate electricity. Furthermore, they determined that the electrical signal created was much higher with non-sterile bryophytes. This research contributed to the creation of MossFM [51], a radio exclusively powered by bryoMFCs, in collaboration with designer Fabienne Felder. In this work, 10 small bryoMFCs are connected to power a radio made out of electronic components and scrap materials. The radio is only able to work for a couple of minutes. This is due to the time it takes for the MFCs to charge the battery and its limited energy generation. This work offers a vision of the future where we collaborate with nature instead of dominating it.

If we look more broadly at MFCs, they are used and found in various art projects. Caravel [36] and Mudbots [52] are some examples of technology and MFCs being brought together to ask questions about microbial life and autonomous technology.

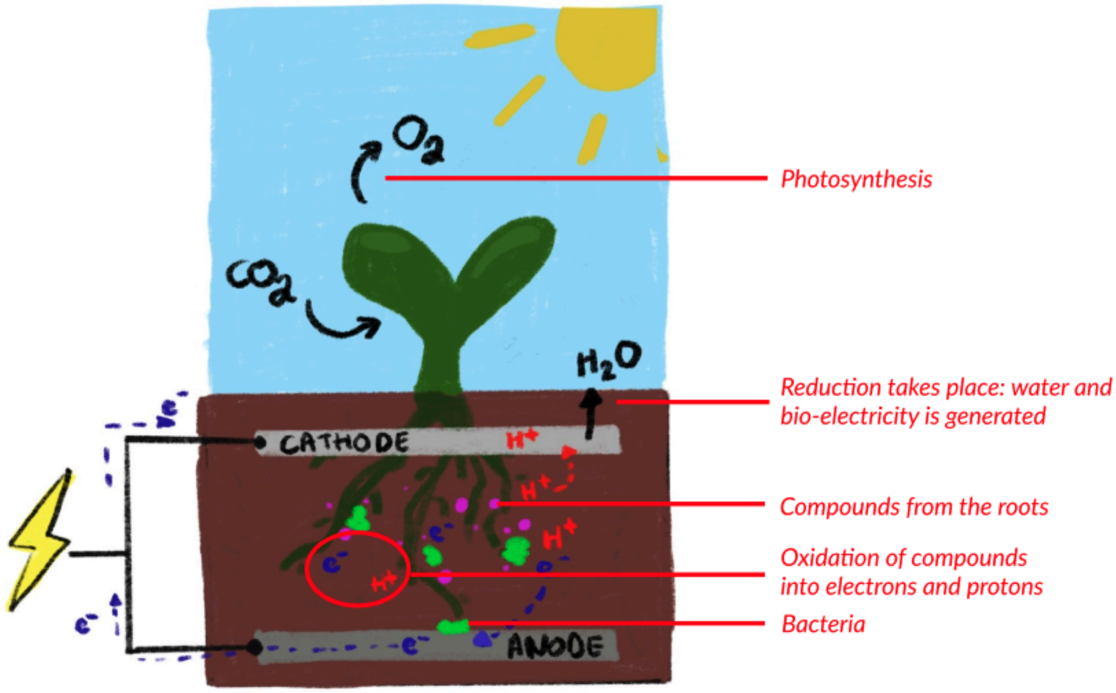


Figure 2: Simplified drawing of PMFCs energy generation.

5.2. About the Moss

Before even starting to build the bryoMFCs, I needed to find moss. To find moss, I first did a round of the city where I lived, in Delft. Since I wanted to keep my project contained and easy to reproduce, I needed to be sure that moss was easy to access. Turns out there are plenty of spots where you can find moss if you look closely, especially in the Netherlands where it is quite humid.

Moss likes shades and high levels of humidity, meaning you can find it alongside canals but also in the cracks of the pavements, old walls and the bark of trees. The moss alongside the canal of the Schie in Delft seemed optimal because there was a large quantity of it. Also, it was easy to collect due to resting on soil mixed with sand. Throughout the project the moss was collected at various spots along the canal, to make sure not to deplete the ecosystem. I also made sure to harvest as little moss as possible, which meant reusing the moss between MFC and working to keep it alive throughout the project. As this project explores plant-robot relationships, I also want to stay conscious of the species of moss and not leave a mark on the environment.

At home, the moss was kept in plastic containers covered with a lid. I found out that the lid was important to keep the humidity inside of the container. Moss thrives in environments with high levels of humidity. At first, I didn't have lids on them, but they turned quickly to brown and dried out. Only with lids can they survive properly, however like any plants they need CO2 so be sure not to close it completely. This also meant watering the moss almost every day for small containers and every three days for the bigger ones. For the placement, all the moss was kept away from direct sunlight in a corner of the room. In the later winter month of the project, when the sunlight was lessened, the moss was moved closer to the window to still catch some of the light. While moss doesn't like direct sunlight, it still requires photosynthesis. It’s easy to tell if the moss is lacking sun when it starts turning darker green. Finally, the moss should never lay directly on the anode of the MFCs, because it also impacts its health. Moss laid directly on the anode would die fast, so I always have a layer of potting ground, that is good for both indoor and outdoor uses, between the anode and the moss.

5.3. Building bryoMFCs

5.3.1. Process Overview

Throughout this section, I experiment with various builds of moss-powered MFCs. The objective is to maximize the voltage generated by the MFCs to power the robotic side. To achieve this, I led various iterations and tried, to find the best possible set-up. To facilitate the understanding of the process, I have created an overview of the process with its steps and the related section. The unexplored areas were also added as help for future research.

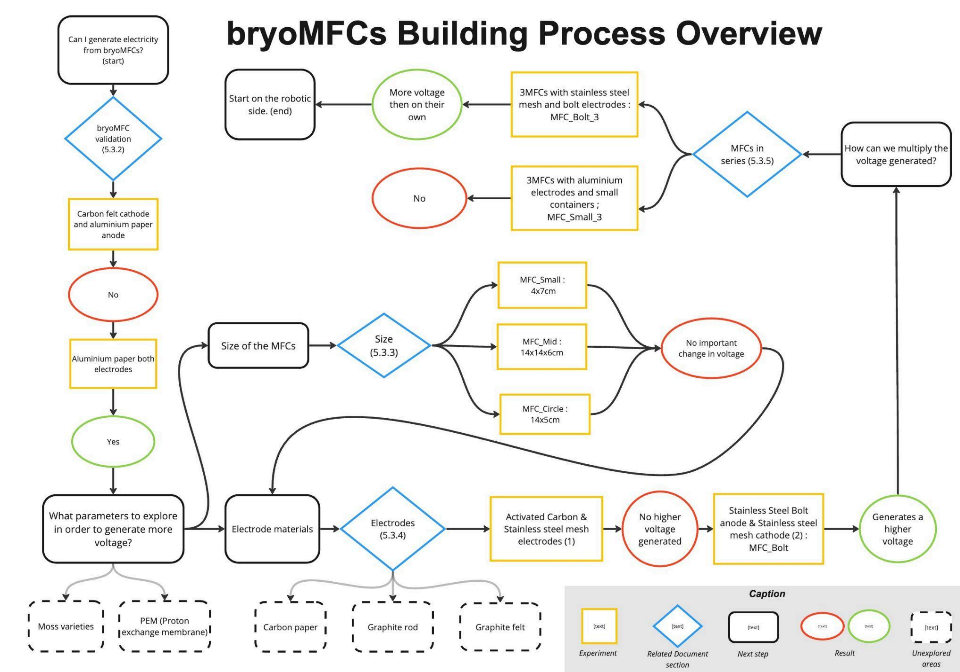


Figure 3: BryoMFCs Building Process Overview.

5.3.2. bryoMFC Validation

The first step of my process was to realise concept validation. The idea was to test if it was even possible to generate energy with bryoMFCs with cheap and easy-to-find materials. To do this, I used two DIY set-ups found online. The first one from Brayden Noh[1] on Instructables offers a simple step-by-step build using aluminium foil (cathode) and carbon felt (anode) as electrodes, and zeolite powder as dielectric. The dielectric prevents the electrons from travelling between electrodes, it separates the chambers recreating a double-chambered PMFC. It is also called an insulator. The other setup is inspired by a project blog[2] by two students. In this blog, they used aluminium foil for both the anode and cathode, as well as soil to separate the electrodes, for their first attempt.

For the first MFCs I made, I followed Brayden Noh's instructions to the letter. This means that the cathode, at the bottom of the container, was aluminium foil. The cathode (at the top) was a carbon pad from the brand SuperFish[3]. To each electrode, wires were tapped down with copper tape. The cathode and anode were separated by zeolite powder that I bought online. Zeolite powder is a mineral known for its ion-exchange properties [53]. It is used in the medical field thanks to its detoxifying, antioxidant and anti-inflammatory qualities [53]. It is a cheap and in-demand product, which makes it easy to find a nutrition and well-being website or even Amazon. Finally, the potting ground was added on top of the anode before placing the moss (see Figure 3, number 2). All of this was contained in a plastic food container with holes at the bottom so that the cathode would be in contact with outside air. The result of this first try was not successful, as MFC gave no electrical signal, even after waiting a couple of days. It's only after reading the tutorial again and taking apart the components, that I realised that I had bought a carbon pad and not carbon felt. Since I wasn't sure this was the problem, I decided to try making new MFCs without a carbon pad. Carbon felt is difficult to get for cheap so it was discarded as a potential electrode material.

The tutorial found on Hackaday.io involved aluminium paper for both electrodes. Taking inspiration from this build, I decided to use the same setting as before, but this time using aluminium foil for both electrodes. The set-up of the MFCs was as follows; aluminium foil for the electrodes, zeolite powder in between, potting ground and moss (see Figure 3, number 1). This allowed me to test if the carbon pad was the problem with the previous build. As a result, this set-up was able to generate around 0.06 volts of energy, putting at fault the carbon pad of the previous set-up.

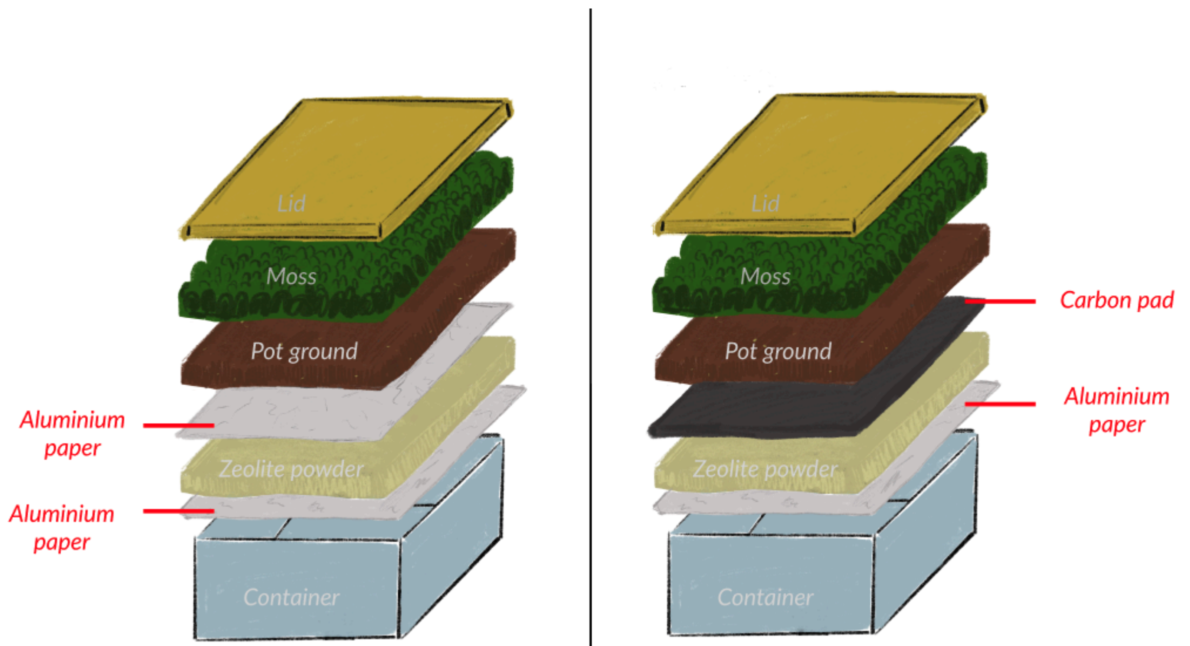
Furthermore, I decided to make other bryoMFCs using the full procedure from Hackaday to see if there was a difference. It meant replacing the zeolite powder with potting ground. The

[1] Indoor Moss Microbial Fuel Cell, Instructables, https://www.instructables.com/Indoor-Moss-Microbial-Fuel-Cell/
[2] Moss Microbial Fuel Cell, Hackaday.io, https://hackaday.io/project/185108-moss-microbial-fuel-cell
[3] SuperFish - Carbon Pad, onlinequariumspullen.nl, https://www.onlineaquariumspullen.nl/nl/superfish-carbon-pad.html

rest was the same (aluminium foil for electrodes). This MFC was able to generate around 0.01V of electricity.

In the end, both of the MFCs were able to generate energy as measured on the day they were realized. The Hackaday.io-based MFCs would produce 0.01V whilst the other MFCs using zeolite powder could generate around 0.06V. It isn't much energy but it proved that it was possible to generate a small voltage using MFC. However, for my application and circuit, there wasn't enough power to sustain the robotic side. The objective then became to build MFCs capable of generating higher voltages. Also, I deduced that zeolite powder was more efficient in separating the electrodes than potting ground.

The next step was to try and build MFCs capable of generating a higher voltage.



1. MFC setup aluminium paper as cathode and anode.

2. MFC setup carbon pad as cathode and aluminium paper as anode.

Figure 4: The two MFCs setups, 1. With a carbon pad cathode, 2. With an aluminium cathode.

5.3.3. Size

To generate a higher voltage, I first wanted to know if the size of the container had an impact on the voltage generated. Also, I wanted to see if the voltage of MFCs changed over time.

For that, three MFCs of different sizes were realized, based on the plastic containers I found at various stores. The setup of the MFCs was identical to the first build that created the most energy; aluminium for electrodes, zeolite powder for dielectric and moss from the same spot in Delft (see Table 1). The MFCs were set up side by side and were checked every day at the same time for a week. To check the voltage a simple multimeter and crocodile clamps were used.

As a result (see Figure 4), I observed that the activity of the MFCs varied constantly. On some days the voltage was much higher than on others. These changes can happen for multiple reasons, such as the growth of the bacteria or seasonal factors such as temperature or humidity [54]. Also, by looking at the table, it seems that the small MFCs can generate more energy on average than the other two. However, no proper conclusion can be drawn on which one is better, because of the lack of data points and similarity of results. Furthermore, after building the MFCs I realized that the circle shape was more challenging to work with since everything needs to be circle-shaped. This is inconvenient for the electrodes as they were to be made out of a different material than aluminium foil. In brief, the only clear conclusion is that all the voltages are too low to power any type of electronic device. The shape size doesn't seem to have a big impact on the voltage created as well. Overall, I still need to be able to generate more voltage.

MFC Name	Cathode	Anode	Dielectric	Moss	Container Size
MFC_Mid (18/09/2023)	Aluminium foil	Aluminium foil	60g Zeolite powder	Collection point and time: Schie, Delft, 18/09/2023 at 12h.	14x14x6 cm (square)
MFC_Circle (18/09/2023)	Aluminium foil	Aluminium foil	60g Zeolite powder	Collection point and time: Schie, Delft, 18/09/2023 at 12h.	14x5(h)cm (round)
MFC_Small (18/09/2023)	Aluminium foil	Aluminium foil	15g Zeolite powder	Collection point and time: Schie, Delft, 18/09/2023 at 12h.	4x7(h)cm (round)

Table 1: MFCs size and builds.

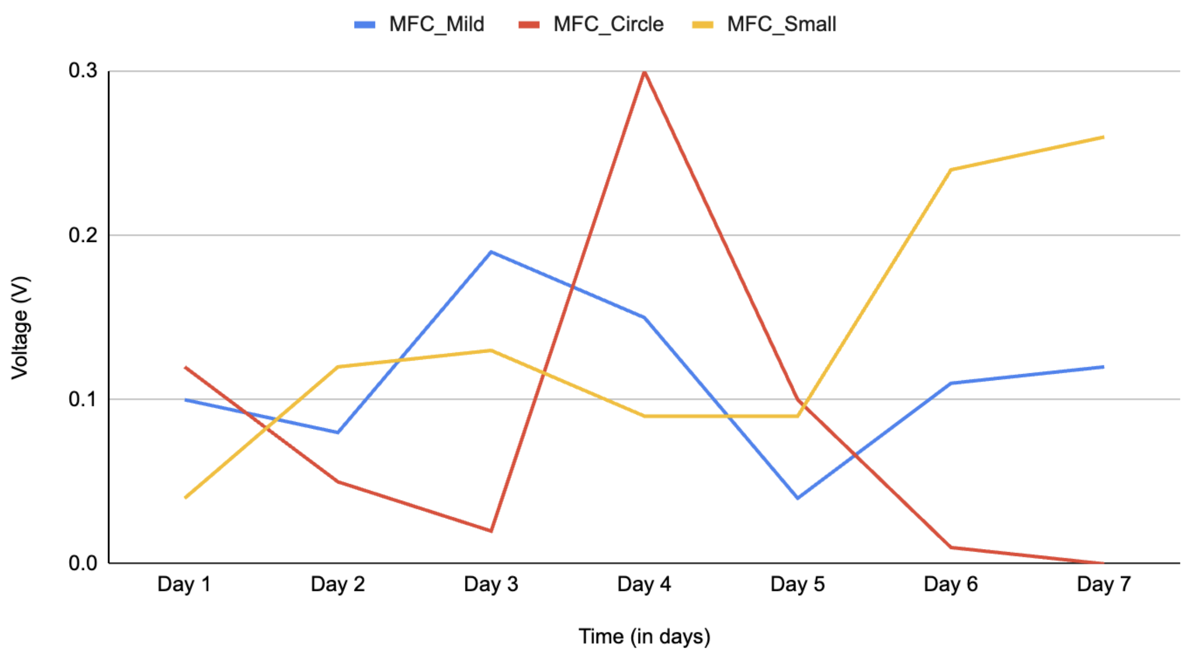


Figure 5: MFC_Mild, MFC_Circle, MFC_Small voltage generation over a week.

5.3.4. Electrodes

After trying to experiment with size, I wanted to find out if I could make new electrodes. Electrodes are key in the design of MFCs. They impact the MFC's performance in terms of electron transfer, bacterial adhesion and electrochemical efficiency [55].

In PMFCs, the ideal material for the anode should be conducive for electron transfer but also resist corrosion as cited by Ci S et al. in Mounia A. Y., Tou, I and Sadi, M paper [55], this is why carbon-based electrodes are preferred. Some examples of electrodes used for PMFCs are graphite felt, graphite granules, and carbon paper, with graphite being the highest electricity conductor compared to all of them [55]. This is because they are good at conducting current and thermal stability, not toxic for the plants and moderate in costs [55]. Furthermore, stainless steel has also been explored as an alternative material for electrodes. It has been proven efficient in various PMFC studies [55,56]. Even tho, graphite is more suited for MFCs in comparison to stainless steel as shown in the study [56] because of biocompatible problems [55, 56]. The biocompatibility problem comes from the lack of biofilm formation on the stainless steel, this biofilm is important to the various chemical reactions inside MFCs.

For the build of my electrodes, I decided to go with stainless steel, even if they are less suited for MFCs. While it is possible to find graphite rods online, they are pricey, especially if multiple MFCs are needed. On the other side stainless steel is easy to get on hand, especially stainless steel mesh. Stainless steel mesh is a good choice because they are resistant to corrosion, easy to shape into electrodes, and helps the chemical reaction that is reduction (which happens at the cathode) [55]. Furthermore, stainless steel mesh for electrodes is used in a pdf done by Matthew Halpenny[4] on Open Source Microbial Fuel Cells. In this pdf, the “DIY Mortar & Pestle Method” is used for making electrodes. Those electrodes are composed of stainless steel mesh and activated carbon. As said in the name it’s a DIY method so all the materials are easy to find online and it includes a step-by-step to reproduce at home.

In the next parts, I go over the various builds I realized with stainless steel to make electrodes. To test if the electrodes built worked, I always used the same MFC setup. It was composed of zeolite powder, potting ground and moss. The electrodes were always doubled, meaning the anode and cathode were the same. The voltage was first taken on day 0 of the MFC build and then checked randomly over a week.

1) **Stainless Steel and Activated Carbon**

For the first few tries, my reference was the presentation slide of Matthew Halpenny, with their stainless steel mesh (see Figure 5, number 1) and activated carbon build, which is the same as the video by “chemicum”[5]. The general idea is to glue activated carbon using epoxy to the stainless steel mesh to create a conductive shell around it. Then an electrical wire is connected to the mesh to drive the current.

For each electrode, the process was the same. First, I cut the stainless steel mesh into a shape adequate to the container, either using scissors or a wire cutter. Then the wire was connected to the mesh (Figure 6). After that, the epoxy glue was layered on the mesh before adding the activated carbon on both sides. Once it was done, I would lay them down on a piece of paper and try to press them down with a stack of books (Figure 7).

The first try-out of electrodes didn’t work with the complete MFCs set-up. This was because I had glued the wires down, which was problematic since epoxy is non-conductive and thus impacts the current flow. This first try made me realise that epoxy glue takes a long time to dry and needs a dedicated space to dry. After this, I paid extra attention not to glue the wires. Instead, they were woven into the mesh and in contact with both the carbon and the mesh (Figure 6).

On the second try, I took note of my past mistakes and tried again. Again, the electrodes didn’t work. This could be happening for two different reasons, either the stainless steel mesh wasn’t proper stainless steel or there was a problem with the carbon I had acquired. It turns out I had bought activated charcoal instead of activated carbon. They are almost identical but charcoal is made through the process of burning wood, whilst activated carbon is human-made and has a larger absorption surface which is preferred for chemical applications. So I decided to buy

[4] Matthew Halpenny, Workshop on Open-Source Microbial Fuel Cells, rencontres.hexagrams.ca, https://rencontres.hexagram.ca/en-ca/allcategories-en-ca/21-emergence-y/arselectronicacontributions/115-workshop-on-open-source-microbial-fuel-cells

[5] Microbial Fuel Cell - DIY Elbonian Style, chemicum, https://www.youtube.com/watch?v=_zCsAfEbVRc

activated carbon and see if it would impact the final result. Furthermore, working with epoxy glue was expensive since it is sold in small tubes that I had to buy again after each try. It was also a mess to work with. So I decided to use UV Resin instead, it was cheaper and faster to dry with a UV lamp.

I used the same stainless steel mesh and the new activated carbon for the third try. No electricity was generated from the MFCs with those as electrodes. My last guess as to what was going wrong was the stainless steel mesh. After some consideration, I bought a different type of mesh that was thicker (see Figure 5, number 3) than the previous one (see Figure 5, number 1). In this case, it worked only a couple of days later, with a higher voltage generated compared to before (~0.4V against 0.06V for the first working one). However, it stopped working shortly after which was problematic. The mutualistic relationship should be able to work for longer periods and the voltage should be more stable to be able to power a battery. In this case, I tried to replicate the electrode to see if it was a construction error, but it kept happening. Also one of the biggest problems here was that the electrodes could easily touch each other because of the thickness of the stainless steel mesh. The solution for that was to add more zeolite powder in between, but that ended up costing more money each time. So for this method, I recommend using a less thick mesh, such as the one shown in Figure 5 with number 2 (1mm thickness).

At this point, I was coming to an impasse. It wasn't able to make those electrodes work and they were quite costly to produce. I decided to take a step back and look at other potential solutions for the electrodes.

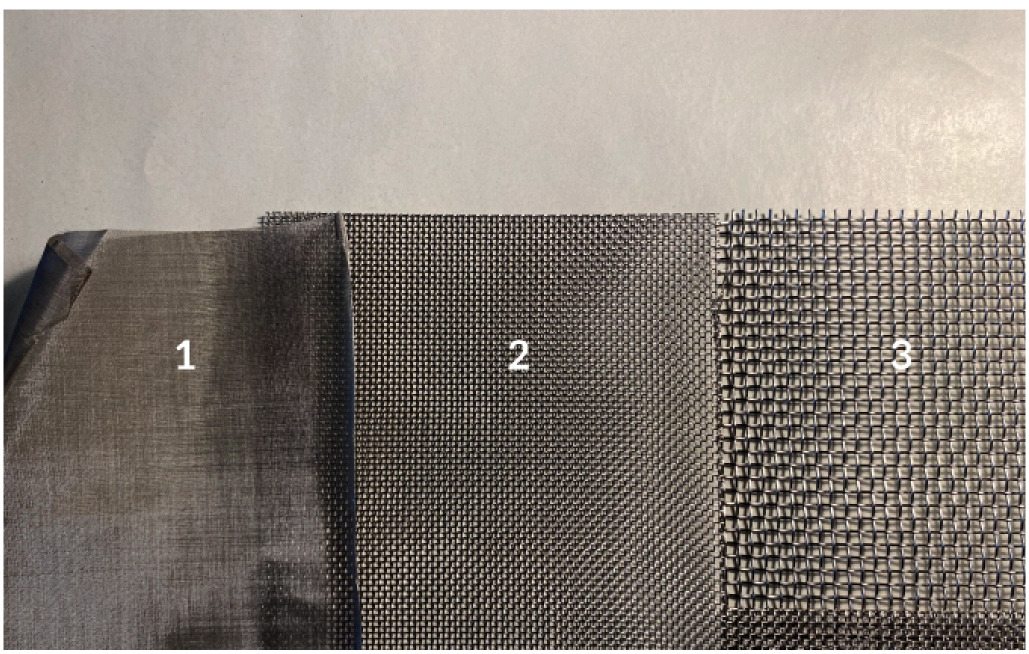


Figure 6: All stainless steel mesh used. 1 -80 µm, 2 - 1mm, 3 - 2.375mm

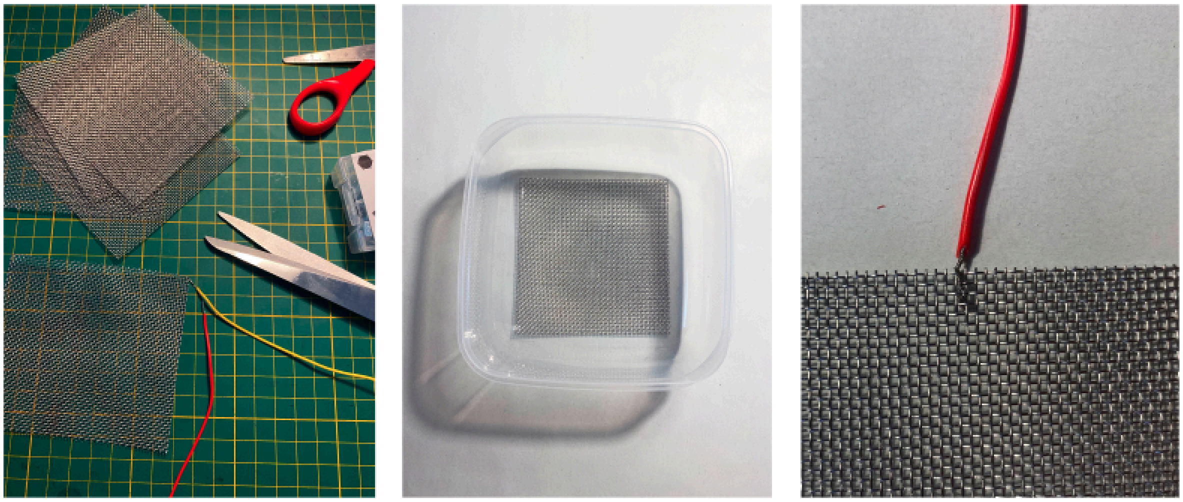


Figure 7: Cutting the stainless steel mesh to shape & adding wires.

Electrodes with activated charcoal powder. Electrodes with activated carbon pellets.

Figure 8: Electrodes activated charcoal and carbon pellets.

2) Stainless Steel Bolts & Stainless Steel Mesh

After unsuccessful attempts with activated charcoal, I decided to try without the activated carbon and rely on stainless steel bolts. The idea of a stainless steel bolt came from observing the MossFM project [51], which is also shown in the paper by Bombelli et al. [50] concerning MossFM. The paper doesn't only use stainless steel bolts, they also have carbon paper or platinum for the cathode and an anodic matrix constituted of paper pulp and carbon fibre. However, platinum and carbon paper are difficult to get, so I needed to replace them with an easy-to-find material. From previous studies, I know that stainless steel mesh works [55,56], so I decided to use stainless steel for both the anode and the cathode.

For this try, I used stainless steel/galvanized bolts for the anode and stainless steel mesh for the cathode. I refer to this build as the MFC_Bolt (Table 2). For this build, I bought a new type of stainless steel mesh that was less thick (~1mm compared to ~2,375 mm for the past one), so it would be easier and faster to cut into shape (Figure 5, number 3). The idea was the bolt would be both inside and outside of the container. To do that I made a hole in the bottom of the plastic container. Using scissors was unsuccessful as it would break the plastic instead of making a clear hole. The best way to do it was to melt the plastic using a soldering iron.

The MFCs set-up for this was the same as before. I made sure to cover the top of the bolt with zeolite powder so it wouldn't be in contact with the mesh (Figure 8). This worked from the first day on, with around 0.4V, which was promising. I decided to track the voltage to see how it would change over time. The result was that the voltage generated was pretty stable (Figure 9). It was able to produce more than what I had before. The overall voltage still seems too low for any application, but this can be fixed by building more MFCs and connecting them.

This set-up was promising because I was able to get a decent voltage out of them, but also they were easy to build and cheap in comparison to the activated carbon and mesh electrodes. The estimated price of all components for one single MFC is 5 euros. This decreases if more MFCs are made since most of the components are bought in bulk.

MFC Name	Cathode	Anode	Dielectric	Moss	Container Size
MFC_Bolt (14/11/2023)	Stainless steel mesh	Stainless steel bolt	60g Zeolite powder	Collection point and time: Schie, Delft, 18/09/2023 at 12h (re-used)	14x14x6 cm (square)

Table 2: MFC_Bolt set-up

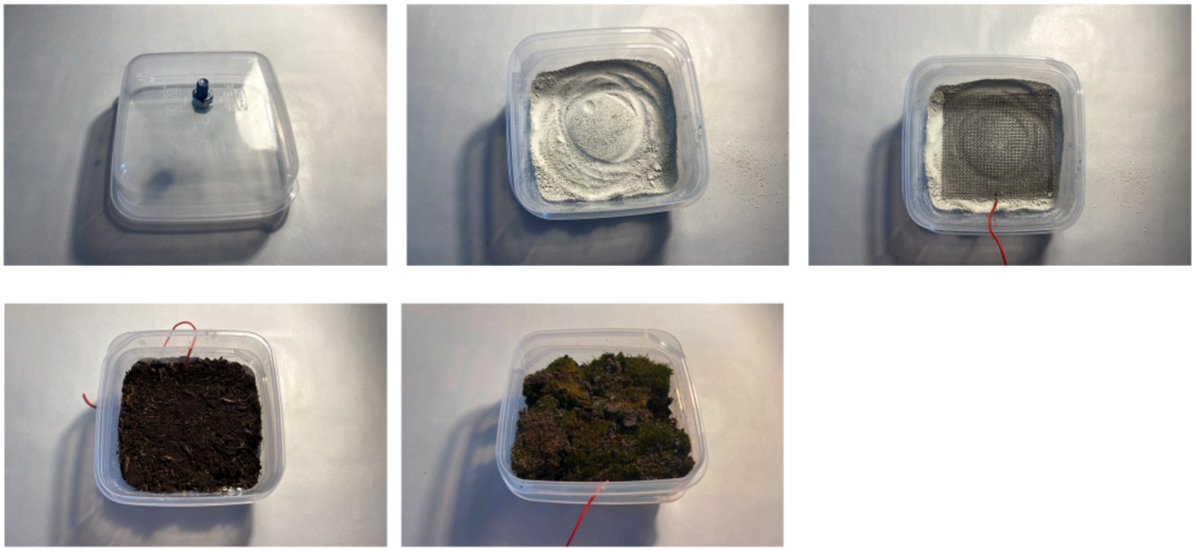


Figure 9: Step by Step of a MFC_Bolt build

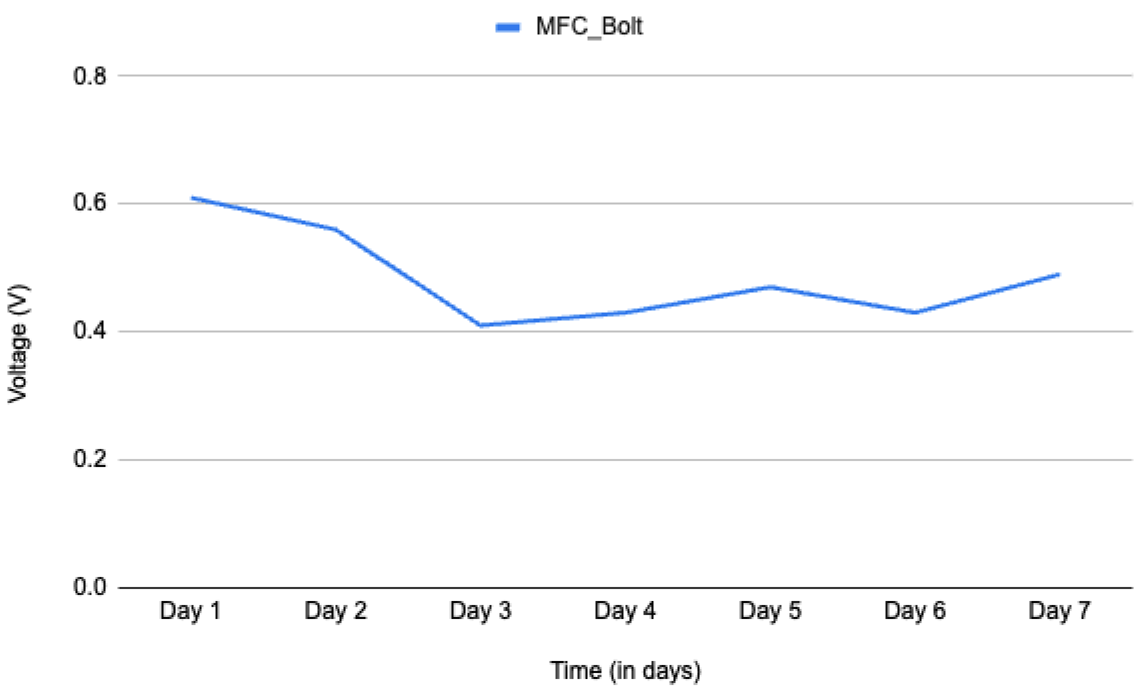


Figure 10: MFC_Bolt Votlage over a week.

5.3.5. MFCs in Series: Generating a Higher Voltage

On its own, one MFC does not generate enough voltage to power any appliances. To maximize the voltage created it is needed to build multiple MFCs and connect them in series. By connecting them in series it is possible to generate a higher voltage crucial for the robotic side to work.

To observe what would happen to the MFC voltage when they were connected in series, I built some more MFCs. On one side, the MFC_Bolt with a stainless steel bolt for the cathode and stainless steel mesh for the anode. On the other side, MFC_Small with the basic aluminium paper for both electrodes and small containers. I decided to try the aluminium electrodes because they were the only ones working out of all the MFCs I had made. I thought it was interesting to compare both and see if the aluminium electrodes could be a viable option.

For both types of MFC, MFC_Small and MFC_Bolt, the set-up consisted of 3 MFCs each. Each set-up was monitored for a total of 11 hours on the day they were built, to see the evolution of the voltage generated. The result was that the MFC_Small was only able to generate an average voltage of 0.02V, whilst MFC_Bolt had an average of 0.15V over one day. After this, I decided to monitor both MFC setups in series over a week to see the further evolution of the voltage over time.

As a result, I found out that the MFC_Small in series didn't generate voltage, or at least very little. The reason why the most likely due to polarity changes. It seems that the current direction would change randomly which would mean that the voltages were canceling each other. It is not clear why this was happening, it could be the electrodes being too similar or being too close to each other. This meant that I could not use this setup as it generated too little voltage for the robotic side.

On the other side, the MFC_Bolt in series were able to generate an average of 0.51V in a week, which is the most I was able to generate throughout the project. Overall, the MFC_Bolt in series had a better evolution than the MFC_Bolt on its own (Figure 10) and an overall higher voltage was generated. This shows that setting the MFCs in series helps increase the voltage generated. It seemed promising for the next parts of the project using energy harvesting, but also for the aim of building plant-robot mutualism using a DIY method. However, to validate this even further, measurements would need to be run on longer periods.

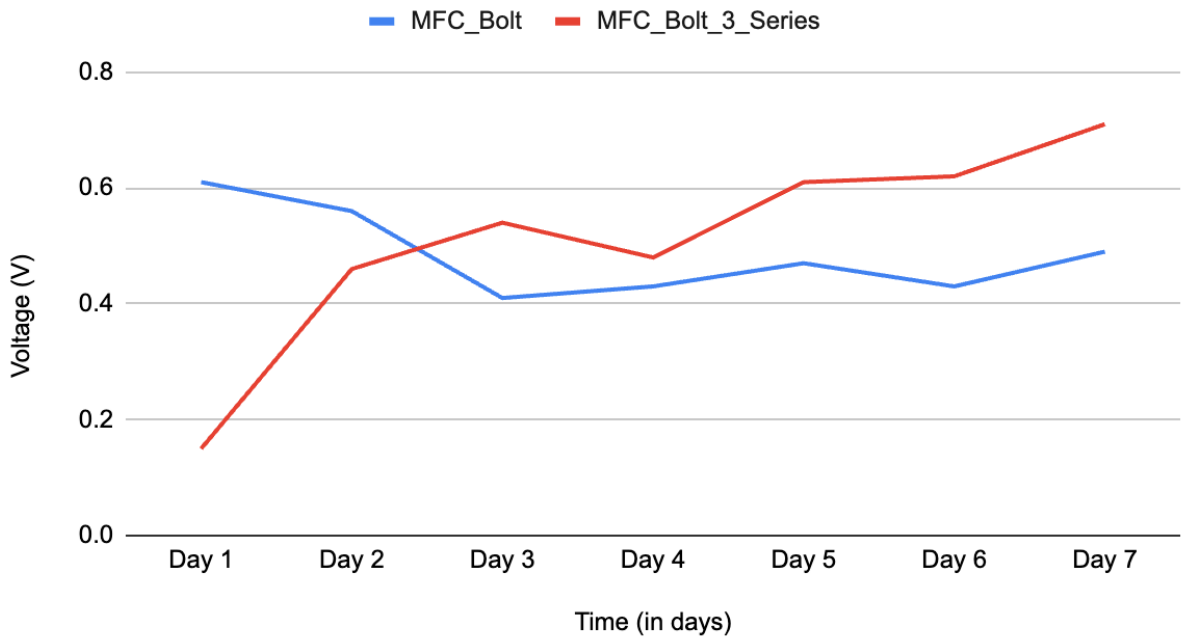


Figure 11: Comparison of MFC_Bolt and MFC_Bolt (3) in series over a week.

5.4. Discussion

While MFC_Bolt can generate a much higher voltage than the first working MFC realised, further modification could have been explored. In my process, I focused my attention on electrodes to amplify the voltage since it was easy to improve with cheap materials and the various literature on the subject. I briefly looked into the impact of the MFCs' size on voltage, but no clear results came out of it. Whilst it allowed me more freedom to work with the MFC containers, I only tested size with one type of electrode. It is possible that with the stainless steel bolt, the result would have been different. This is something to further explore. Furthermore, I did not look into other options for the membrane separating the electrodes (the zeolite powder) or the variety of moss used. Those are important whilst setting up MFCs and can impact the voltage generated. Also, with access to highly conductive materials such as graphite or graphene, it could have been possible to generate more voltage.

Overall, building electrodes was a complicated task because of the lack of clear guidelines or protocols, especially when it came to stainless steel and carbon electrodes. A lot was explored Furthermore, the results could have been improved if I documented my work more thoroughly and regularly. I didn't respect the first rule of research through design which is to be thorough about the process and what guided my decisions.

While the process could be improved, it did fulfil its purpose of raising awareness about the complexity of working with MFCs. It was foretold in the literature, but nothing compares to learning by doing. Ultimately, MFCs are powered by microbial activity, an activity which has phases. This means that the electricity generated is never the same and can fluctuate, which I was able to observe first-hand. It also meant a lot of randomness and sometimes misunderstanding. I could make six MFCs the same way and get different voltage generated, sometimes even no voltage. I wasn't always able to understand why. Also, I learned to take care of moss in a home setting. They need much more water than I imagined and a lid is crucial to keep the humidity high. MFCs are complex problems because they involve living beings. Working with MFCs means adapting to the cycle of life, not only with the microbial activity but with the needs of the moss. This knowledge gathered shows the challenges that plant-robot mutualism faces. The robot needs to be adaptable and aware of the cycles of nature. It should be able to work efficiently and only when enough energy is generated while giving back at the appropriate times.

In the end, I was still able to build MFCs that are capable of generating a high voltage and using cheap materials. Now it's time to see if it works to power the robotic application.

6. The Robotic Side of Mutualism: Harvesting Energy and Watering System.

This section focuses on the technical parts of mutualism and answers the question of how mutualism can be achieved. It relates to the development of the circuit, apparent to the robotic side of the relationship, diving into energy harvesting and watering systems. First, I discuss what the robotic side does in more detail before going into the process and result of building it.

6.1. Robotic Side: What does it do?

I was able to generate energy from moss using MFCs, completing the plant side of the relationship. Now, it was time to think about what the robot should give to the plant in exchange.

As talked about in the Shape of Plant-Robot Mutualism section, I had two main ideas for the benefits the robot could offer to the plant. The first idea was for the robot to give back by managing the sun exposure of the moss. The second was that the robot could give nutrients by watering the moss. However, it was clear from the low voltage generated by the MFCs that the possibilities for the robotic application were limited. It would be impossible to power a robot with multiple functionalities with the MFCs. The robot, or more the robotic application, needed to have low energy requirements while still functioning with easy-to-find and cheap electronic parts.

While the idea of a robot monitoring the sun exposure of the plant seemed interesting, as it would be closer to an actual robotic structure with movement, the voltage was too low to power a motor. Especially, to power the motor regularly throughout the day to adapt to the sun's position. Furthermore, to make sure the moss is never in the sun a light sensor would have been needed, adding to the energy demands of the robotic side. However, based on the MFCs results, it was clear that the energy needed to be managed carefully and that the application couldn't run constantly. This problem is also shown in the MossFM [50] work where the radio could only be active for a couple of minutes.

However, it seemed possible to find more low-energy applications for watering systems with mist-makers and dripping systems. Not only that but the moss itself needed a lot of water to survive, so it seemed beneficial that the robot would take care of the watering. Those are the reasons that pushed me in the direction of the robotic side taking care of watering the moss.

The main idea is that the robot would water the moss in exchange for energy, closing the circle of mutualism. To realise this, I need various electronics, such as a watering system but also an energy harvesting chip to collect the energy of the MFCs.

6.2. Energy Harvesting

Energy harvesting is a key part of the robotic system. It allows energy collection from the MFCs and its use for the rest of the circuit. Understanding its functioning and application is crucial for the development of the robotic side.

Energy harvesting is a technology built to collect small amounts of energy from various sources such as heat, vibration, radio waves and so on. They enable batteries that have finite energy capacity to charge back up, even in remote places. It can allow devices to be self-sufficient by letting them scavenge for energy physically or chemically from natural or man-made phenomena [57]. Photovoltaic panels are an example of energy harvesting; they convert the sunlight's heat into energy. Some other applications involve the harvesting of Kinect energy from passing cars to count their numbers [58].

However, energy harvesting comes with its challenges. First, only devices (microcontrollers) that operate on very little power can be used with energy harvesting and need to integrate self-shut-off functions when the power generated gets too low. Lastly, the device's duration of life is affected by the degradation of some pieces such as batteries.

In robotics, energy harvesters are found in various applications in the context of research. Energy harvesting is used in soft robotics with for example dielectric elastomer energy generation [59]. Some research about in-vivo nanorobots [60] also proposes a novel design for producible nano-particles using electrodes to harvest electricity from the blood serum, energy that can be later used for sensing and other activities. Energy harvesting is also used for classic robots, such as looking into the state of human walking-induced energy harvesting technology and the potential it could have for walking robots [61]. In the end, they conclude that energy harvesting on walking and wearable robotics seems more promising in efficiency if some specific problems are solved [61].

When it comes to MFCs, various energy harvester circuits are used to collect energy. However, advanced skills are required to build them for MFCs. This is discussed by Wang et al. [45] in their paper offering a review of the various components and methods used to create energy harvesting circuits. All circuits include maximum power point (MPP) tracking, which tracks the peak voltage and power of an MFC, and power management systems (PMS) which harvest the energy from MFCs and make it usable [45]. Some components of PMSs are capacitors, batteries, inductors, diodes and potentiometers.

Most circuits are complex to understand and replicate. However, it is possible to buy energy harvesting chips that encompass most of the requirements into a chip, such as the BQ25570 by Texas Instrument. The BQ25570 is capable of extracting low voltages from various sources like solar panels. It integrates battery charging and management features. It can also offer power to another possible circuit thanks to a buck converter. In his pdf on MFCs, Matthew Halpenny[6] discusses using the LTC3108-1 board. He explains how to adapt the board to make it usable to harvest MFC energy. It demands a lot of modification and addition.

[6] Matthew Halpenny, Workshop on Open-Source Microbial Fuel Cells, rencontres.hexagrams.ca, https://rencontres.hexagram.ca/en-ca/allcategories-en-ca/21-emergence-v/arselectronicacontributions/115-workshop-on-open-source-microbial-fuel-cells

While it is challenging, the development of energy harvesters pushes forward the wish to power devices without access to electrical plugs. Furthermore, energy harvesting relies solely on renewable energies, meaning that investing in this technology could lessen the use of fossil fuels and help with the climate crisis. It could also allow us to create technologies that are less energy-reliant and built to last in remote areas. As an evolving field, it raises questions about the autonomy of future technologies.

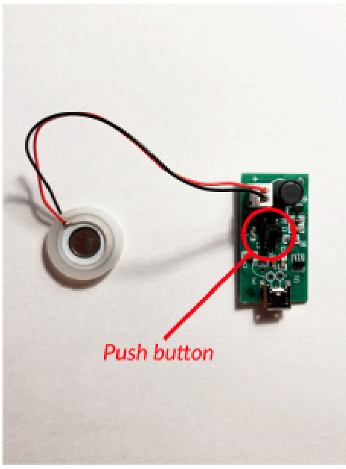
6.3. The Circuit

With the decision to focus on a watering system, I started working on assembling the circuit. At the core of the circuit, is the energy harvesting chip, which allowed me to store the energy of the MFCs in a battery and then power the watering system.

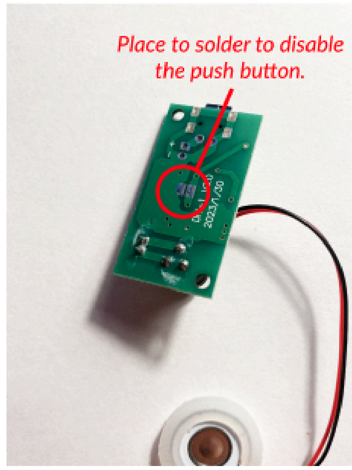
6.3.1. Watering System

The first part was to figure out what to use to water the moss. There are various types of watering systems, like water pumps, but they require high voltages. For my application, the device needs to be low-energy and cheap.

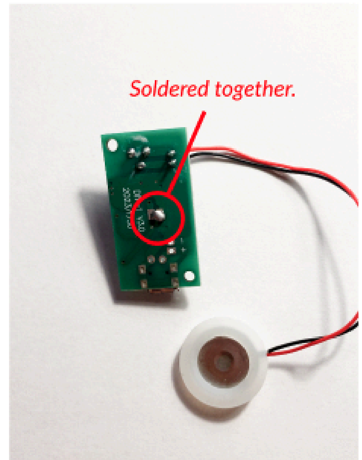
I decided to go for a mist-maker (or vaporizer) because, compared to the other systems, they didn't require too much energy. They were also cheap, around 4,5 euros per piece, and easy to find. The mist-maker selected is the Ultrasone Mist Maker OT3322-F41. It requires 5V and 300mAh to work, which seemed like a lot compared to what my MFCs could output. However, after some tryouts, I found out that it could function fine with a 3.7V battery at 250mAh. The spray was less efficient but it did enough to water the moss. Finally, while the OT3322-F41 includes a press button to activate it, it is possible to disable it by soldering parts of the board (see Figure 11).



Mist Maker (OT3322-F41) front side.



Mist Maker (OT3322-F41) back side.



Mist Maker (OT3322-F41) back side with soldered push buton.

Figure 12: Disabling the push button of the mist maker.

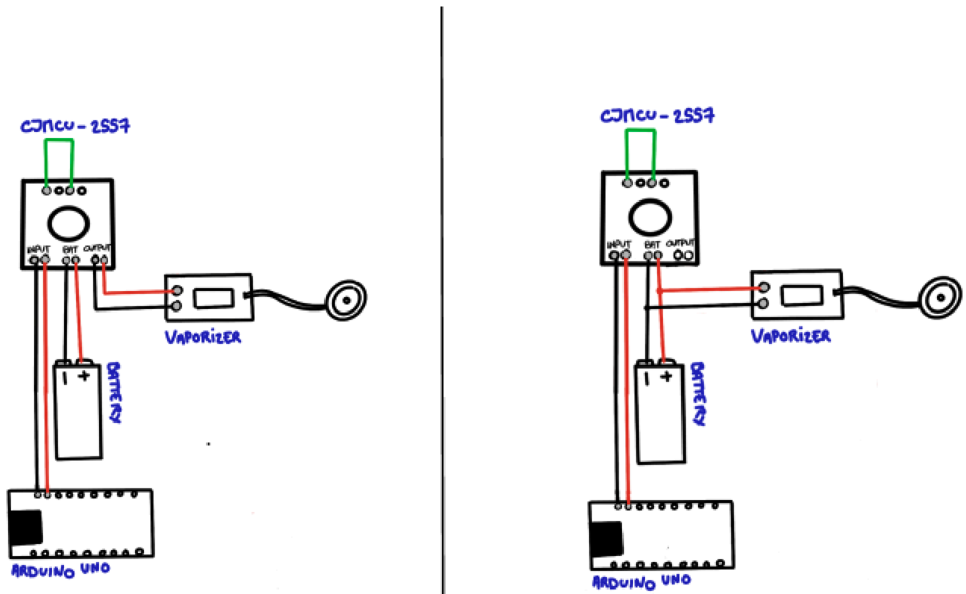
6.3.2. Energy Harvester

Now, my objective was to understand the energy harvester and set it in action. The energy harvester I'm using is the CJMCU-2557, a knock-off version of the BQ25570 by Texas Instruments. It resales for around 8 euros on AliExpress without the shipping costs. With this energy harvesting chip, it is possible to extract the voltage generated by the MFCs and use it to charge a small battery or capacitor. In more detail, the CJMCU-2557 is an IC capable of harvesting low voltages, as low as 100mV, and transferring it to the battery of choice. It includes a battery management system so as not to overcharge or discharge the battery. Furthermore, it can set small voltages (>=0.6V) up to 5.5V thanks to its boost converter. For the chip to work, the pins GND and EN need to be connected and the starting voltage should be up >=0.6V.

First, I tried to charge a battery using the energy harvester. Since the IC includes a battery management system, I chose to use a lipo battery of 3.7V and 250mAh. To charge it, through the energy harvester, I used Arduino Uno 3.3V as input, instead of the MFCs, and connected the battery to the battery pin. It worked accordingly and I was able to charge the battery safely and fast.

Then, I decided to add the mist-maker to the system. This means that my energy harvester received input current from the Arduino (3.3V), then charged the battery and used the rest of the energy to power the mist maker (see Figure 12, number 1). While trying it out, I realized that the energy harvester was only able to output 2.5V at the OUTPUT pin and nothing more. After looking at the datasheet, it was indeed confirmed that it could only output 2.5V at the OUTPUT pin. It was problematic since my mist maker needed at least 3.7V to work. Furthermore, no other water systems could work on 2.5V or less.

To solve this problem, the energy can be taken directly from the battery pin (see Figure 12, number 2). This is what atomic14 does in his YouTube video[7] where he uses the same energy harvester (CJMCU-2557) to store the energy of a solar panel and then activate an LED screen. It helped explain in more detail the workings of the chip and how he set it up. However, that meant adding a low-powered microcontroller to activate the mist-maker when needed.



1. Mist maker connected to the OUPUT pin of the Energy Harvester (CJMCU-2557)

2. Mist maker connected to the BAT pin of the Energy Harvester (CJMCU-2557)

Figure 13: Diagram of the two setups with the Energy Harvester (CJMCU-2557) and the mist maker.

6.3.3. Microcontroller

Since I couldn't use the OUTPUT pin of the energy harvester and needed to rely on the battery input, I needed to add a microcontroller. More specifically a low-powered microcontroller that would not drain the battery whilst the MFCs were charging it.

[7] atomic14, Harvesting Solar Power for Low-Energy Electronics: Can We Run Forever on Scottish Winter Sun?, Youtube, https://youtube.com/watch?v=fRfm0HUeX4o

I decided to use the XIAO ESP32S3 by SEEED Studio. The ESP32S3 is a low-powered microcontroller that can work with a 3.8V at 22 mA battery set-up. The XIAO ESP32S3 microcontroller can be coded to enter a deep sleep mode. In this deep sleep mode, the microcontroller does the minimum and uses around 14 µA, which means it should not drain the battery. Also, the XIAO ESP32S3 uses Arduino IDE which is a coding language I am familiar with and is easily accessible to anyone wishing to reproduce the project.

The first task was to understand the deep sleep mode and how to implement it. The ESP32S3 cannot read the values of the battery, which is a missed opportunity, since it would have been optimal to take it out of deep sleep only when the battery was fully charged. Instead, I used an internal clock to turn the deep sleep on and off. It means the ESP32 would go to sleep and wake up when the timer reached its given value, for example after 1 hour.

The code was easy to implement since it is possible to find it in the documentation of the chip. Using the ARDUINO IDE, I simply uploaded the code directly to the microcontroller. Using the deep sleep code, I tried various lengths of sleep time. Everything worked accordingly.

Now that the ESP32 was coded to go into deep sleep, it needed to activate the mist-maker when out of deep sleep mode. To do this, I used a N-Channel MOSFET (IRLB8721). The MOSFET acts as a switch for the mist-maker. When the ESP32 wakes up from deep sleep, it puts the MOSFET gate on high which allows the current to pass and turn on the mist-maker. The rest of the time the gate is set on low, which prevents the current from passing through. I coded the mist maker to work for 15 seconds, enough to water the moss. Everything worked fine when I used the Arduino UNO as input.

Now it was time to test out the circuit with the MFCs as input. Before that, I coded the ESP32 so that deep sleep mode lasted 6 hours, to leave a chance for the MFCs to charge the battery. It worked at the start, with the mist-maker turning on, and then the ESP32 going to sleep. However, after 6h the vaporizer did not turn on, which was surprising because even if the MFCs didn't charge the battery much it should still have enough energy to activate the vaporizer one more time. By measuring the battery, I realized that it was empty. My first instinct was to change the deep sleep cycle to a longer one and shorten the mist maker's working time. The deep sleep mode was set to last 12 hours and the mist-maker was to work for 6 seconds. With this setup, I tried again to make it work, but the same thing happened. The battery was fully drained and showed 0V, which was a bad sign for the life of the Lipo battery.

After reflection, I realised that I didn't use the MOSFET correctly and used the output of the ESP32 to power my mist-maker instead of directly using the battery. I changed the circuit so that the ESP32, MOSFET and the mist-maker would all be taking energy directly from the battery pin of the energy harvester (Figure 13). Also, I changed the battery to a new one, just to eliminate the possibility that it was defective. When I tried to circuit, nothing happened. The battery was again fully drained.

It seemed that the microcontroller was draining the battery too fast compared to what the MFCs were capable of producing. Even in deep sleep mode, it seems to be too energy-hungry. The first possibility was that the deep sleep mode was not working and thus using more energy. With some tests, I tried to find it was indeed going to sleep and waking up according to the timer. For that I connected the microcontroller to a laptop and had a serial monitor warn me when it went to sleep and woke up. For both 3h, 6h and 12h, the microcontroller deep sleep mode worked as expected.

This meant that the problem was most likely due to the microcontroller draining too much energy. By connecting the microcontroller in deep sleep to the 3.7V 250mAh battery and monitoring it every hour, it became clear that this was indeed the problem. The battery would drain totally after 2h of being connected to the microcontroller. It was the same result with a 3.7V and 350mAh battery. This problem can come from multiple sources, either the microcontroller is defective or it's a problem with an internal short-circuit, the soldering of the battery was not done properly, or the performance of the data sheet doesn't match reality. From a quick search online, it seems that it might be due to code performance or using the ARDUINO IDE.

Overall, it seems that they aren't blocking issues for the robotic side. It would need more time to be explored and tinkered with, time that I didn't have at hand with the end of the project. I stay confident that with more time, I will be able to fix the issues and make it work. Also, for now, the problem can be solved partially, by using an external source of energy or human interaction for example. The microcontroller could be powered with an external source, so it doesn't collapse the battery. It means that the vaporizer would still be powered through the battery that is charged by the MFCs. Another idea could be to remove the microcontroller and simply press manually the button of the mist maker. This way the battery wouldn't drain. However, none of those solutions are satisfying for the plant-robot mutualism. The plant-robot mutualism becomes dependent on humans or current energy, which is not something I want. I want it to be fully independent and remote from humans.

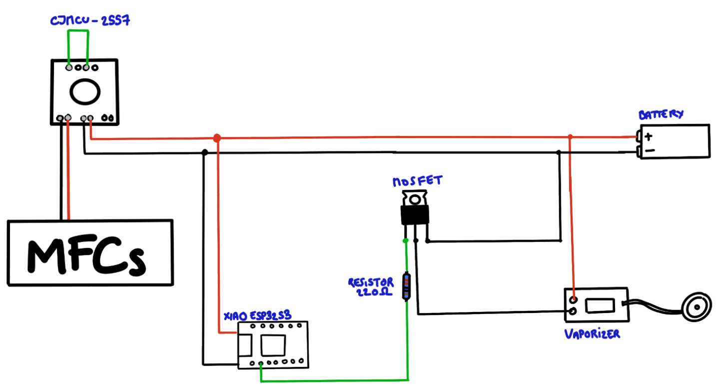


Figure 14: Drawing of the connections of the final circuit.

6.3.4. Charging the battery

While I couldn't debug the circuit, I decided to see how much the MFC could charge up the battery. The idea was to see how long it would take for the battery to charge and by how much. If possible, it would confirm that the MFCs are generating enough voltage to feed the robotic side and it's only a question of adjustments.

For this test, the battery was connected to the BAT pin of the energy harvester while the MFC was connected to the INPUT pin. The GRND and the EN of the energy harvester were connected to allow the IC to work. The MFCs used were 3 MFC_Bolt set-ups in series as we know they are capable of producing the most energy out of all the builds done before.

On the first try, I was able to charge the battery up to 0,02V in 24 hours with an overall MFC power of 0,8V. This wasn't promising, as it would take a long time to charge a battery up even 0,1V. Meaning that the MFCs could only be watered every couple of days by the robotic side.

I then tried a second time but wasn't able to charge the battery at all, even after 24 hours. What I realized during this time is that the input voltage on the energy harvester was only 0.2V, meaning that a lot of electricity was lost. I tried again, this time with more MFCs in series (5) to see if it would improve the voltage at the input pin, but even with a MFC voltage of 0.9, the multimeter would read 0 Ah and not charge the battery even after 48h. Then, I went back to 3 MFCs in series, and it still didn't work and gave me 0 amps.

The possible reason for this is that the MFCs were still new on the first try, meaning that the internal resistance was low. This resistance went up over time impacting the power of the current and the charging of the battery, which is a problem known to MFCs [61]. The power of the current is too low for the energy harvester to catch it up, maybe another chip or circuit will see a different result.

6.4. Discussion

Throughout this part, I encountered various problems that I could not solve completely in the end. While the process of building the robotic part of the mutualism wasn't successful, a lot was learned. This learning can help in further exploration of mutualism and serve as a future direction to work towards in the future.

The first problem is that the microcontroller drains the battery. While I wasn't able to find an alternative for it in the time given, I believe that is possible to fix the problem. Also, other solutions could be explored to replace the microcontroller, such as an on/off switch and a timer. It's a question of researching alternatives and trying over again till the problem is fixed.

The second problem is that the MFCs aren't able to output enough energy for the battery to charge. This could have been prevented by working on the MFCs and Energy Harvesting at the same time. Also, I focused on one energy harvesting chip, but there are other solutions. Matthew Halpenny with his pdf does propose a circuit to harvest energy for MFCs. While it requires more time and parts, it is still within reach. It could be interesting to try his circuit with the MFCs created in the last section, to see if the result would be any different. Furthermore, the mist-maker requires quite a lot of energy compared to the rest of the circuit. A low-voltage alternative to a watering system could greatly improve the energy needed. Such as a simple latch opening for the water to fall. Exploring even more low-powered alternatives could bring forth new possibilities to shape the plant-robot relationship.

The last problems come from the process. A lot of it was done blindly, but planning small experiments to test parts of the circuit would have been a great help and direction. For example, before doing the whole circuit, I should have seen how the microcontroller and the battery worked together. By planning those experiments and deepening my understanding, I would have managed my time more wisely and spent less time trying over and over again. Furthermore, I believe enrolling someone with experience in low-powered electronics would have been of great help.

As a result of this section, I only have, for now, a concept of what a working prototype could be shaped like. Whilst the parts work separately, the robotic side and MFCs, have yet to work together. The MFCs not being able to charge the battery is a critical problem that requires more time and attention. If the battery can't be charged that means that the mutualistic relationship isn't viable. For now, I cannot say that I did manage to create a working plant-robot mutualism.

While I cannot solve those problems within the time frame of the project, they are not impossible to fix. With more time and iteration of the MFCs set-up, it could be possible to find a suited setup for the utilisation. The fact I was already capable of generating a voltage of 0.8V with the MFC_bolt setup in series sets us a step forward to the creation of cheap and easy-to-reproduce MFCs. This comforts me with the fact that it will be possible to realise a working plant-robot mutualism, especially if the right materials are used for the electrode. It is a step forward to building a viable prototype of plant-robot mutualism.

7. Result: Demonstration of Mutualism

Whilst the prototype isn't fully functional, it is still possible to demonstrate mutualism. The demonstration discussed in this section is based on the learning experiences gained throughout the prototyping and stays aligned with my original shape. As a result, I came up with a demonstration of mutualism that takes on two different shapes. The first is an installation, where mutualism becomes an object and is used to spark the first interests in mutualism. Then, the second part is a guide retracing how to build the same prototype as I have done, to make my research accessible and the wish for it to be built upon. Foster a community around it where plant-robot mutualism is explored.

7.1. The Installation

7.1.1. The need for an installation

While I never shared or showed the prototype to everyone, my project was often a topic of conversation. At first, I would present it as a research exploration of mutualism between plants and robots. It would make people frown. It seems that nothing would come to mind, or at least nothing exciting. Interest would only spark when I explained the idea of a relationship based on equal exchanges of benefits between robot and plant, and the idea for robots to be covered in plants. Gears would start turning in people's heads and they would instantly start asking questions. Some wondered about the more technical aspects and some about the potential real-life application of such relationships. All those exchanges made me realize the curiosity and spark that plant-robot mutualism can create. It has the potential to help foster conversation about their relationships, but also about our relationship with both of them.

Those discussions showed the need for a visual depiction of the relationship. The importance of making it tangible. Multiple times I was asked for pictures of the prototype, but the prototype even in the latest version is rough-looking. It is only boxes connected to a small circuit. As a result, it misses the mark of being visually striking for an audience and attracting attention. People can't see either the robot or the plant, even less how they interact with each other unless explained. In this state, it cannot be used to showcase mutualism on its own.

However, if it were only about demonstrating mutualism and fostering curiosity, a Wizard of Oz prototype would work perfectly. It might not be actual working mutalism behind the scenes but looks like it to the audience. For example, the microcontroller could be powered by an external source, so as not to drain the battery as much and be able to power the vaporiser. A Wizard of Oz would allow gathering people's reactions and starting a discussion on the topic without the need for it to fully work.

This installation would need to highlight the plant-robot exchange of benefits. The audience should be able to understand with a glance what is happening. While it would be easy to create a fancy robot, I believe sticking to a simple design would be more telling about the actual difficulties of mutualism and its beginnings. By creating an installation showcasing mutualism, it would be possible to foster interest in mutualism but also gain insights into what people think of the subject. People's feelings and emotions are a key part of design. They can help find new shapes and needs for the object in question. Opening the discussion could lead to new design problems and help refine the areas of work for the final prototype. It could help broaden the topic of mutualism, and maybe open the door to research the impact of robot-plants on Human Robot Interaction (HRI).

7.1.2. Key Points for the Installation

Throughout the process of prototyping and discussing my topic, I gained various insights that can help to form a comprehensible installation showcasing mutualism. Those insights can act as key points when building the installation.

First, moss is a living being and should be cared for. The need for the right sun exposure and water is crucial to keep the plant alive. This means that a functioning watering system is essential in the installation as well as a cover on top of the MFCs to keep the moisture contained. Optimally, the mist maker and the MFCs would be in the plastic case, allowing the audience to see whilst keeping the humidity high inside. For the vaporizer, it is usually hard to see in the light of day, so a dark background could make it more visible to the audience. Also, it's important to take into account the need for a water container for the vaporizer to be able to work.

Furthermore, this installation is about mutualism and that should be understandable from a glance. On their own, the moss, energy harvester and vaporizer have difficulty conveying the idea of mutualism. The audience needs to understand that they aren't separated but actually exchange benefits and can only work when together. Placing them all together in the same space or box can help with that as it gives the impression of a holistic system. Seeing the connection of the MFCs to the battery can show the connection. This could be taken even further by adding sensors and information, for example about the voltage produced by the MFCs in real time.

While the installation can use a Wizard of Oz technique for some parts. It needs to stay realistic. MFCs produce voltage based on the microbial and moss cycles, which means it is inconsistent and takes time. The mist maker should only run for a short time or every hour but on a plant-like schedule. The plant schedule reflects the need for water, which was 3 days for the bigger containers, and the potential long time it would take for it to charge a battery. It means that the installation would only go a couple of times during, for example, an exposition. The inclusion of a countdown to the moment the mist maker turns on could bring excitement to the audience.

As it is the energy harvester and vaporizer system doesn't look like a robot which can be misleading. Spending time to find ways of making it look more like a robot could be beneficial for the understanding that this is a work where robots meet plants. However, the balance to maintain here is complex as I believe the installation should stay simple and realistic, staying true to the challenges of mutualism. The idea here isn't to offer a utopian vision of mutualism but grounded in the realities of it, whilst still conveying its prime idea of robot and plant exchanging benefits.

7.1.3. Proposal for a future installation

While it is out of scope to realize the installation, I propose a potential design to demonstrate mutualism with an installation based on my prototype and using a Wizard of Oz technique. This design is only an idea and does not take into account the challenges of building it. Its objective is to spark interest in potential visitors and relay the message of plant-robot mutualism (Figure 14).

The MFCs and the vaporizer are all situated under a plastic dome to keep the moisture in. The MFCs are propped on a stand, for the audience to see the full MFCs and how they are connected, as well as the rest of the circuit. This stand is situated on a box that hides the rest of the electrical devices that power the vaporizer, such as a battery and the microcontroller. For the audience to understand it’s a mutualism between robot and plant adding some extra information could help. For example, the bottom part which holds the electronics could include an LED screen with the real-time voltage the MFCs are producing or the battery being charged. It’s a complex balance because I believe it should stay simple and realistic. No complete robots can be powered by plants and the audience shouldn’t believe it could yet. I want to reflect on the difficulty of maintaining the relationship. For this reason, the vaporizer should also turn from now and then, to show that it works but also it takes time for the battery to charge thanks to the plants. It would be interesting to include movement to make the electrical part seem more robotic. I thought about adding movement to the watering system, but that would require using a different system than the vaporizer since it needs to be in contact with water to work. Furthermore, it’s also important to think about when the timer would enter into action.

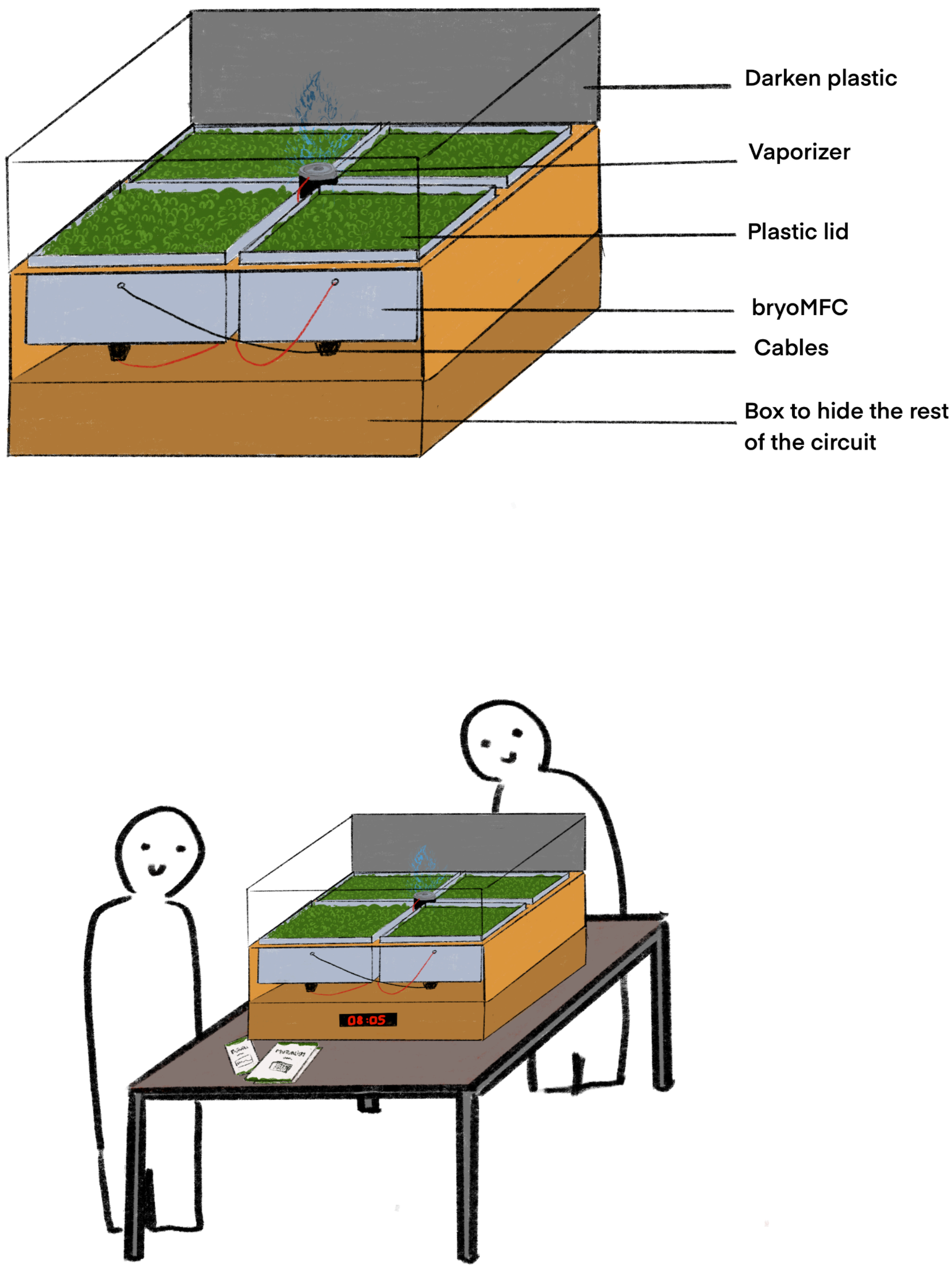


Figure 15: Installation Sketch

7.2. Guide to Mutualism

In this section, I explain why I believe a guide is a relevant result for my research, before explaining how the guide was realised.

7.2.1. Why a guide?

The installation is great for capturing people’s attention and creativity, however, it does not show or explore the complexity of mutualism. Throughout the prototyping, it became clear that mutualism is challenging to realize on a technical level. Not only does it require various cross-disciplinary skills, but also loads of searching for information. For bryoMFCs, the number of DIY set-ups was small and most of them lacked information. It was difficult to understand in detail, especially with the lack of pictures to support each described step. In research papers MFC set-up information where missing or unclear which made their reproduction impossible. On the other side, energy harvesting in the case of MFCs, information was also lacking or required complicated circuits. I had to rely on YouTube videos and the presentation by Matthew Halpenny, but even then it was complicated. This lack of information makes robot-plant mutualism hard to reach.

Throughout my project, I have accumulated knowledge about how to realize a simple mutualism, something that I could not find. I made various MFCs and played around with energy harvesting. Ultimately the final prototype tries to combine everything. While it is not fully functional, it can still be used as a basis for further projects. With more time and tinkering, it could work. As a result of this research, I have accumulated knowledge that I believe is useful and can help people explore mutualism on their own.

This lack of information and my work are the reasons why I believe a guide is needed as an outcome of this research. In this guide, I want to share how to build the final prototype from scratch. All in the idea to give free and easy access to my learnings and findings. It is driven by the wish to reach a broader audience and maybe have people build from it. Furthermore, it is a great addition to the installation. While the installation showcases mutualism, the guide invites the audience to try it for themselves. This is key because I believe only by building, or seeing how it is made, can they understand the complexity of mutualism. Mutualism is about living on the moss and bacteria time scale. It is an act of precise balance where one party cannot take more than the other one.

7.2.2. Creating the Guide

1) The design

For the design, I kept the design simplistic in order not to take away from the step-by-step process. I used science protocols as inspiration because I believe it is familiar to most people and they are straightforward step-by-step instructions. Science protocols have a very minimalist design with only black and white text. They have a clear structure thanks to titles, bullet points, and bold and underlined words. All of those notions were kept in mind throughout the guide. The guide includes titles and page numbers for easy guidance. Also, the two parts of the guide can be viewed separately from each other, so that people choose what to focus on. However, I added colors to make it more inviting. The color palette is green, white and black. I picked green because it connects to the moss side of mutualism and its link to green energies. Furthermore, contrary to science protocols, I added pictures and drawings to make it enticing but also add clarity. The border of the guide is green to give a plant feeling but also a DIY approach. While inspired by a science protocol, it is not a science protocol, but more crafting projects (Figure 15).

Finally, the text was kept to a minimum and easy to read. In its final form, the guide doesn't teach about mutualism. It explains how to replicate my prototype. It is an extension of the installation, a way to be transparent and give an idea of what it takes to realize it. Optimally, the installation would use the same setup as the guide and not Wizard of Oz, once all the parts worked together.

2) Electricity from Moss: BryoMFCs

In terms of information, the guide contains the minimum necessary to understand what are bryoMFCs and what the setup used in this guide is. The guide doesn't teach about the mechanics behind MFCs, but still wishes to offer a simple explanation of how they work. All the content is based on what is written in this paper.

When it came to the MFCs step-by-step, I wanted the information about the materials to be specific as well as the quantities. In other DIYs, it was not always clear what was needed and this got me into complicated situations, for example with the thickness of the mesh or the carbon/charcoal dilemma. Also, the steps have detailed descriptions and pictures to make them easy to follow. All the pictures are taken by me using an iPhone camera and a white surface as background. Some concepts were difficult to picture, such as the structure of the MFCs or how to connect them in series. This is why I relied on simple drawings to express those ideas more clearly and arrange the information as preferred. I tried to keep the style of the drawings consistent to create cohesion in the guide.

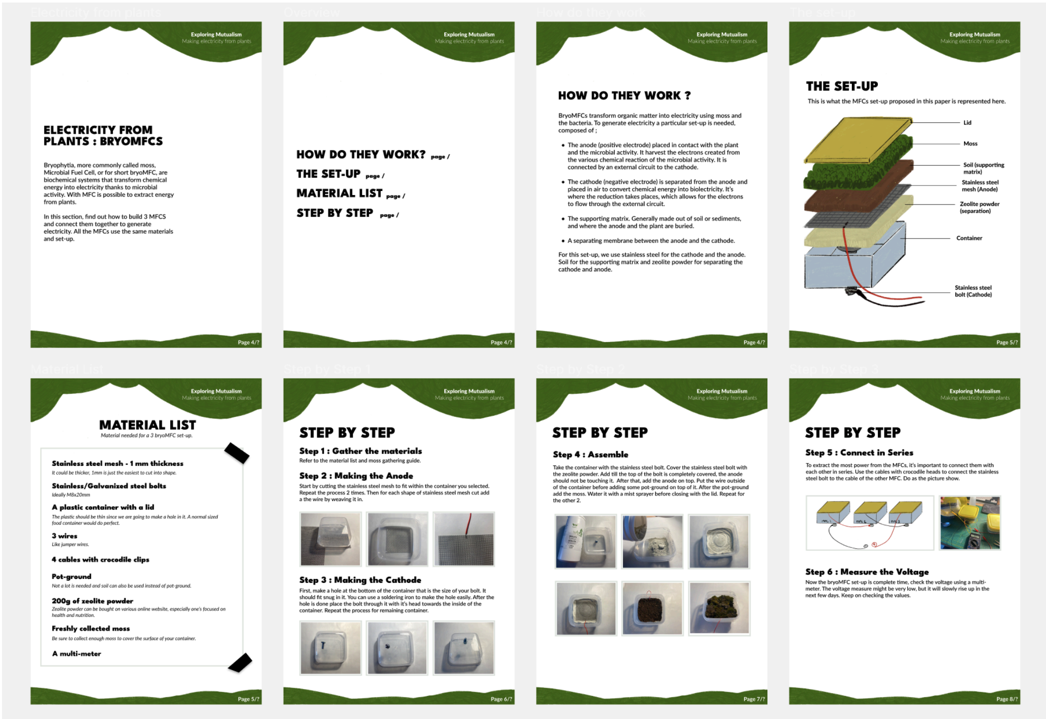


Figure 16: Guide - Electricity from Plants: BRYOMFCS.

3) Robotic Side: Energy Harvesting

For the robotic side of the relationship, I explain how to build the circuit I used at the end of the prototyping phase. The guide allowed me to reflect and organize the information. While there is debugging to do on part of the circuit, it is only a small change in the main structure of the guide. Here, the main components are to share the materials needed to realize the circuit, giving information about the models and where to find the datasheet. I wanted everything to be centralized in one spot. After the material section comes the step-by-step of how to recreate the circuit. It's the same template as the MFCs, with first an overall view of the set-up, and then the clear split up step by step. What was different here was the need to integrate part of the code for the esp32, so a separate page with the code was added. This isn't the best way to share code, so the guide includes a link to a GitHub repository[8] with the code file and extra information. For the circuit build, I tried my best to get to the point. The circuit scheme is done by hand because all the helpers to draw schematics do not include ESP32 or energy harvesting chips. While a drawing isn't optimal, it was still important that people could refer to an overview. Finally, I included some remarks about how to best do it based on what I found throughout the process (Figure 16).

[8] Wrendraya, Github, https://github.com/Wrendraya/plant_robot_mutualism_thesis_doc

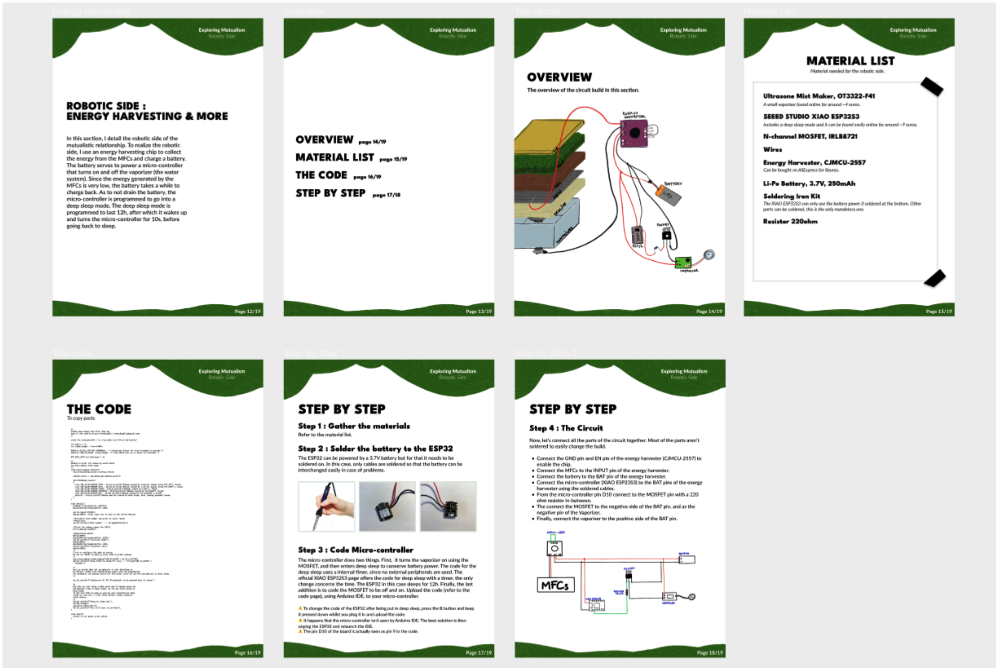


Figure 17: Guide - Robotic Side: Energy Harvesting & Circuit

7.3. Discussion

The demonstration is split into two distinct parts, the installation and the guide. Both of them are the result of the aim of the paper which was to see if it was possible to build a demonstration of mutualism. While for now the demonstration is not fully functioning, I believe it is capable of fostering curiosity and demonstrating actionable mutualism. The installation acts as a potential showcase of mutualism in action and the guide as a deep dive into its working. With those two combined, the demonstration manages to show how robot-plant mutualism works and understand its functioning. Ultimately, with more time and exploration, it is possible to create a working prototype of mutualism based on what I have done.

If more time was available to me, I would spend time building and testing the installation. Only by showcasing it can I measure the full impact of the project and if it is an efficient way to demonstrate mutualism. Iterations and extra information are needed for the installation to be impactful. Furthermore, it's only a drawing, so I cannot guarantee that it will look like this in the end. Drawbacks and complications can appear quite fast when building an installation. This is why further research is needed to build a working and compelling installation to demonstrate mutualism. For the guide, it would need to be changed based on the improvement given to the prototype and the issues fixed. Using it in a potential workshop could also tell of its efficiency and impact. Leading workshops whilst asking questions regarding mutualism might foster discussion more easily.

Ultimately, this demonstration could turn into Citizen sciences, where non-scientists participate in the process of scientific research. I believe that making the demonstration and process accessible, can allow for it to grow and change directions. It will require work, such as sharing the outcomes on various platforms (forums, internet) and going to exhibitions. Sharing and opening the project, would take mutualism further and offer new insights into its future.

8. Discussion

In this section, I first reflect upon the process of prototyping a working demonstration of mutualism, paying attention to its challenges and improvements. In the second part, I focused on mutualism and answered the question of what I learned about mutualism through its exploration.

8.1. On The Process

My project is a design exploration of mutualism through the prototyping of a demonstration. This required threading the line between design and technical aspects. In some parts, I performed design actions such as spending time thinking of the shape of mutualism and coming to the design of the installation. On the other side, the prototyping phase was grounded on the technical needs of mutualism. This combination allowed me to explore all sides of mutualism and reflect on its potential. Whilst the prototype is yet to be completed, I can affirm that it is possible to demonstrate a working plant-robot mutualism using cheap and easy-to-find materials. The core elements of the relationship are working, it is only a matter of small changes to have it completed. Furthermore, through its making, I was able to understand the complexity of the artefact and transform those into actionable learning. The results are proof of the learning. They show that mutualism can be demonstrated and reproduced by anyone. They lay down the foundation for building plant-robot mutualism for anybody interested, with little knowledge of the parts at play. Ultimately, this project is but the start of what mutualism could be and its possibilities. There are other types of benefits plants and robots can exchange. Other installations and prototypes can be made based on what was brought forward in this paper.

Furthermore, throughout this project, I used a DIY approach. This meant that all the experiences were run in a home setting with little to no lab-grad materials. The DIY approach is challenging. It required teaching myself new skills and having no one to rely on. Also, it stopped me from acquiring high-level materials and required more rigour from myself. However, this approach allowed me to explore the unusual idea that is plant-robot mutualism. A topic that is outside of the boundaries of what could be considered ‘classic’ research. I was able to fully dive into my creative ideas and follow my instincts. It allowed for quick iterations and following ideas, which didn’t always work but at least I could put them aside without regrets. Furthermore, while self-teaching was hard, I was able to learn a lot about subjects I wasn’t familiar with. With no knowledge about what MFCs were at the start, I was still able to build some and generate voltages. Throughout this DIY approach, I dug deep into the subject at hand by getting my hands dirty. I believe that this approach is valuable for research as it allows people with little knowledge to follow their ideas and open new topics of discussion. It makes research more accessible for anyone interested.

Overall the process was clear and helped me get results. There are parts, however, that could be improved. For example, in the prototyping process, I first focused on improving the voltage of the MFCs, and then on how to harvest this energy and use it to power the mist maker. Only towards the end did I bring the MFCs and robotic side together. While it made sense at the beginning to first explore what is possible to do with MFCs and how much power they can produce, they should have been brought together sooner. The building of MFCs and the robotic side should be done hand in hand. By working on them simultaneously, the MFCs and circuit could evolve together. This helps prevent finding the MFCs too low-powered for the robotic side, or the robotic side being too energy-demanding for the MFCs. By bringing them together it is possible to optimize the relationship and create a more balanced exchange of benefits.

The project was focused on the feasible aspect of demonstrating mutualism. It explores how plant-robot mutualism could work as an artefact and how to share it with the audience. This paper is only the beginning, new opportunities to develop the concept arise, especially when it comes to its design. Mutualism is an object of interest, that captures people's attention. It has a futuristic quality to it that should be explored. By placing mutualism in various scenarios and contexts, we could imagine the future of mutualism and the new shape it could take. In the project, the prototype and installation are built for indoor settings, but it could also happen outdoors. This shift in context already puts the benefits exchanged between robots and plants into perspective. Is water needed for the plants? How will the robot be protected from the weather? All those questions can help fill the gaps in the possibilities of mutualism.

While plant-robot mutualism was deemed feasible to create and reproduce at home, there are still many questions and avenues to explore. Questions about the technical aspects and its realisation, but also the future of mutualism and our relationship to it.

8.2. On Mutualism

In this project, I explored mutualism through the prototyping and concepting of its demonstration. This led to a two-part demonstration consisting of an installation and a guide to replicate the final version of the prototype. While I was able to make mutualism more accessible through the guide and this research, it is impossible to deny its challenges and difficulties. They come from the complexity of the topics involved and the various skills necessary for their realisation. However, passing over this difficulty, plant-robot mutualism can teach us about the world around us. It can be a tool to learn new skills and develop interesting discussions on mutualism.

In this section, I go over what I have learned about mutualism through its exploration and the building of the demonstration. Those learnings can serve for future projects and resume what I consider the most important to know before starting to work on plant-robot mutualism.

The first learning point is that mutualism is an act of balance. Mutualism is defined as an exchange of benefits, benefits that should serve both parties, but should serve them equally. One side can not take more than what the other side has to offer. This would lead to the death of one side or simply the stop of interaction between the two species. Mutualism can only exist if the power between parties is somewhat equal, which can be a difficult line to maintain. If the balance were to be off, the relationship could turn parasitic with one side killing the other one to survive longer. This means that maintaining a balance while building mutualism is key. It requires a precise and equal system. In the case of plant-robot mutualism, the robot must never take more than what the plant can offer. Spending time measuring the voltage generated by the plant and the right electronics is crucial for its functioning. While this act of balance can be complex to build for, it raises interesting points. It reflects the importance of balance in nature and how everything should have its place. Also, it asks the question of how much can plant-robot mutualism be extended. How much can one side take before it is not considered mutualism? This could be an interesting exploration for future works.

Secondly, another important point is that plant-robot mutualism involves the living. It is necessary to realize that much time is spent watering and monitoring the health of the plant, or in this case moss. Before working with plants it is important to know their needs and see if they are fit for the environment of work. While moss is overall resistant, it requires a lot of water and a high level of humidity. I could not recreate this humidity level without the use of containers with lids. Also, today's challenges of preserving the environment, require being conscious when collecting plants. This raises ethical questions about the handling of the plants in HCI and HRI. Taking care of plants takes time and care. However, the closeness with the living that the plant requires is ultimately beneficial. By working with moss, I have learned to look for it everywhere I go. I marvelled at its availability to grow anywhere, even the smallest crack. I also learned about its importance in the ecosystem. With mutualism, it is possible to send a message about the importance of plants in the balance of the world. The installation puts forward moss as a plant, asking to be looked at and acknowledged. Exploring plant-robot mutualism in projects could help foster interest in plants and put them forward in the discussion of future technologies. Ultimately, it is quite incredible to think about such a small plant powering a system, even if limited.

Lastly, what makes mutualism complex as well as interesting, is that it requires working on a different time scale. MFCs are powered by moss or plants, more exactly by microbial activity. It takes a couple of days for the electricity to ramp up, but electricity generation is slow. Working with MFCs requires adaptation to different rhymes and cycles. Working with different time scales translated into waiting hours to see if the battery would charge and for the MFCs' power to go up. To constantly adapt to the needs of plants concerning water and sun exposure. This time scale doesn't only affect people working on the topic, but also the robotic side. The microcontroller had to shut off for hours, storing energy, to vaporize the plants for short seconds. It probably takes a couple of days to charge a battery and then activate a circuit. This is a stark contrast to the pace of the current world, where everything needs to be fast and operational at all times. It offers a reflection on how society is a fast-paced machine, adapted to one specific timeline while non-humans have different rhythms. While it is something to adapt to while building for mutualism, it does offer a view of what life is for plants and how time is all but relative. It pushes forward the opportunity for robots to be able to adapt to different time scales and share rhythms closer to nature. What if, indeed, robots could last as long as trees? Diving into those questions could push forward the need for autonomous robots, as well as dive into new utilities for robots that last beyond our time.

Those are the important points I have come to learn about mutualism throughout my projects. It provides a basis for reflections for future projects and works but is still quite limited. They are much more to dive into and learn about plant-robot mutualism.

My idea of plant-robot mutualism only focuses on the aspects of exchanging benefits for a short duration. However, mutualism between species lasts over time, it seems they are almost tangled forever to survive. It is something I didn't get to explore with my mutualism. It is interesting to imagine how mutualism would persist in the future and for how long it could work. What would happen if one of the parties were to die? Those questions could help dive deeper into the potential of the design of mutualism. Reflecting on them could allow for a more holistic vision and concept of robot-plant mutualism. With the use of speculative design, it would be possible to explore the future of mutualism and how it could find a place in society. This development is not tangible with the current state of my plant-robot mutualism, but it should be part of future reflections. To me, the future potential of mutualism feels huge. With mutualism, not only can we create an intersection of two different worlds that work in harmony with each other, and depend on each other, but we can also imagine a future where robots do not only take care of the plants they are covered with, but also of other things around them. Maybe when they have enough accumulated energy, they spend time tending to the nature around them or other tasks. My robot was only built indoors, but I would like to imagine it would fit better in outdoor spaces, using the water and sun already given by nature.

9. Conclusion

This paper explores mutualism between plants and robots through the building of a demonstration. This exploration led to the creation of a concept installation and a guide to mutualism. Both of these results serve as a demonstration of mutualism. The installation puts in light plant-robot mutualism for an audience, as an object of curiosity. The guide to mutualism shows that mutualism can be made accessible and easy to replicate whilst using off-the-shelf material. This paper also brings this paper brings forth interesting insights useful for the conception of future plant-robot interaction. Mutualism entails complexity, balance and understanding of nature’s rhythms. Plant-robot mutualism can foster new discussions about non-human interaction and their palace in the future. Future research on mutualism should seek to explore other possible variations of plant-robot mutualism and how they could be realized. Also to look at the bigger context around mutualism and its possibilities for the future. Furthermore, improvements on the prototype are needed to deepen our understanding of mutualism and showcase a working relationship in the final installation. Building this installation and gaining feedback from audiences could put it into perspective as a future technology or way to reflect on non-human interaction.

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