RoBotanics

Exploring Design for Plant-Hybrid Robots

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RoBotanics: Exploring Design for Plant-Hybrid Robots

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How might we design with living plants as ROBOT components?

Abbreviations

Frequently Used Words and Abbreviations

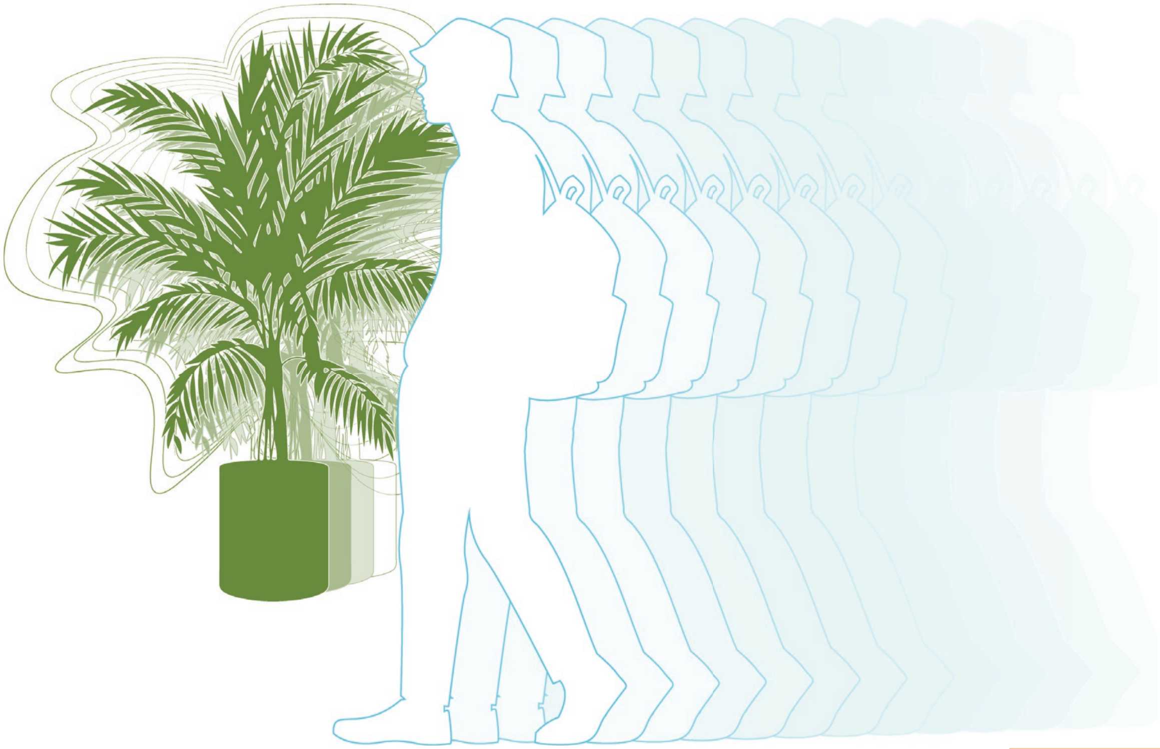
Term	Abbreviation
1. Human-Plant Interaction	HPI
2. Human-Robot Interaction	HRI
3. Human-Swarm Interaction	HSI
4. Plant-Hybrid Robotics	PHR
5. Swarm Robotics	SR
6. Technology Readiness Level	TRL

Abstract

Using plant-hybrid technologies presents an unusual design opportunity, by combining living plants with technology. This master's thesis delves into the integration of plant-hybrid robotics, exploring human-plant interaction systems. The study explores the potential design implications of this field, particularly in public settings where interactions with humans are unavoidable. This way, the project aims to stimulate design for physical and psychological connections between humans, nature and technology.

RoBotanics, the case study in this exploration, focuses on designing an **extremely slow-moving** swarm of plants that subtly roam public indoor spaces. This way the concept subtly tries to express the passage of time. Plants lack the capacity for verbal communication or auditory perception like humans. Instead, the concept allows the plants to rely on sensing through its leaves. The physical properties of the selected plant, ***Dypsis Lutescens,*** allows the plant-hybrid robot to have a large amount of 'antennae' (like insects) on all sides. This quality enhances the range of the plant sensor. The plant collects data on human-plant activity, which informs its navigation. This equips plants with subtle autonomy, bringing more liveliness to an otherwise static environment.

The prototype have demonstrated that inattentional blindness allows the plant to quietly navigate shared spaces with humans without causing distraction. Moreover, varying slow speeds affect the plant's physiological dynamics uniquely, triggering different responses. This case study contributes to the field of human-plant interaction by highlighting the potential for plant-hybrid robots to coexist alongside humans.



Contents

Introduction

The field of plant-hybrid technologies provides an unusual design scope that combines living beings with technology. The objective of this case study is to investigate the potential design implications for plant-hybrid robotics, specifically in a public context where interaction with strangers is inevitable. The mixture of biological and robotic elements, allows this research to bring a new design perspective to robotics that coexists with humans, stimulating the physical and psychological connection between nature, technology and society.

The result is a project called *'Robotanics'*. The goal: Design a plant-hybrid robot in the context of indoor public spaces, with focus on HRI and technologies in plant-hybrid electronics.

This design report is a summary of the most relevant insights gained during this projects. It is divided into three main sections:

- **SECTION I: PRELIMINARY WORK**
  Project motivations, literature research, approach etc.
- **SECTION II: CREATING ROBOTANICS**
  Conceptualisation, Main Challenges, Prototyping Results, Lessons etc.
- **SECTION III: DEPLOYING THE ROBOT**
  User testing, Evaluation Results, Design Implications etc.

Every section ends with a special chapter that includes **thoughts for designers** and also serves as a reflection on the main insights in the section.

✲ SECTION I: Preliminary Work

01. Before RoBotanics

This chapter is a story about how this project came to be and provides background information about who, how and why it resulted into a project about plant-hybrid robots in public space.

1.1 Starting Point

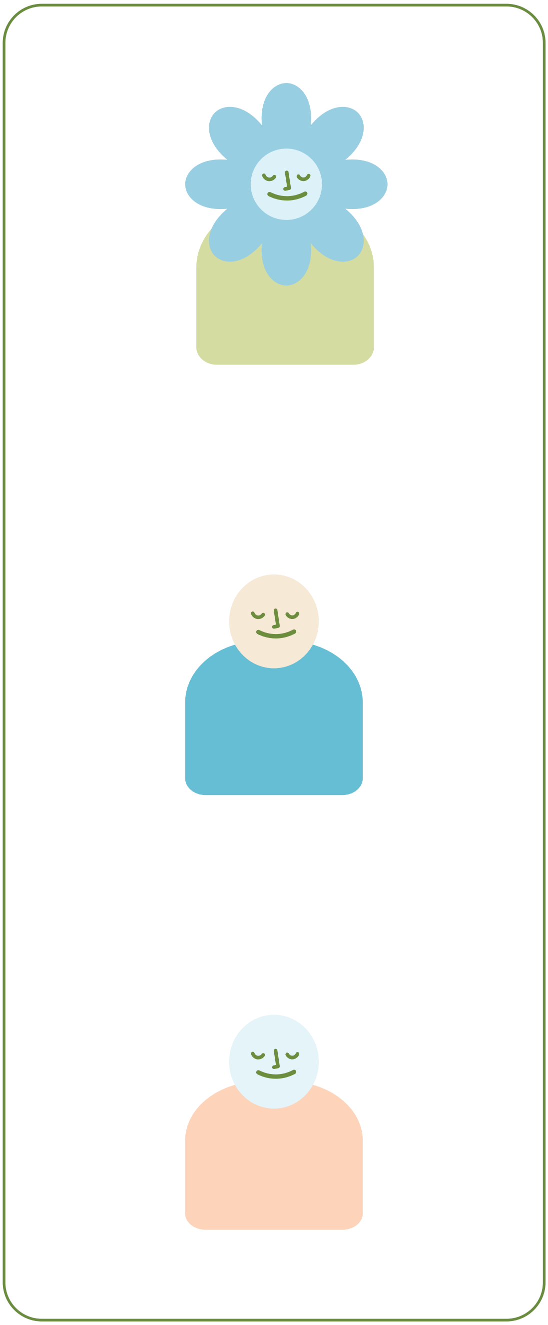
Where it all started - a brief summary of practical motivations and general background information.

► **Design Team |** This project was initiated by **Cin Yie Chang**, a student that was looking for a challenging, but exciting, graduation project to complete her master's programme. It was realised at the faculty of Industrial Design Engineering (IDE), Delft University of Technology (TU Delft), The Netherlands. The team was completed after **Jordan H. Boyle** and **Dave Murray-Rust** joined as supervisors. Although the scope shifted quite a bit during the project, there were fundamental elements that provided direction:

✲ **Design for Robotics |** Overlapping interests of the supervisors and student

✲ **Swarm Robotics, HRI |** Research fields of supervisors.

The project brief was constructed in collaboration with the supervisors, keeping the above mentioned elements in mind. This resulted in the initial project brief (**Appendix A**). The motivations for the overarching themes can be found in **Paragraph 1.2**. However, the main element, plant-hybrid exploration, was not included until later in the process. This turning point is explained further in **Paragraph 1.3**.



► **General Design Approach |** The iterative design process is not a linear one, but defined by key milestones (see **Fig. 1**). This dynamic approach ensures that each phase builds upon the last, guiding the design journey towards complete and effective solutions. Insights obtained within the research space, e.g. relevant case studies, inform the process throughout and open doors to additional opportunities for iterations and prototypes in the design and evaluation spaces. The design route does not move in a straight line through all phases, but rather in loops. This approach proved to be beneficial for design with plant-hybrid technologies, considering the experimental nature of the project caused obstacles and opportunities to appear along the way.

► **Project Priorities |** Given the limited time frame, this graduation project has several priorities that do not only focus on exploring the research field, but also includes personal objectives such as improving and applying (physical and digital) prototyping skills. See a more detailed plan in **Appendix A**.

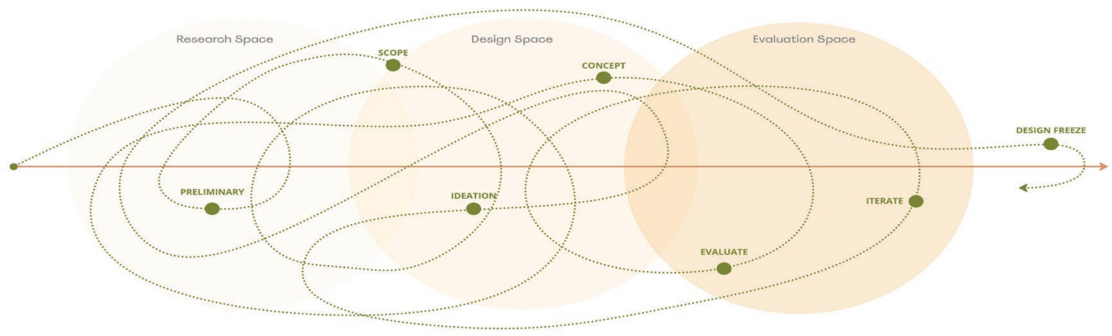


Figure 1. A visual representation of the design process as experienced by the designer. Although it may look messy, the dotted line is led by key insights, challenges and/or obstacles and a realistic journey through the displayed spaces; research, ideate, evaluate.

1.2 Overarching Themes

This paragraph summarises the first findings that shaped the project proposal. Since this is a preliminary overview of topics, it should be noted that these references include sources that are not necessarily academically written. A more in-depth literature review conducted later in the project can be found in **Chapter 2**.

1.2.1 Swarm Robotics

As a designer, the world of Swarm Robotics (**SR**) is quite a foreign one. This curiosity led to a brief exploration on opportunities for design.

► **Swarms |** SR investigates the coordination of numerous simple robots, or a swarm, to perform complex tasks collaboratively (Jevtić & Andina, 2007; Dias et al., 2021). SR often draws inspiration from the organisational structures of social insects like ants, bees, and termites, as well as schools of fish and flocks of birds (Hinchey et al., 2007; Dias et al., 2021). Although the general public may not be familiar with it, the research field has been active for over two decades. According to a review by Dorigo et al. (2021), research platforms such as Google Scholar and SCOPUS suggest that although the basic ideas for SR were established in important works from the 1990s, significant development did not really take off until around the year 2000. Since then, the number of publications and case studies have been increasing (see **Fig. 2**).

► **Key Applications |** Examples of applications such as SR for disaster relief missions (Abraham et al., 2019) and warehouse logistics optimization (Liu et al., 2017), demonstrate the potential of SR. From an initial orientation, the following main categories are identified:

✲ **Monitoring |** e.g. crop monitoring in agriculture, retrieving research data

✲ **Safety |** e.g. rescue missions, military operations

✲ **Automation |** e.g. warehouse management and logistics, manufacturing production lines

✲ **Maintenance |** e.g. roof inspections, window cleaning

✲ **Leisure |** e.g. drone shows, art installations

✲ **Fabrication |** e.g. 3D printing, large structures

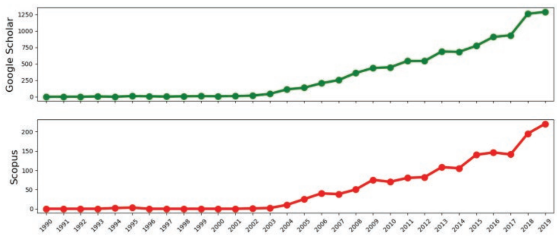
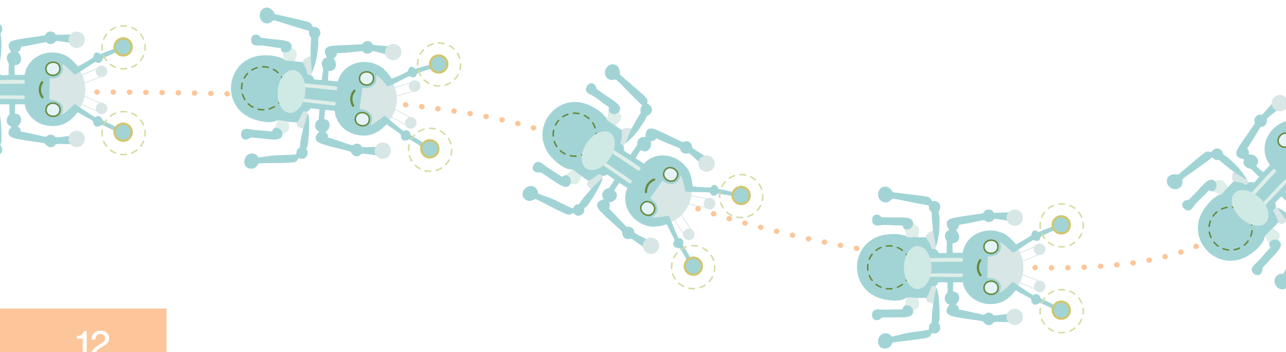
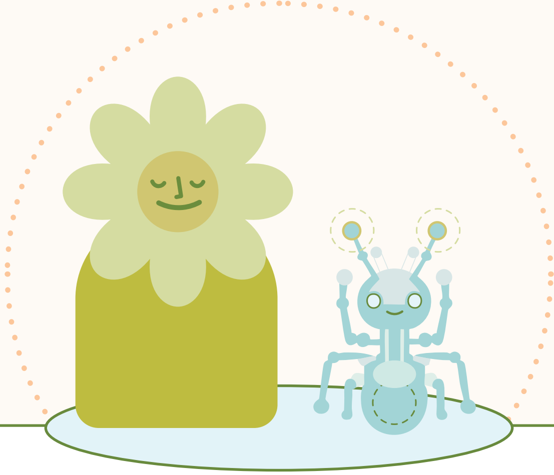


Figure 2. Citation count for the search "swarm robotics" in Google Scholar and in Scopus by Dorigo et al. (2021).





► **Selecting a Context |** Looking at these categories, the team quickly determined that the preference does not lie with industrial and military applications. Instead, applications in big public buildings, such as university buildings, public libraries, hospitals etc. were contexts that sparked interest and realistically fit within the project's resources, time frame and team's motivations. Besides, for the design of robots in public space, it is impossible to ignore Human-Robot Interaction (**HRI**). In order to envision a context in which robots and humans share a space, it is essential to study this aspect. In SR, it is commonly referred to as Human-Swarm Interaction (**HSI**). This is a field that explores the interaction and effective collaboration between humans and robotic swarms. It includes the development of human control interfaces, communication protocols, and coordination of actions between humans and swarms (Nagi, 2014).

1.2.2 Fiction: Magical Swarms

► **Nature vs Imagination** | Although metaphors that are derived from nature provide great inspiration for robotic working principles, human interactions are often not present in these natural swarm interactions. Example: A swarm of ants can demonstrate great teamwork through allocated roles (Terminix, 2023). The decision-making processes seen in ant colonies could inspire algorithms for coordinating large groups of robots autonomously. This is a great inspiration for SR as researchers can copy this same natural mechanism and apply it to robotics. From a HSI perspective however, there is no conscious interaction between a swarm of ants and a human. Perhaps an exception, and a more indirect one, is a human keeping an ant-farm or leading them to a trap. This sparked the start of a search for inspirations elsewhere: **Fiction**.

► **Life imitates Art** | A swarm of drones performing the task of knotting a bridge out of intertwining ropes in 2015 [**A**], may remind one of the iconic scene of Cinderella's birds tying knots in the 1950 animation movie [**B**], 60 years earlier (see **Fig. 3**). This is a great example of how fiction, or rather the team behind creative storytelling, provides a world in which things are possible before they are feasible in reality. Therefore this is an alternative source for metaphors, in particular fantasy & sci-fi movies. In contrast to real-world swarms, those depicted in fiction represent imaginative visions of HSI that may become reality in future applications. While the objective is not a literal replication of these fictional characters, they serve as a source for inspiration, offering insights into potential interactions between humans and swarms that defy current technological boundaries. Added to that, fiction often attributes personalities and abilities to inanimate objects or animals, as seen in characters like the magical Fantasia Brooms in Sorcerer's Apprentice (See **Fig. 4**). This contributes to the ideation phase where the personification of inanimate objects and interaction between humans and those objects are significant inspirations.

This parallel is also acknowledged by computer scientist and roboticist R. Murphy, specifically in an article about SR in science fiction (Murphy, 2021). The author emphasises the importance of taking science fiction's warnings about SR seriously, urging roboticists to prioritise the development of safeguards and policies to mitigate potential risks before deploying these technologies, stating: 'Science fiction rightfully raises the specter of swarm robots destroying the world'. Although it is about a literal depiction of robots, and not magical swarms or entities, it does have an element of magic considering that robots in fiction often have capabilities that are not feasible (yet).

Figure 3. Parallels: [A] Aerial Construction - Drones making knots. (ETH Zurich, 2013-2015); [B] Cinderella - Magical birds making knots.(Walt Disney Productions, 1950)

Figure 4. Magical Mobs in Sorcerer's Apprentice (Walt Disney Productions, 1940)

Figure 5. A group of Woodsprites in Avatar: The Way of Water (Cameron, 2022)

Figure 6. Soot Sprites ('Susuwatari') in Spirited Away (Miyazaki, 2001)

1.3 Turning Point

After many 'circles' in the design process, there was an important turning point that shaped the project and left a lasting impact: **Design for Plant-Hybrid Robots.**

► **Motivation |** Through brainstorming and selection sessions, the idea of incorporating plants proved to be a topic that the team was excited to explore. The field of plant-hybrid robots was quickly identified as a promising design space for the project, because this area allows researchers to be creative and use unconventional methods. This was confirmed in the conducted literature review (**Chapter 2**). Plants in public space are already common and usually placed with multiple others in the same space, making it interesting for seamless swarming behaviours. Additionally, bringing normally passive objects more liveliness connects well with the inspirations from fiction. For the team, it is both intriguing and challenging, which was a crucial requirement for the design scope.

► **Plants, Fiction and Tech |** A well-known example of fictional plant entities that live in groups are the Ents in The Lord of the Rings, created by J. R. R. Tolkien (see **Fig. 7**). These magical creatures are guardians of the forests, representing the theme of nature conservation. It does not necissarily demonstrate swarm behaviour since each member has their individual characteristics, but it does demonstrate collective decision-making and a shared purpose. Perhaps comparing it to a multi-agent system is more accurate. The Ents are an example of imagining Human-Plant Interaction (**HPI**), or in this case Hobbit-Plant Interaction, and introduces the idea of non-human entities that play a crucial role in their world.

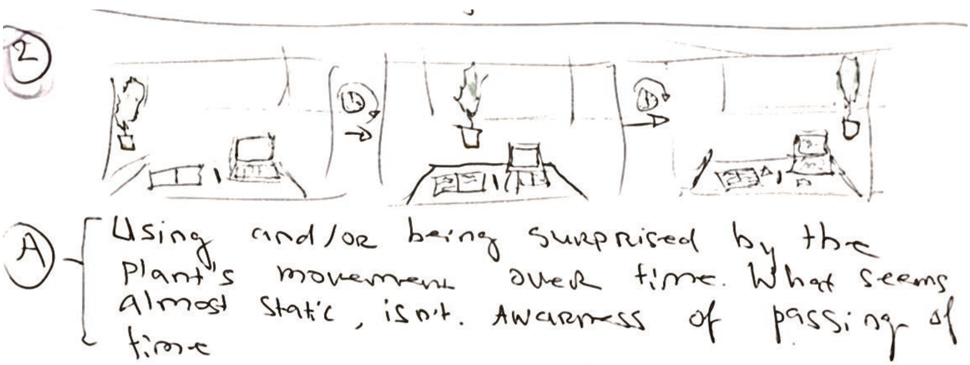
In an article that draws parallels between the Ents and the 'Random Forest' algorithm (Numbers around us, 2023), the author explains the conceptual idea behind this metaphor and demonstrates this with pieces of code (see **Fig. 8**). This showcases the usage of fictional entities like the Ents as an inspiration for non-traditional approaches, understanding and creating complex systems.

Figure 7. Ents in The Lord of the Rings (Tolkien, 1954). Visual Depiction 'Assemble the Entmoot' by Brock (2023).

```
# Crafting the council of Ents
rf_spec <- rand_forest(trees = 1000) %>%
 set_engine("ranger", importance = 'permutation') %>%
 set_mode("regression")

# Invoking the council's wisdom on our data
rf_fit <- rf_spec %>%
 fit(mpg ~ ., data = training_data)
```

Figure 8. Exploration of Ent metaphor expressed in code in the context of data science (Numbers Around Us, 2023).

► **Early Ideas |** Following the team's excitement about incorporating plants into the project and identifying plant-hybrid robots as a promising design space, early ideas began to form (see **Fig. 9**). Discussions revolved around various potential applications and functionalities for these robots. Ideas ranged from wall forming plant-robots to expressive plant characters. These initial ideas reflect the team's enthusiasm for the innovative possibilities offered by Plant-Hybrid Robotics (**PHR**) and lay the groundwork for further exploration and development in the project. **Chapter 5** establishes the final chosen idea to be developed in this project.



"Using and/or being surprised by the plant's movement over time. What seems almost static, isn't. Awareness of passing of time."

Figure 9. Excerpt out of the sketchbook: The idea that led to the concept in Chapter 5. Moving plants over time. Transcription for readibility.

02. Literature Review

This chapter summarises main observations from literary works related to the project's scope.

2.1 Review Objectives

This literature review is divided in three sections; The first section (**Par. 2.2**), is about technologies. In this section, the main objective is to find technological opportunities for design. This is done through a short assessment in which opportunities, limitations and common Technology Readiness Levels (**TRL**) are identified. The second one (**Par. 2.3**), is a shorter section about further topics that do not require the same assessment and go beyond technological opportunities, e.g. plant's effect on humans. Here opportunities and limitations are also identified. Finally, the last section (**Par. 2.4**) gives an overall conclusion with the most important insights and further steps for the project.

The **three main goals** of the literature review:

✲ **Opportunity |** Position this project within the field to identify design opportunities

✲ **TRL |** Identify TRL of related works in order to set realistic expectations

✲ **Limitations |** Collect inspiration and useful technologies from previous works

► **TRL definitions |** The TRL scale that is used is retrieved from the Netherlands Enterprise Agency (RVO), a Dutch government agency which is part of the Ministry of Economic Affairs and Climate Policy (RVO, 2023). They use this scale for grant programs and state that the TRL definitions they refer to, are as established by the European Commission. The RVO has identified four phases (see **Fig.10**).

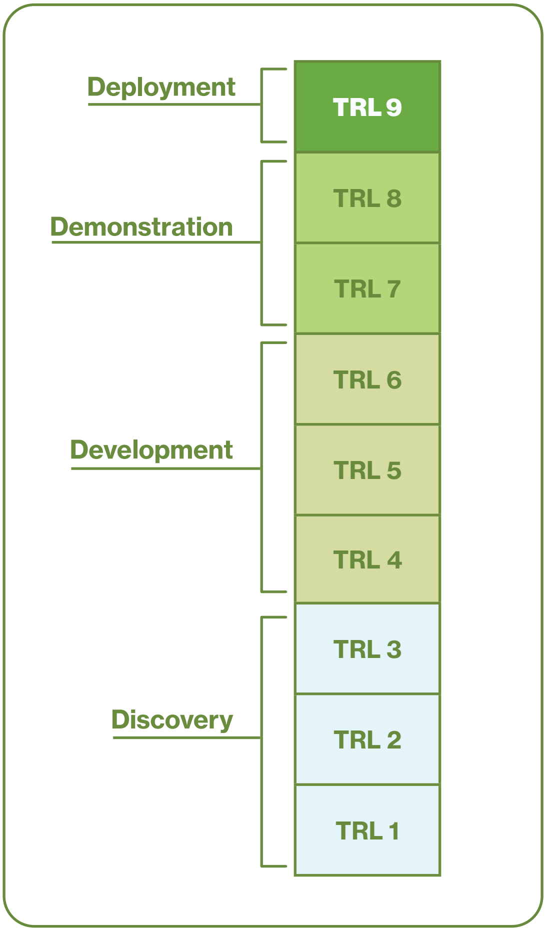


Figure 10. Technology Readiness Level (TRL) scale with four phases as defined by RVO: 1. Discovery, 2. Devlopment, 3.Demonstration, 4. Deployment.

2.2 Choosing a Technology Focus

This section is divided into three paragraphs. This division is done to maintain a clear overview of each element; The first part (**Par. 2.2.1**), is about further works on SR and HSI. The second one (**Par. 2.2.2**), is about work in plant-hybrid technologies. The third (**Par. 2.2.3**), is about works on robotics in public spaces. The assessment setup is described below.

2.2.1 Works about SR and HSI

► **Growing Field |** A general observation of this sub-field is that it is a relatively young field and therefore lacks standardised language to describe different types of concepts. In previous works, some have attempted to establish frameworks and/or terminology to describe interactions between a group of robots and humans (Wang et al. 2017; Dahiya et al., 2022; Rodríguez & Hilaire, 2023). This is also confirmed in a review by Nedjah & Silva, who conclude that the field of SR lacks a standardised methodology and generic robots in order to become 'mature' (2019). Only in 2023, authors Benabbou, Khaldi and Benslimane claim to have conducted the **first** bibliometric analysis of the HSI field, including works from 2002 to 2022. In its conclusion chapter, Kolling is mentioned as one of the most referred writers in the field. Together with others, this presumed pioneer published work that is described as 'the **first** survey of HSI', in which they identify the core concepts needed to design a human-swarm system. (Kolling et al., 2015). In their conclusion they confirm that HSI is a 'young sub-discipline'. This shows that this topic is growing field, which is attractive for the project because it offers spaces to explore and find ways to express these complex concepts into words.

► **Controlling Swarms |** A main challenge of SR is control systems (Kolling, Nunnally & Lewis, 2012; Suresh & Martínez, 2020). A larger number of robots that have to operate tasks simultaneously, such as in logistics, require precise coordination (Wen & Zhu, 2018). This shows that in HSI, control is often interpreted as one of the main interactions between humans and swarms. Popular exploratory approaches include controlling swarms through gestures (Podevijn et al., 2014; Suresh & Martínez, 2020). As Podevijn et al. state in their work, gestures allow humans to communicate directly without needing a another display. Others explored the control through second displays, such as tablets (Paas et al., 2022). There is also research on the possibility of self-organising swarm robotics, in which swarms learn how to manage themselves and collaborate with humans in a more balanced way (Walker et al., 2013; Hasbach & Bennewitz, 2021). In this context, Rockbach intepretes the swarm as an 'extended part of the human organism' (2022).

► **Other Case Studies |** Although SR is expected to have a significant market growth in the coming five years (MarketsandMarkets, 2023), the lack of real-world applications of SR suggest that the general TRL of SR projects are still quite low (Nedjah & Silva, 2019). In the meantime, recent research shows that researchers are starting to test swarms outside labs on a small scale, in real world applications. Recent work demonstrates the effectiveness of object avoidance in a forest, for example (Zhou et al., 2022). For those that do not have this capacity, solutions many turn to are simulators or Artificial Reality (AR) and Virtual Reality (VR) experiences in order to test applications (Calderón-Arce, Brenes-Torres & Solis-Ortega, 2022; Blais & Akhiourfi, 2023; Karunarathna et al., 2023).

Main insights

✲ **Opportunity |** A young and active field with potential and room to explore. Many focus on controlling swarms.

✲ **TRL |** Research projects in SR and HSI tend to span a broad range of TRLs, but generally stay on the lower end of the spectrum. Commercialisation is not widely tackled yet, levels 1-6.

✲ **Limitations |** Due to lack of capacity, resources and/or feasibility, one may turn to virtual experiences (VR or AR).

2.2.2 Works about plant-hybrid technologies

For this section, a slightly more extensive analysis was conducted to gain insights. The works mentioned are found through keywords related to plants in combination with robotics or electronics. Plant-like living organisms such as algae or fungi are not considered.

► **Defining PHR |** A noteworthy observation is that there is no fixed terminology for these types of products or technologies (See **Table 1**). Similar to observations on HSI terminology (see **Par. 2.2.1**), it shows that this field does not have any standardised definition of what qualifies as PHR and what does not. To elaborate further, not all projects refer to their electronic plant as a robot in their written works. In the project Touchology (Seo, Sungkajun & Suh, 2015), researchers created a prototype of a plant that reacts to touch. In this case, they refer to the product as an interactive plant and do not define it as a robot at all. On the other hand, project PotPet (Kawakami et al., 2010) does call their product a robot, but does not claim it is a hybrid and, as the name suggests, mainly focuses on applying electronics to the flowerpot, calling it a 'flowerpot-type robot'. This example is noteworthy, because the authors do list the work 'I/O Plant' (Kuribayashi, Sakamoto & Tanaka, 2007) as one of only three related works. Unlike PotPet, that project clearly states in its paper's abstract that it is for creating 'hybrid circuits' and mainly focuses on applying electronics directly to the plant. This shows that although they do not claim their own project is hybrid, they do position themselves in the same category of those that do. This raises the question:

> *'What should we consider a plant-hybrid robot?'*

Part of the conducted analysis involved marking down whether the projects were in fact hybrid, not hybrid, or debatable. Because of lack of standardisation, determining whether projects were hybrid or not is challenging and somewhat subjective. Therefore it is relevant to specify a definition for the design project's scope.

Table 1. Description examples of related works.

Used Terms		
Plant-electronic hybrid (Sareen & Tiao, 2018)	**Bio-hybrid** (Wahby et al., 2018)	**Interactive Plant** (Seo, Sungkajun & Suh, 2015)
Cybernetic lifeform (Sareen & Tiao, 2018)	**Plant Robot** (Bhat et al., 2021)	**Hybrid Bio-robotic Swarm** (Ayali, A., & Kaminka, 2023)
Cybernetic-plant (Nanda et al., 2021)	**Plant-Human Interface** (Steiner et al., 2017)	**Plant–robot biohybrids** (Skrzypczak et al., 2017)

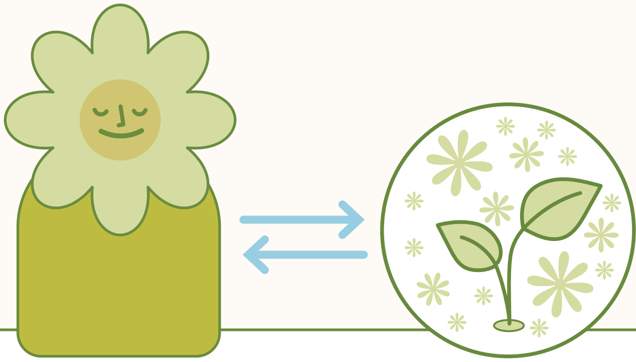
Merriam-Webster is referenced for the quoted definitions below. It should be noted that dictionary entries are criticised (Gouws, 2017) and that these definitions are not claimed as the only truth. For the sake of this project however, these definitions are chosen by the designer to specify the scope and accepted as the definition within this project.

✲ **Plant |** *Dictionary: 'any of a kingdom (Plantae) of multicellular eukaryotic mostly photosynthetic organisms typically lacking locomotive movement or obvious nervous or sensory organs and possessing cellulose cell walls' (Merriam-Webster, n.d. a)*

✲ **Hybrid |** Dictionary: *'having two different types of components performing essentially the same function'(Merriam-Webster, n.d. b)*

✲ **Robot |** Dictionary: *'a machine that resembles a living creature in being capable of moving independently (as by walking or rolling on wheels) and performing complex actions (such as grasping and moving objects)' (Merriam-Webster, n.d. c)*

✲ **Plant-Hybrid Robot |** A machine with both plant and robotic components integrated within its system collaborating to perform actions.



▶ **Human-Plant Interaction |** A number of sources did not create a 'hybrid' robot according to the chosen definition, but rather created a robot that housed a plant. To elaborate, several works included a plant species that was not a vital part of the system and rather provided a structure that carries a plant instead. For example, in a project that called its product the 'PlantBot' (Bhat, A. S. et al., 2021), the main focus was actually on the functionality of the flower pot alone. It elaborated on using the plant robot for helping manage depression through nature therapy, but mostly gave insights on its hardware components (e.g. LED display). The plant is added at the end for decorative purposes and is not planted in the flowerpot itsef. In this case the plant species was not relavant for the system. Similarly, 'non-hybrid' projects were easily recognisable by their lack of disclosed (scientific) plant names. These would instead call the object 'plant' or 'leaf' without further specification. Eventhough this is the case, one could also argue that the plant's presence alone automatically makes it part of the system.

In a systematic review on Human-Plant Interaction (**HPI**) works, a distinction is made between four types of system architectures in prototyping - also see **Figure 11** (next page): **1.** Indirect Integration, **2.** Proxy Integration, **3.** Embedded Direct Integration and **4.** Augmented Direct Integration (Chang et al., 2022). This review, structurises the ambiguity of this highly experimental field and claims that it could serve as *'a blueprint for HCI practitioners seeking to create physical prototypes with live plants'.* If we would apply this framework to the PlantBot project, *Indirect Integration* would be a way to describe its system architecture, since the functionality of the hardware does not seem to directly rely on the plant system for neither the sensing nor the actuation.

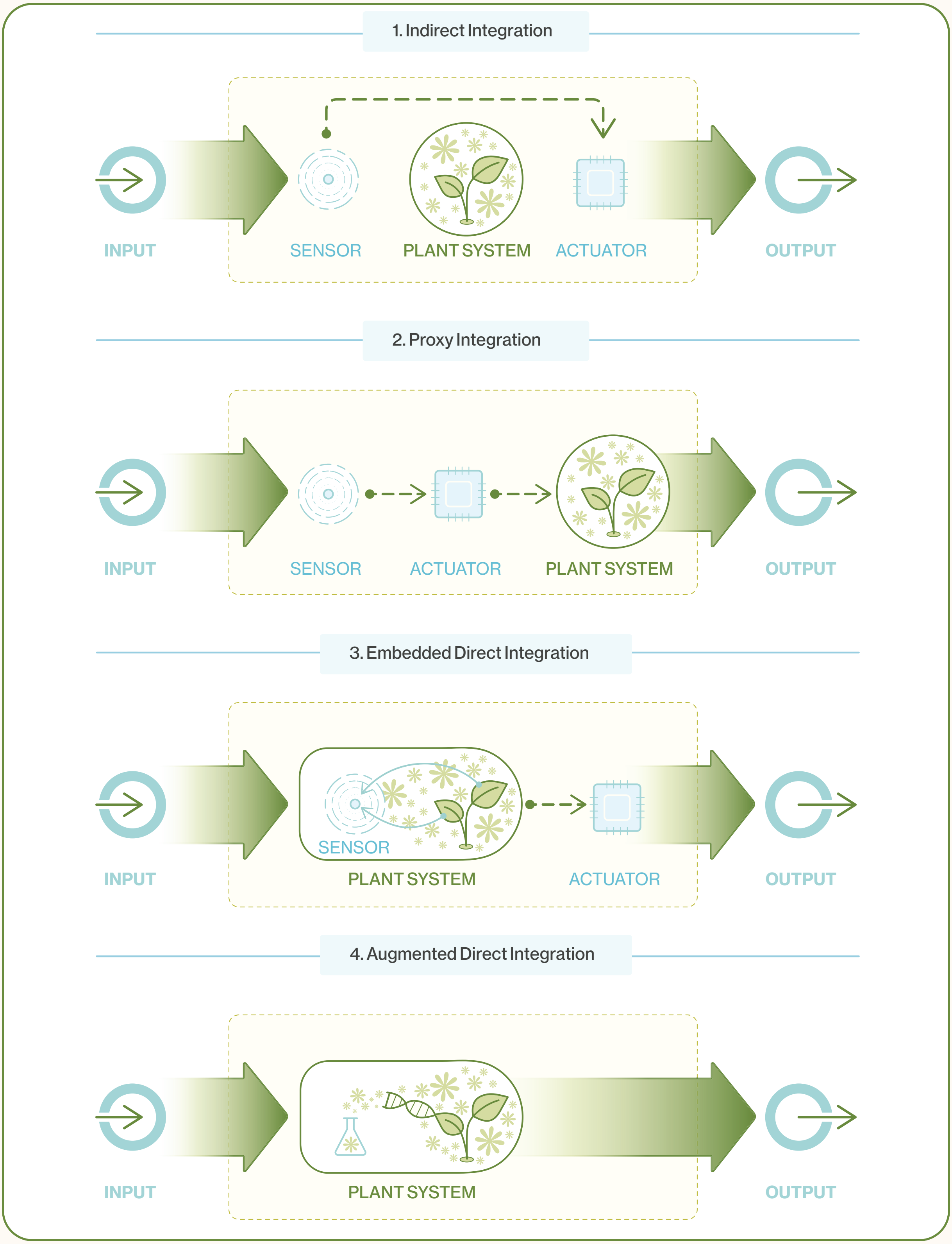


Figure 11. Four HPI prototype confirguration categories as defined by Chang et al. (2022) in a visual framework. This figure is based on the original with permission from the author.

► **Selecting a technology to explore |** The technologies or applications with most potential for the project are ranked and highlighted here:

1. **Using plants as sensors |** Ways to collect data through living plants, as done by Poupyrev et al. (2012) for 'Botanicus Interacticus' and the previously mentioned 'I/O Plant' by Kuribayashi, Sakamoto & Tanaka (2007). In these studies, researchers experiment with ways in which plants can 'sense' input and form interactive installations, mainly through touch. In a study by Armiento, Meder, & Mazzolai (2023), it was possible to detect an insect's leg on a leaf and therefore could potentially tell something about how plants are affected by populations of insects. This may offer possibilities in the future to collect agricultural data in a seamless and precise way.

2. **Energy Harvesting through PMFCs |** Researchers found ways to collect power from living plants, through Plant Microbial Fuel Cells (**PMFC**) (Deng, Chen and Zhao, 2011; Helder et al., 2012; Wetser et al., 2015;). With this PMFC technology, it might even be possible to turn fields of grass into tools for WiFi enhancement (Xu, Lu & Zhu, 2021). An noteworthy observation about this topic is that a Dutch researcher started a company with this technology and is moving towards a marketable product with what she has called 'Plant-e' (NL Greenlabel, 2023). Although the product portfolio and capability of the fuel cell is limited, it shows that there is potential in plant-hybrid solutions for energy generation. The main reason this technology is on number two and not one, is its low TRL. Although the technology is inspirational, the lack of resources and technological feasibility make it less desirable to incorporate into the project.

3. **Design toolkits or frameworks |** Ways to make PHR explorations more accessible. As demonstrated by Chang et al., with their HPI framework (see **Fig. 11**), there lies value in constructing resources specifically for designers. In 'I/O Plant', a hardware toolkit was created that included all necessary components to create sensing and/or actuating plants (Kuribayashi, Sakamoto & Tanaka, 2007). Much like Plant-e for PMFCs, it shows the desire of experts in the field to increase accesibility to this tech. As a designer, creating such toolkits can introduce other designers to this technology and stimulate work in this field.

Main insights

✲ **Opportunity |** These examples show that this sub-field is extremely diverse and open to creativity and exploration. Using the plant as a sensor is an interesting technology for the project. Inspiring ways of energy harvesting through plant-hybrid applications is not feasible for the project, but a valuable technology to note down. Toolkits and frameworks may be relevant for the design world, by making the field accessible for design exploration without much biomechanical knowledge.

✲ **TRL |** Many are in the concept phase (TRL 1-3), such as the concept by Xu, Lu & Zhu . While a minority are working towards a product that can be marketed (TRL 6-8), such as I/O Plant and Plant-e.

✲ **Limitations |** Underdeveloped technologies might make it challenging to prototype with. Lack of knoweledge in bio/environmental technologies make the exploration of technological feasibility out of scope.

2.2.3 Works about Robots in Public Space

► **Welcoming Robots |** Several works show that the TRL of public robots is at a level that allows it to be in demonstration or even deployment stages for years (Foster et al., 2016; Chen et al., 2017; Yousuf et al., 2019; Bu et al. 2023). This is also clear by looking at robots increasingly appearing on the market and become more visible in public spaces, fulfilling different roles. However, most of these robots in public seem to be service based robots: delivery, hosts or venue guides, waiters, dish-collectors etc. Service robots, found in restaurants and shops, assist in tasks ranging from order taking to dish-transportation. Pudu Robotic's delivery robot 'BellaBot' has even gone viral for its cat-like character design, triggering restaurant owners to implement robots in their business (Randall, 2020). On its product page, Pudu highlights its unique HRI capabilities, as it has a clear focus on aesthetic design (Pudu Robotics, n.d.). Besides B2B service robots, there are also companies that put robots on the market as a consumer product, such as the cargo-carrying following robot by Piaggio Fast Forward (n.d.): Promoting a personal robot that follows you everywhere on the street. These examples highlight the growing integration of robotic technology in everyday life.

► **Social Robots for Human Well-being |** Apart from service based robots, social robots have can also be found in therapeutic contexts, offering interaction and support to the elderly and individuals with autism, contributing positively to their well-being and social integration (Cabibihan, 2013; Pennisi 2015).

► **Sharing Space with Robots |** In research about robots in public space, a main theme is the investigation on how humans should share that space with robots (Samarakoon, Muthugala & Jayasekara, 2022; Hopko, Wang & Mehta, 2022). This explores ways in which robots should move and in what proximity they should position themselves amongst human (Sumartojoet al., 2021). This research topic aims to optimise the co-existence with these robots, now that public robots are increasingly being deployed.

► **Pain point |** There are crucial pain points that designers deal with during the implementation of robots in public. A relevant one to this project, is the concern that robots present risks for **human physical safety**. According to Salvini, Paez-Granados and Billard (2021), this is because robots that travel in close vicinity to pedestrians are likely to enter in physical contact with humans and also states that robots are 'heavy and can travel faster than humans'. Another previous study found that humans generally prefer slower robot speeds and states that an overtaking robot was considered to be less comfortable than passing the robot themselves (Neggers, 2022).

Studies also bring up other essential design implications related to robots in public:

✲ **Vandalism |** Designers should take seriously into account robot vulnerability with respect to abusive physical interactions to avoid vandalism. A part from practical design choices, such as materials that can handle impact, it could also be done by optimising the robot's behaviour; In a study that aims to mitigate abuse from children, the researchers trained the robot to approach a parent, lowering the odds of abuse (Brščić et al., 2015).

✲ **Ethics |** There should be focus on policy design to make sure that deployment of public robots is done in an ethical way (Mintrom et al., 2021). For example, ensuring transparency on why the robot is there and what it is doing (Babel, Kraus & Baumann, 2022). Added to that, identified threats include cybersecurity attack and the danger to hacked social robots (Oruma et al., 2022).

Main insights

✲ **Opportunity |** Explore co-existence with humans and robots, ways that robots can improve human well-being. Design for safe public robots.

✲ **TRL |** Broad range, but on the higher side due to commercialisation, levels 5-9.

✲ **Limitations |** Potential safety hazards and careful consideration for ethical deployment.

2.3 Choosing a context focus

The final part of this literature review, is about remaining works that are worth mentioning, but are not necissarily connected to a technology. **Paragraph 2.3.1** is about the effect of plants on humans. **Paragraph 2.3.2** is about overlapping elements of the design scope.

2.3.1 Effects of Plants on Humans

► **Human attraction to Plants |** It is a common assumption that plants have a positive effect on mental health. This is also used as motivations in previously mentioned studies in the PHR section (**Par. 2.2.2.**), such as Touchology. In this study the researchers even claim in their abstract that gardening is noted for its potential to boost mindfulness, enhance memory, and improve cognitive abilities. Others believe that humans have a natural connection to nature, or even say that it is spiritual (Wedel, 2017; Ryan, 2023). Regardless of what one believes, it shows that humans often have a natural attraction to nature and plants.

► **Skepticism |** Some studies challenge the notion that plants directly improve mental health, arguing the lack of strong evidence to support this claim. A critical review concludes that the found benefits in the reviewed studies, may depend on the context in which individuals encounter the indoor plants, as well as the characteristics of the people encountering them (Bringslimark, Hartig & Patil, 2009). Another study evaluated whether the seen benefits are truly from plants or related to the green colours alone, but concluded that in the end, the plant element seemed to be essential (Michels et al., 2022).

2.3.2 Design for a Niche Market

► **Combining All Fields |** The literature review shows only a few works on **SR** related to **Plants** within the context of **Public Spaces**. One of the only projects that fit all these areas is the Sunbot Swarm project by McDermott (2019): A group of robotic houseplants that explores the concept of plant autonomy and collective movement, tested in a public park. The author claims that the prototypes generated 'a massive response from bystanders'.

► **Innovators and Early adopters |** Plant-hybrid products can already be found on the market. Living Light, Bioo tech, Plant-e are all examples of companies that try to make plant-hybrid products marketable and already have several products on the market for sale or pre-order (Arkyne Technologies-Bioo, 2023; Living Light, 2021; NL Greenlabel, 2023). Another sign that shows interest is the funding that these companies receive. Arkyne Technologies, the company behind Bioo has been co-funded by the Horizon Europe Programme of the European Union. According to CORDIS (2020), they received almost €1.3M in funds to develop their BIOO Panel; Green Electricity from plants' photosynthesis.

Main insights

✲ **Opportunity |** Promote natural human-plant connection. Contribute to a nice market.

✲ **Limitations |** Scepticism could form resistance for investment in such products.

2.4 Conclusion

In this literature review, overarching elements were investigated and illustrated through related works. Main insights were collected and are considered during the ideation and conceptualisation phases.

This review suggests that the chosen design scope is young and within an active field that takes on a broad range of innovative and explorative approaches. Furthermore, the TRL level of this case study is most likely not expected to present a marketable product, but rather level 3-4. This is also due to the limited time frame of this project. Therefore, this project is an explorative case study to learn about this side of robotic and interactive design with living plants. The main opportunities and limitations that derived from this review are stated below:

✲ Opportunities

Field: PHR is a field with potential and room to explore. Previous works are inspirational and provide some realisitc **starting points and frameworks** for ideation.

Technology: Exploration on using the **plant as a sensor** seems to be most realistic for this project. It is a hybrid technology that has a relatively higher TRL compared to PMFC technology, which makes it a better option to prototype with.

✲ Limitations

Resources: Lack of practical knowledge, learning more about it presumably results in a big part of the project's workload.

Uncertainty: Although some starting points are given, there is no accurate prediction of feasibility. Therefore many iterative steps with much trial and error is expected. Added to that the project planning might be adjusted multiple times.

These insights helped shape the design scope and the basis of the project. The observations are used in the ideation phase and provide arguments for further design choices. In Chapter 3, these findings are developed further.

03. Design Scope

This chapter is a conclusion of all preliminary work and presents the final design scope in which the design is made.

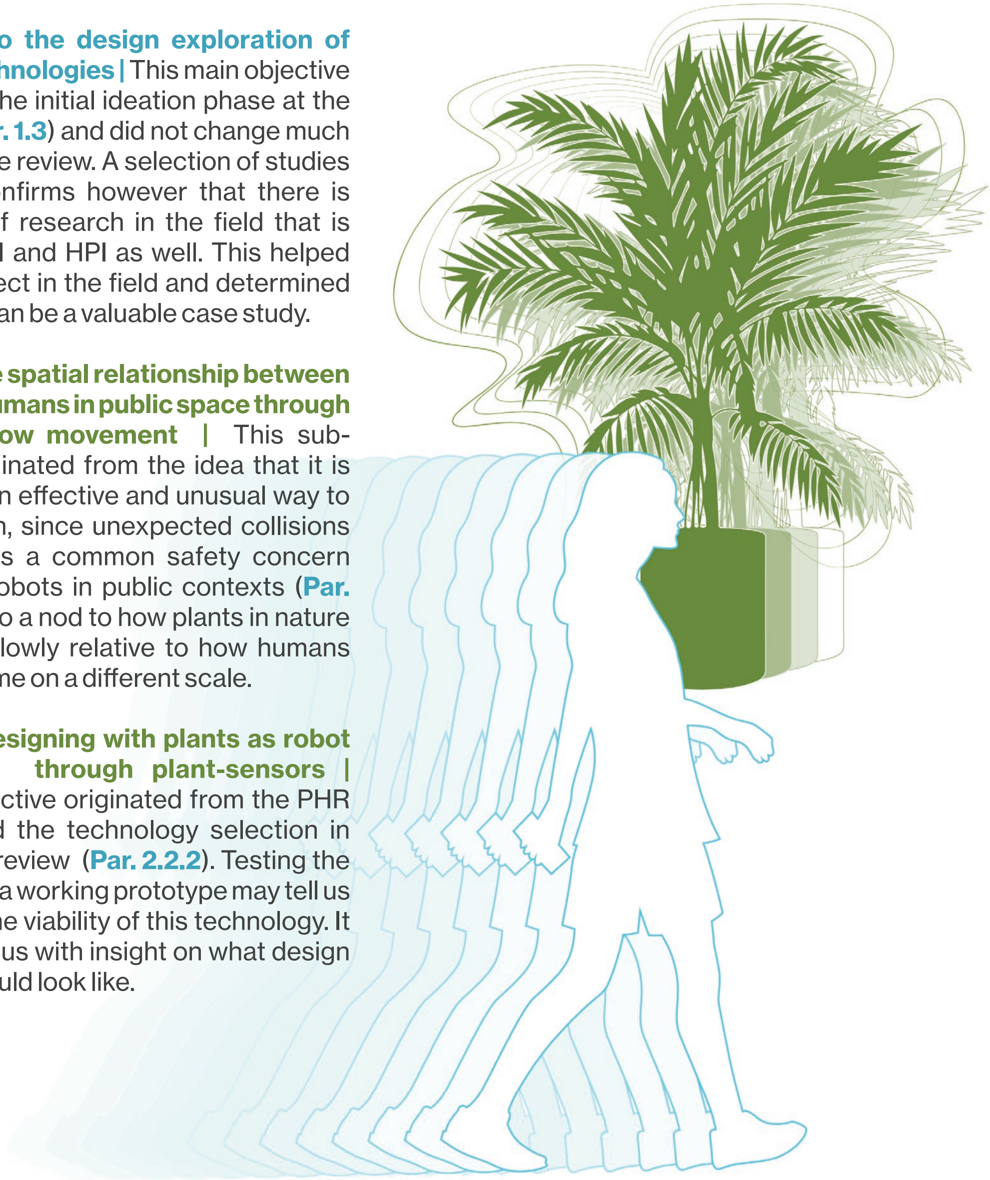
3.1 Main Project Objectives

Through brainstorming with the opportunities from the literature review, resulted into the following objectives:

✲ **Contribute to the design exploration of plant-hybrid technologies |** This main objective originated from the initial ideation phase at the turning point (Par. 1.3) and did not change much after the literature review. A selection of studies in the review confirms however that there is an active area of research in the field that is dedicated to HRI and HPI as well. This helped position the project in the field and determined that the project can be a valuable case study.

✲ **Investigate spatial relationship between robots and humans in public space through extremely slow movement |** This sub-objective originated from the idea that it is presumably an effective and unusual way to avoid collision, since unexpected collisions with people is a common safety concern with mobile robots in public contexts (Par. 2.2.3). It is also a nod to how plants in nature move really slowly relative to how humans experience time on a different scale.

✲ **Explore designing with plants as robot components through plant-sensors |** This sub-objective originated from the PHR definition and the technology selection in the literature review (Par. 2.2.2). Testing the technology in a working prototype may tell us more about the viability of this technology. It also provides us with insight on what design with plants could look like.



3.2 Additional Objectives

► **Product Character |** The C-matrix below shows where this case study fits among other plant-hybrid projects. Several other collected works have been included to illustrate the range within this matrix. It has two axes, showing its intended purpose (artistic-functional), and how likely it is to happen in the near future (practical-speculative). It should be noted that the placement is somewhat subjective and that the matrix is used as a tool for the designer. As shown in **Figure 12**, this case study aims to create and demonstrate functionalities, while also leaving room to be more artistic. On the practical-speculative axis, the project leans more towards practical, aiming to develop a working prototype. Making it a mass produced consumer product, such as the Bioo Lux light, is however not the objective.

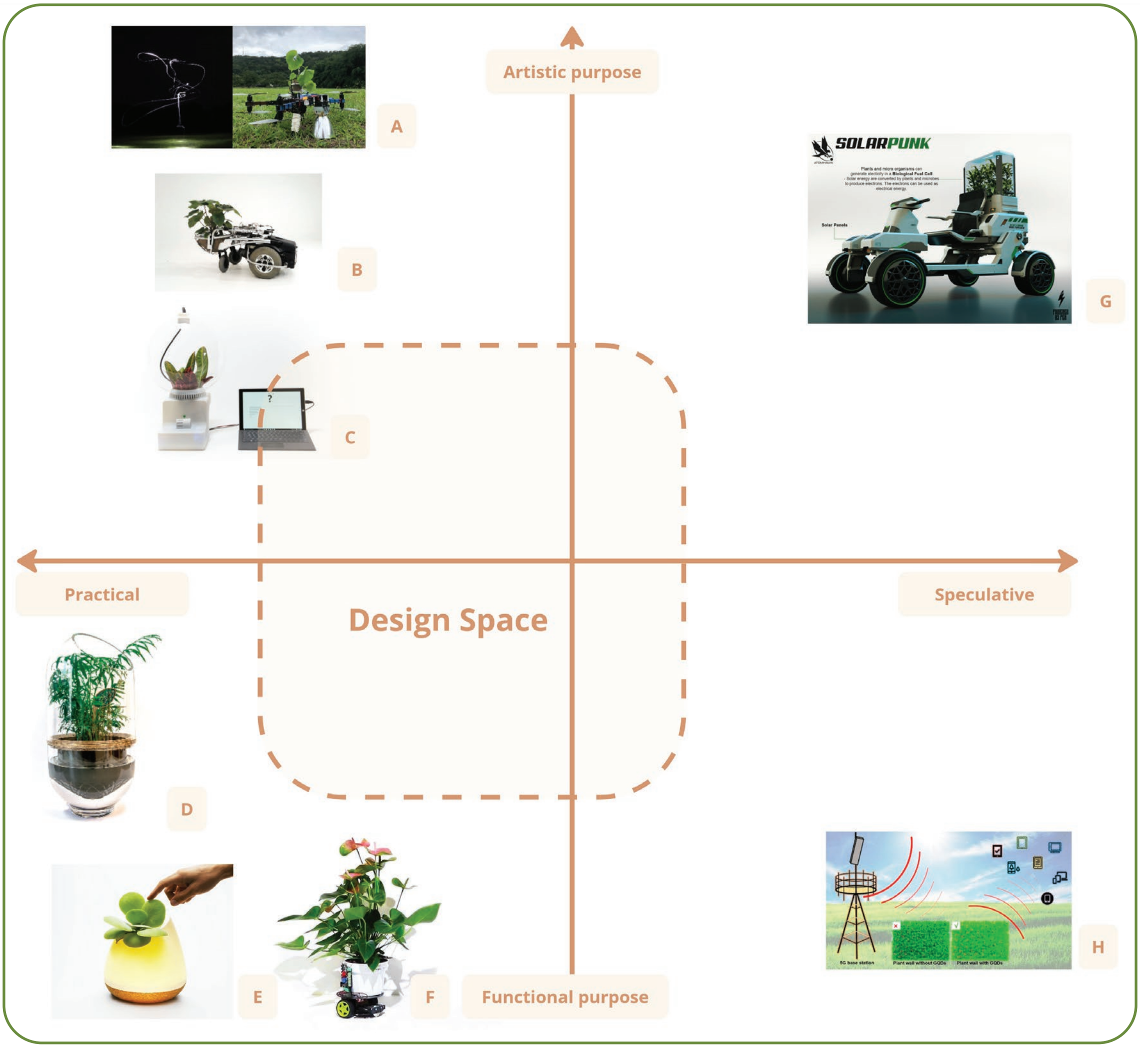


Figure 12. C-matrix of types of plant-hybrid projects, mapped out on axes of purpose type (artistic-functional) and design type (practical- speculative): **[A]** ‘Plant Drone’ (Bowen, n.d.), **[B]** ‘Prototype For a New BioMachine’ (Henriques, 2016), **[C]** ‘Project Florence: A Plant to Human Experience’ (Steiner et al., 2017) **[D]** ‘Living Light - Lamp’ (Van Oers, 2016), **[E]** “Bioo Lux | Bio-switched lighting” (Arkyne Technologies-Bioo, 2023), **[F]** “Elowan: A plant-robot hybrid” (Sareen & Tiao, 2018), **[G]** ‘Welcome to Solarwood’ (Ben, 2019), **[H]** “Toward plant energy harvesting for 5G signal amplification” (Xu, Lu, & Zhu, 2021).

Figure 13. Prototype examples from similar works: **[A]** Elowan: A plant-robot hybrid (Sareen & Tiao, 2018), **[B]** Plantbot (Pictorus, 2023), **[C]** PotPet (Kawakami et al., 2010), **[D]** HEXA (Sun, 2017), **[E]** Plant Host Drone (Verstraete, 2017), **[F]** Sunbot Swarm (McDermott , 2019).

Figure 14. The contrast between classic wooden furniture and a dish-collecting robot at the Kavárna Obecní dům restaurant, Prague, Czech Republic.

► **Aesthetic Design |** While previous prototypes have been well engineered, they sometimes lack attention to aesthetics and focus on whether it is fitting into their environment. Looking at examples (see **Fig. 13**), they for example often show visible electronics and do not consider the aesthetics and/or user context, presumably because HRI was not the focus there. In contrast, example **[D]**, **[E]** and **[F]**, show that thought was put into the aesthetics.Even though the sensors are visible, it is evident that the researcher valued its appearance.

In certain cases, even well designed robots may seem out of place in their surroundings. This is also the case for the robot in **Figure 14**, spotted in a historical building in Prague surrounded by carefully chosen furniture and decor. However, in this classic environment, an industrial-looking dish collecting robot stands out. Unlike the rest of the setting, the presence of this mismatched robot disrupts the overall visual appeal of the space.

In short, the aim is to create a prototype that is carefully designed, seamlessly blending into its surroundings.

04. First Thoughts For Designers

Overview of observations on topics discussed in this section: **Preliminary Work**.

The HPI Design Space

What might be the role of the designer in this field? | Design with plant-hybrid applications is a design space that has a lot of room for exploration, which can be challenging but a fun experience for designers. Although design concepts in this field will most likely stay in a niche market in the near future, it is a challenging design space that allows designers to play with intruiging technologies. The novelty of the field also means that the TRLs are generally low. As discused in **Paragraph 3.2**, a lot of concepts are well engineered, but less designed with focus on HRI and/or aesthetics. This is another opportunity for designers to put more attention to the look and feel of the concepts and to think about how these products should be presented.

How might we design with plants in a methodical way? | Perhaps a 'disadvantage' is the lack of standardised systems in place for such designs. As mentioned in **Paragraph 2.2.2**, some attempts have been done to structure the design space, e.g. the HPI framework by Chang et al. (2022). These tools could be useful for designers that desire structure is to navigate within this experimental research field.

What might motivate investment in this type of work? | One crucial point for designers is the possibility of facing criticism from those who might not immediately grasp the purpose of their work, often asking questions like *"But why?"* It is also worth mentioning that scientific publications in this field have a range of different justifications for HPI; claiming it could improve people's mental health by connecting with nature, that it could contribute to the agriculture sector or that it could assist humans in taking care of houseplants etc. Effective storytelling is key, as it enables designers to explain their work's purpose and value clearly. In contrast, you could also consider to avoid making bold claims and keep it ambigious on purpose, making it free to interpretate the way people want. Drawing from personal experience, some individuals might be more accepting if it is framed as an art project, seeing HPI as a creative experiment, while others do not question it at all.

Design for Robotics

How might fiction or fictitious thinking inspire SR? | In the field of HRI, there is a valuable opportunity to find inspiration in fiction, particularly when it comes to swarm robotics. This does not necissarily have to rely on depictions of fictional robots, as discussed in **Paragraph 1.2.2**, but also on non-technological swarms powered by magic instead of technology. While currently nature is the popular inspiration source for mechanisms within a swarm, fiction often depicts magical swarms interacting seamlessly with outsiders like people or other creatures. Imaginative stories can inspire new ideas for HRI, showing how swarms can communicate and work together with humans effectively. By looking at these fictional narratives, we can come up with fresh approaches to HRI, imagining systems that behave like the swarms in stories.

How might we tackle concerns regarding public robots through design? | A key consideration when integrating public robots is ensuring human safety. Rather than relying solely on for example obstacle avoidance technology, designers may explore alternative methods, such as the method demonstrated by Brščić et al. (2015): Navigating towards parents to avoid abuse by children as mentioned in **Paragraph 2.2.3**. In RoBotanics, extreme slow movement is expected to avoid collision with humans, as it may appear static for people who pass by.

✻ SECTION II: Creating RoBotanics

05. The Concept

06. Building the Prototype

07. Thoughts for Designers

05. The Concept

This chapter introduces the chosen concept to be developed for this case study. These visions are there to describe and capture the meaning of the design project and also serve as guidance for the conceptualisation phase.

5.1 General Vision

5.1.1 Description

► **In short |** A swarm of plant-hybrid robots slowly roams around in a public space over time. The plants act as sensors, detecting human activity which influences how they navigate alongside humans. The slowly moving collective aims to nudge people to stay present and aware of the passage of time, transforming an otherwise static building in a lively environment.

► **Conceptual Idea |** Plants in nature move really slowly relative to how humans experience time on a different scale. This concept makes use of the space between these two time scales, making the plant move faster on a plant-timescale, but still extremly slow on a human-timescale. Imagine this: The sun slowly disappearing at the end of the day. You suddenly notice, bringing you back to the present – a simple reminder of the passage of time. Instead of a slow moving sun, this project revolves around slow moving plants in a fast paced environment.

► **Plant as a Sensor |** The robot detects subtle changes in their close surroundings through its plant-body. Essentially, the plant is a sensor; Our bodies, like plants and most other living things, can carry an electrical current. When a human comes close to the electrical 'field' of the plant, it causes a difference in something called capacitance. This sudden change, signals human presence near the robot. The physical properties of the selected plant, ***Dypsis Lutescens,*** allows the plant-hybrid robot to have a large amount of 'antennae' or 'feelers' (like insects) on all sides. This quality enhances the range of the plant sensor. The system architecture could thus be described as **Embedded Direct Integration,** since the sensing relies on the plant system (see **Fig. 14**).

5.1.2 System Architecture

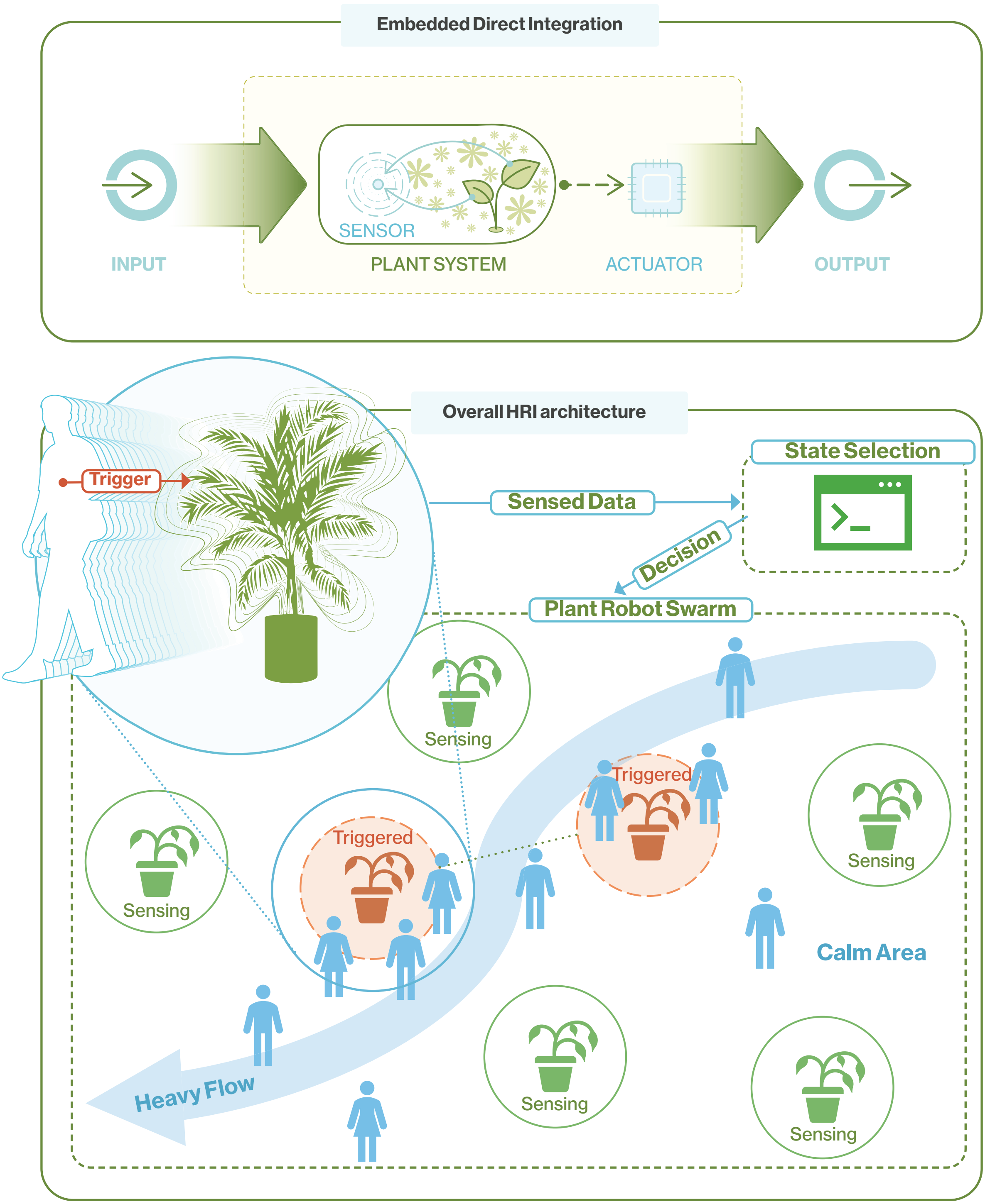


Figure 14. Embedded direct integration system architecture for one plant (top) as defined by Chang et al. (2022) in a visual framework, based on the original with permission from the author. Overall HRI architecture (bottom).

5.2 Envisioned Effect

► **Subliminal Movement |** For this concept, intermittent speed is essential, especially when aiming for subtle effects that are barely perceptible, similar to the slow movements of the sun. By incorporating extreme slow speed, robots can blend seamlessly into their environment. This approach allows robots to evoke a calming effect, intruiging observers whithout disturbing those who do not want to be distracted; maintaining a balance between movement and stillness.

► **Inattentional Blindness |** Connected to the previous point, the concept partly relies on something called inattentional blindness; when we miss noticing something that is right in front of us, even though it is perfectly visible. It occurs because our attention is focused on something else, like a task or stimulus, causing us to overlook other things in our surroundings. So, even if an unexpected object is right there, we might not see it if we are too focused on something else (Kreitz et al., 2015). Others may also call it change blindness or perceptual blindness. Thus, this concept will use this intentionally, but will also play with the boundary of when it becomes noticeable in order to achieve its goal.

► **Plant Intelligence |** In a design case study involving plant-hybrid robots, the concept subtly intertwines with themes exploring diverse forms of intelligence. By considering ways to make plants visibly more alive, the project challenges human perception of plants. While plants are inherently alive and capable of plant-communication, their inanimate appearance and slower timescale may lead humans to overlook their liveliness, unless they die and loose their colour. Moreover, when extracted from earth and put into indoor pots, plants lose some of their natural ability to communicate through their roots, stems, leaves, flowers, and fruit (Yang, 2023). However, by integrating plants into a swarm intelligent robot system, the project aims to restore their autonomy. Rather than exploiting plants for human benefit, the integration of technology allows for the expression of plant intelligence, fostering a symbiotic relationship between humans and the natural world. This approach challenges traditional notions of hierarchy and dominance, advocating for a more equitable coexistence between humans and nonhuman entities.

5.3 Attention Points

► **Feasibility |** Given the low TRL level, there is much to explore regarding feasibility. Building a prototype will provides insights on the speed and plant sensor interaction:

✲ **Speed |** How slow could such a robot move through a public space like this?

✲ **Plant Sensor |** Is the envisioned interaction with the plant sensor feasible for the working prototype?

The project is mainly focused on the HPI and therefore has little focus on energy supply and charging solutions.

► **Desirability & Viability |** The project investigates its perception on long-term marketability. It is expected that potential for mass production is extremely low. Instead, the project is initially approached as a unique intervention (or art project). Understanding how individuals perceive the purpose of the project is however still crucial for guiding its development and ensuring its relevance and impact in its potential future.

► **Ethics |** Considering whether plants would enjoy being touched or used as part of an electric system raises questions about how we treat them. While it is uncertain if plants have emotions like humans have, and given that the debate on whether plants have emotions is an entirely separate research field, it remains relevant to acknowledge. Added to that, some claim that certain plants show they do not like human touch because it affects their overall health (Yarden, 2022).

From a human perspective, it should be investigated whether the subliminal movement of (plant-hybrid) robots could potentially have psychological effects, such as extreme fear or confusion, on what individuals perceive. In that case, the existence of such robots should be questioned.

06. Building the Prototype

This chapter summarises the building process of the prototype and its results.

6.1 General Overview

The prototype development began with early experiments, including dismantling a pre-made remote-controlled car (see **Fig. 15**). However, this approach lacked sufficient control over movement and noise, but still resulted in a basic moving plant that gave a simple impression. This was a motivation to build a platform from scratch.

The second prototype was built with stepper motors, mecanum wheels, an Arduino Uno WiFi Rev 2, a CNC shield and more (see **Paragraph. 6.2.1**). The platform was laser-cut from wood and provided structure for the robot. An enclosure was also constructed to hide the electronics and blend with plant pots in the faculty environment. This custom-built prototype offered improved control and functionality, a milestone in the project's development and was further used in user tests (see **Ch. 8**).

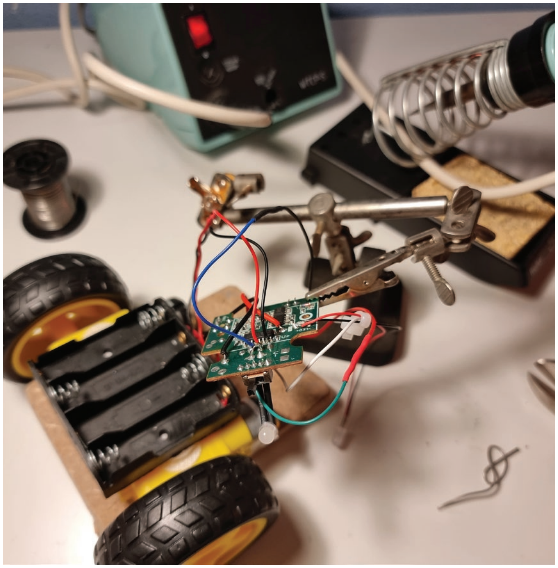


Figure 15. Early prototyping activities: Repurposing parts of an RC car.

6.1.1 Prototype vs. Concept

► **Dissection |** Due to feasibility reasons, the concept has two prototypes: one for the moving platform and another for the plant sensor. A key difference between the prototype and the design is that the design incorporates a plant sensor to gather input for the output of the moving platform. However, the working prototypes are separate.

► **Oz |** The prototype is remote-controlled and does not operate autonomously with an algorithm. This allows the researcher to conduct experiments with the Wizard of Oz method, which is a commonly used method in HRI (Riek, 2012; Zamfirescu-Pereira, 2021).

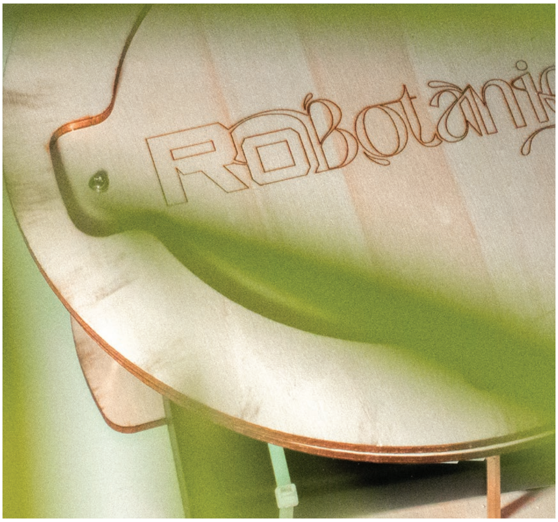
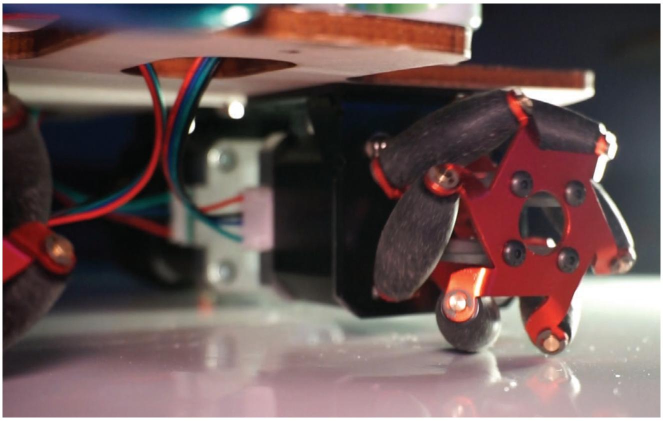


Figure 16. The platform prototype. Custom laser-cut platform.

6.2 Platform Prototype



► **General Description |** This prototype is a mobile robot platform that is built with Arduino and controlled via Bluetooth. The platform can drive in 8 directions, rotate, and is extremely slow; 0.0005 m/s to 0.05 m/s. Additionally has been optimised to be as quiet as possible in order to achieve subtle movement.

► **Use |** Working prototype used to demonstrate and test the envisioned (physical) behaviour (see **Fig. 17**).

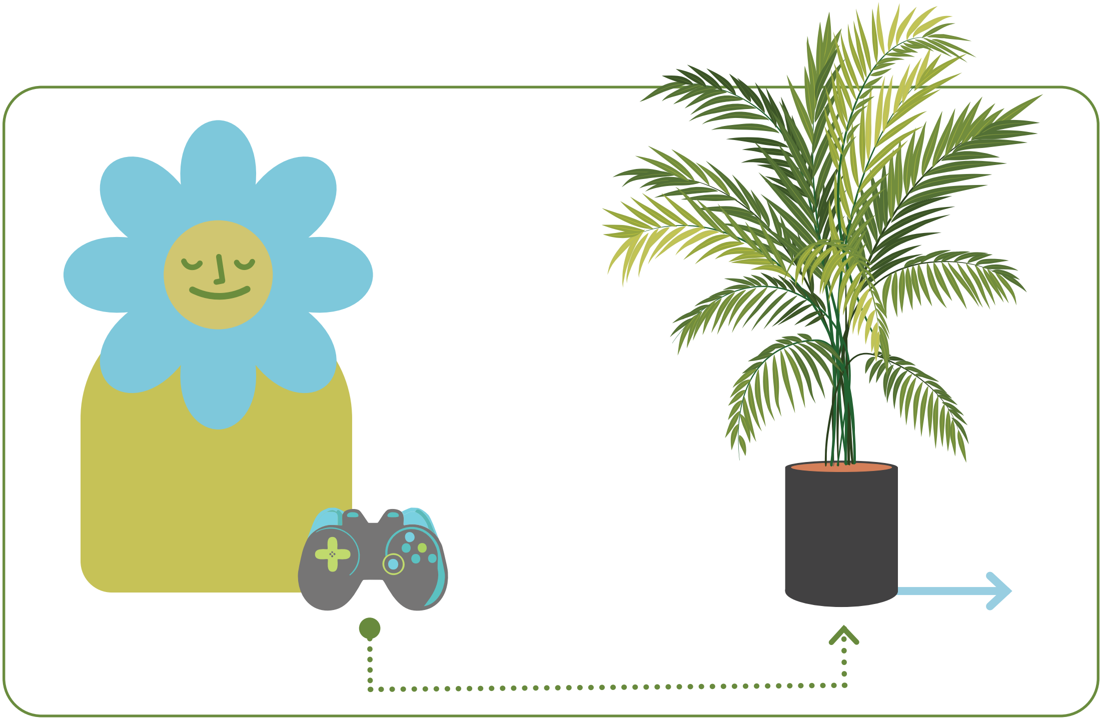
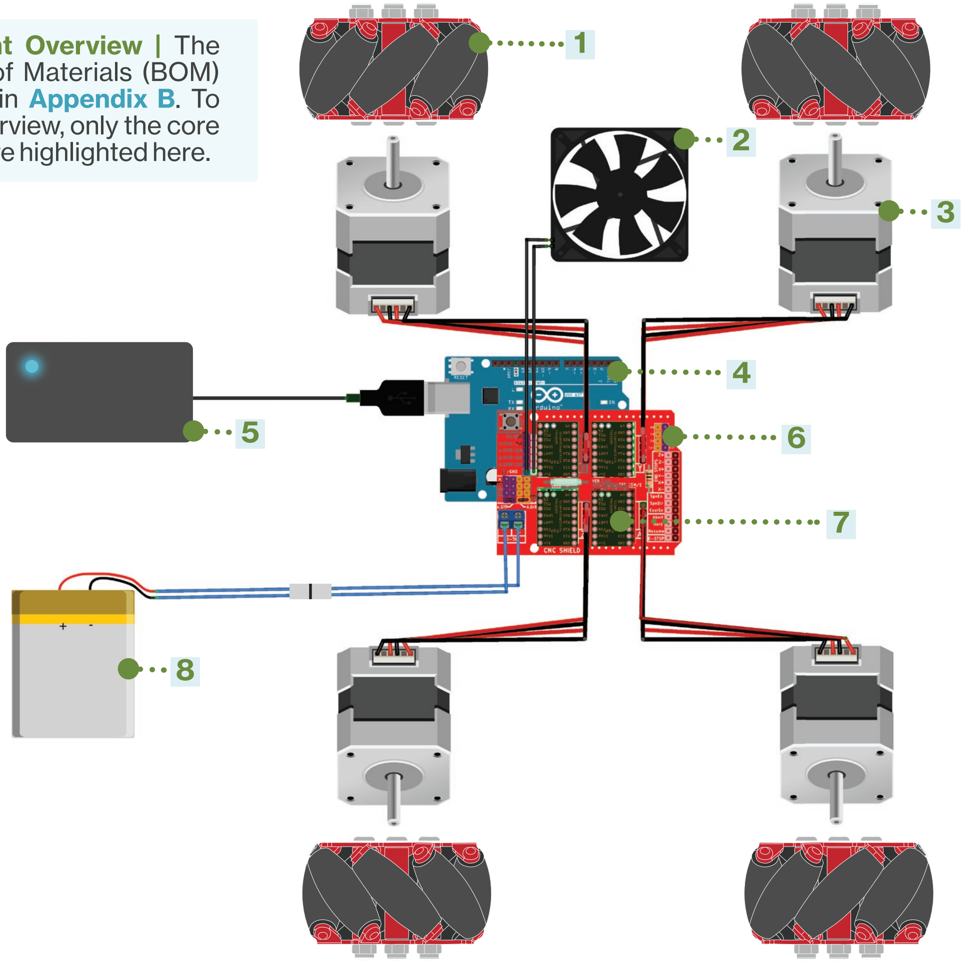


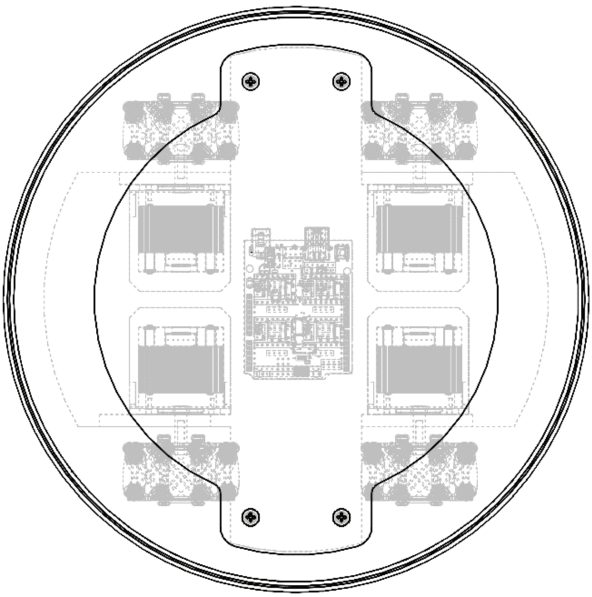
Figure 17. The researcher uses a Bluetooth controller to move the prototype.

6.2.1 Hardware (Configuration)

► **Component Overview |** The complete Bill of Materials (BOM) can be found in **Appendix B**. To give a brief overview, only the core components are highlighted here.



#	Part
1	Mecanum Wheels
2	Cooling Fan
3	Stepper Motors
4	Arduino Board (Microcontroller)
5	Powerbank (5V)
6	CNC shield
7	Stepper Drivers
8	Rechargable Battery (12V)



6.2.2 Software (Code)

```
#include <AccelStepper.h>
#include <Bluepad32.h>

void setup() {

}
void onConnectedController () {

}
void onDisconnectedController () {

}

void processGamepad () {
  if (gamepad->axisRX() < 0 & gamepad->axisRY() == 0) {
  moveSidewaysLeft();
  }

  else{
  stopMoving();
  };
}

void loop() {

}

void moveForward() {
  LeftFrontWheel.setSpeed(-wheelSpeed);
  LeftBackWheel.setSpeed(-wheelSpeed);
  RightFrontWheel.setSpeed(wheelSpeed);
  RightBackWheel.setSpeed(wheelSpeed);
}
void moveBackward() {

}
void moveSidewaysRight() {

}
void moveSidewaysLeft() {

}
```

▶ **Code Architecture |** The complete Arduino code can be found in **Appendix C**. To give a brief overview, the code is broken down into blocks.

Set up | The code includes the AccelStepper library (McCauley, 2010-2021) to control the stepper motors and Bluepad32 library (Quesada, 2021-2023) to set up the Bluetooth connection with the game controller.

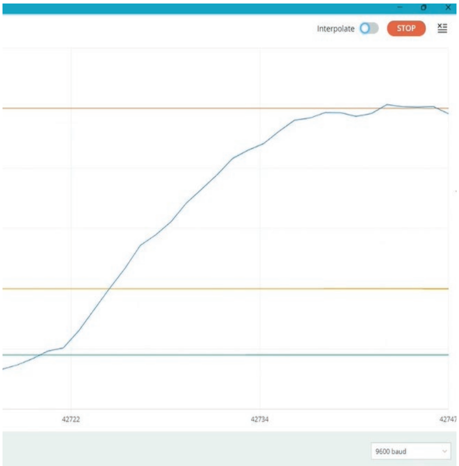
Mapping buttons | This is where the two libraries are combined. If a button is pressed or a joystick is moved, it triggers another function (last block), e.g. moveSidewaysLeft() to actuate the motors.

Loop | Here the controller constantly checks for a new trigger and executes the corresponding function.

Drive Directions | Mecanum wheels individually alternate in rotating direction (using minus to flip it) in order to move the platform in the desired direction as a whole. Due to the hardware configuration, the forwards direction needed 'negative' rotation for the two left wheels in order for them to move in unison.

Figure 18. Prototype configuration of the plant on the platform (top). Prototype is placed in context with a suitable cover, in order to fit into its environment (bottom).

6.3 Sensor Prototype



▶ **General Description |** This prototype is a plant-sensor that senses human activity. The protoype gives insight on the feasibility and practicality of a Arduino based plant-sensor.

▶ **Use |** Working prototype used to demonstrate and test the envisioned sensing capabilities (see **Fig. 19**).

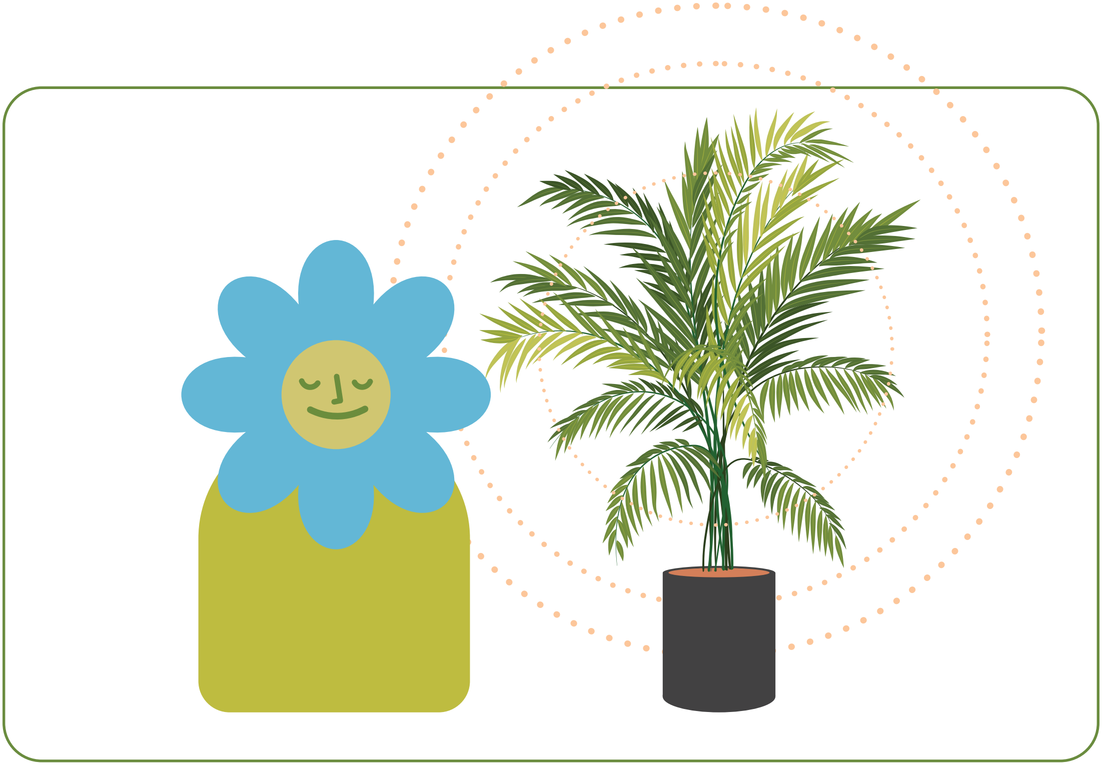
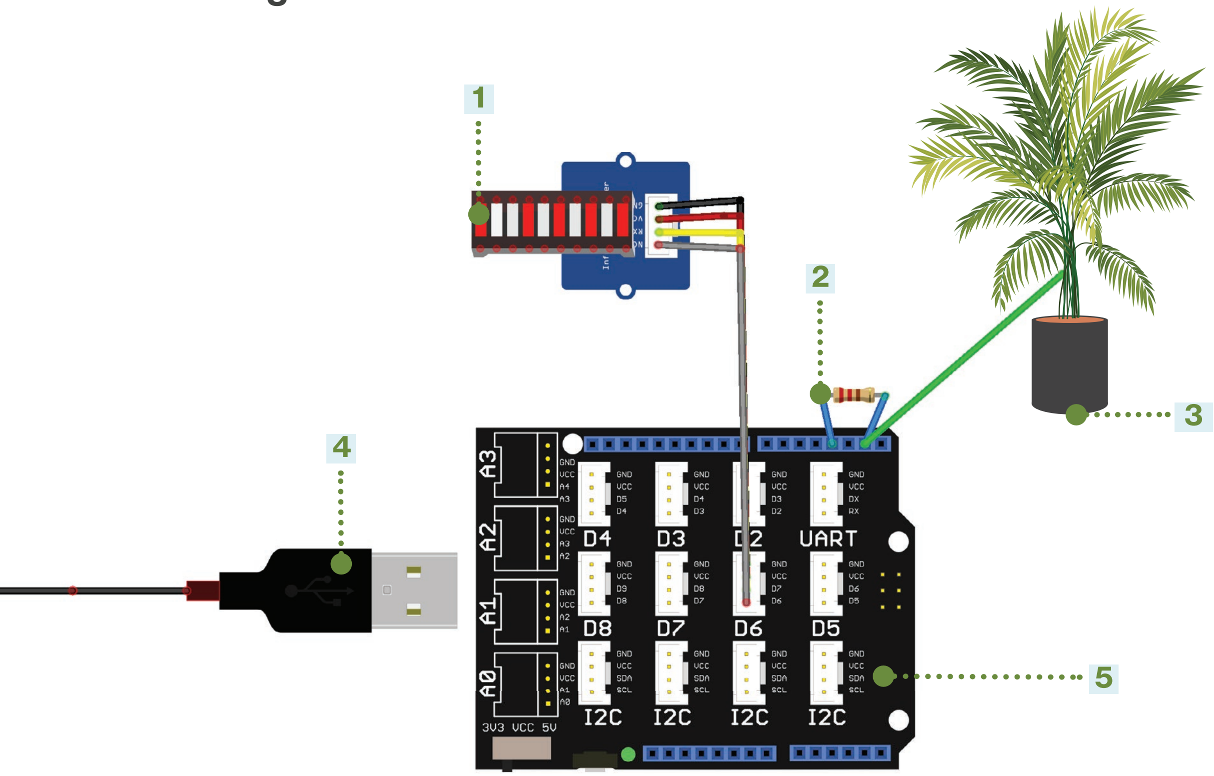


Figure 19. The prototype senses human activity.

6.3.1 Configuration



#	Part
1	Actuator (LED Bar)
2	Resistor (min. 1 MOhm)
3	Plant (Dypsis Lutenscens)
4	Powersupply (Laptop)
5	Arduinio Board
6	CNC shield

► **Plantsensor with Arduino** | The prototype is based on a tutorial by Rajesh (2020) via Circuit Digest. The prototype essentially acts as a capacitive sensor, using the plant body as a contact surface. A wire is connected to the plant to serve as an electrode. Upon contact with the plant, variations in capacitance resulting from our body's presence will be detected by the circuit.

▶ **Code Architecture |** The complete Arduino code can be found in **Appendix D**. To give a brief overview, the code is broken down into blocks.

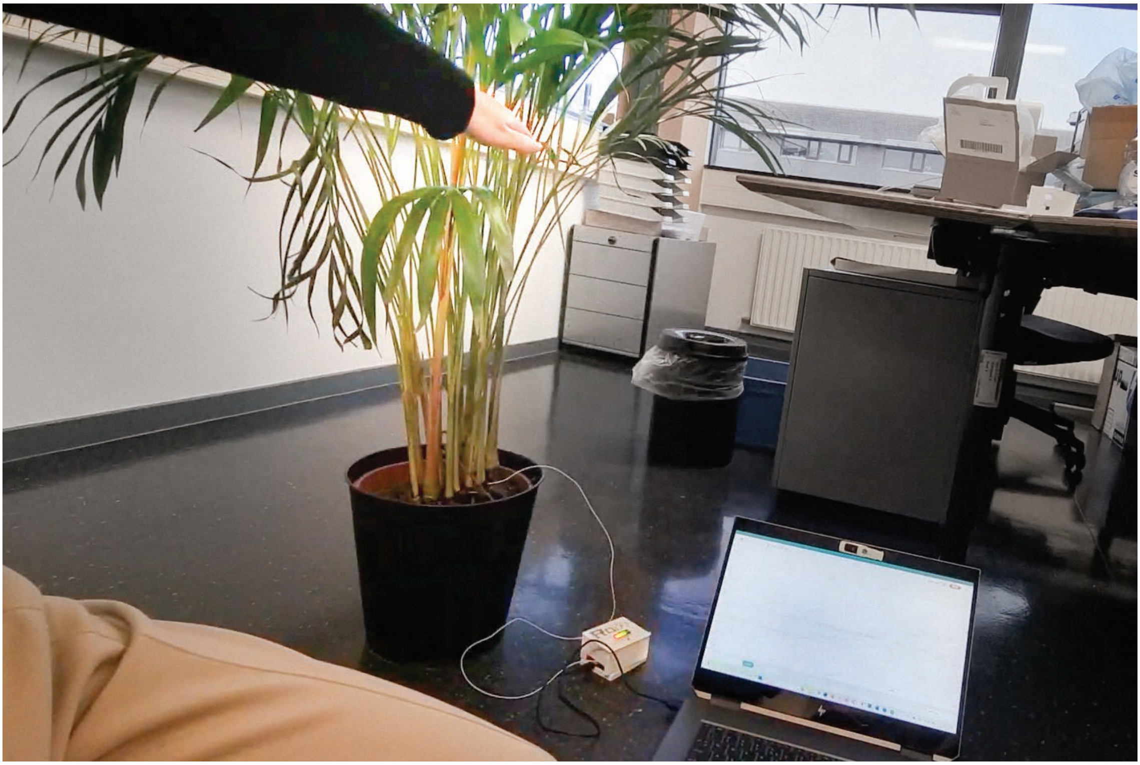
6.3.2 Software (Code)

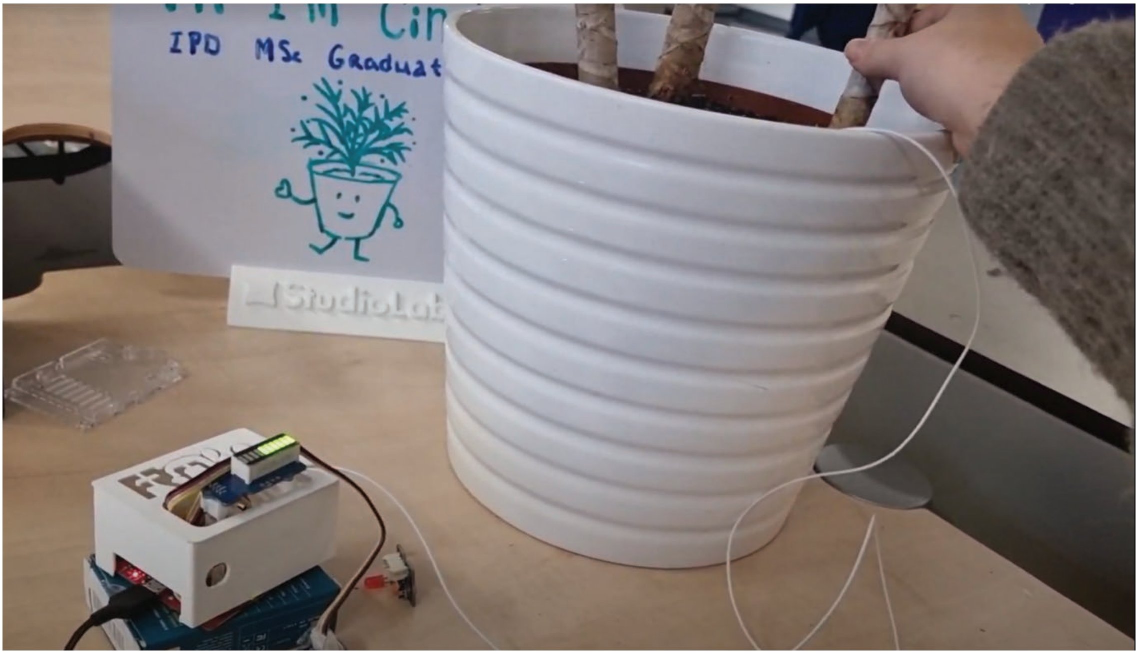
```
#include <CapacitiveSensor.h>
#include <Grove_LED_Bar.h>
#include <MovingAverage.h>

int threshold1 = 75; //baseline
int threshold2 = 180; //close distance
int threshold3 = 210; //touch distance

void setup() {

}

void loop() {
  long sensorValue = capSensor.capacitiveSensor(13);
  filteredOutput1 = filter.addSample(sensorValue);

  if (filteredOutput1 >= threshold3){
   i = 10;
  }
  else if (filteredOutput1 >= threshold2 && filteredOutputz<=
  threshold3){
   i=5;
  }
  else{
    i=1;
  }
  bar.setLevel(i);
 }
```

Set up | The code includes the **CapacitiveSensor** library (Badger & Stoffregen, 2009-2016) to create the sensing capability, **Grove_LED_Bar** library (Seeed Studio, 2010) to set up the LED bar and **MovingAverage** library to clean up the noise values (Carey, 2021).

Getting Values | This is where the sensor data gets retrieved and filtered.

Output | Depending on which threshold is overtaken, the LED bar will show the corresponding level. Given that every plant is different, the thresholds require some finetuning. This also depends on the chosen resistor.

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6.3.3 Prototype Iteration

► **Prototype In a Day |** With the knoweledge gained, a prototype is created to demonstrate plant sensing capabilities, which allows people to experience the sensor through visual feedback (see **Fig. 20**). Similar to related works, but simple Arduino Setup. This serves as a demo-prototype to showcase the concept of having a plant interface, which makes it easier to explain the sensor with direct feedback. Instead of a LEDbar, this prototype makes use of 3 chainable LEDs and a servomotor. These are triggered by 4 situations that all have their own behaviours: Idle, Close Distance, Touch, Long/Heavy Touch.

► **Creative Code |** For this demo-prototype, an additional serial plotter is created with Processing, visualising data beyond the built-in Arduino serial plotter. This visualiser is focused more on aesthetics and interaction. Therefore it does not show the exact values. Increasing values influence the size, placement and intensity of colourful particle generation (see **Fig. 21**). The Processing code can be found in **Appendix E**.

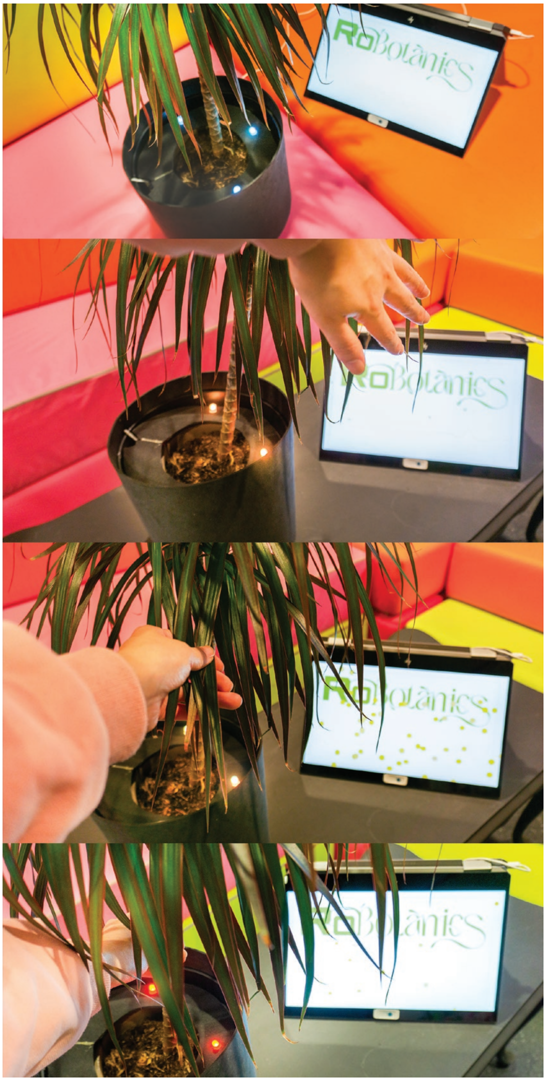


Figure 20. The prototype feedback.

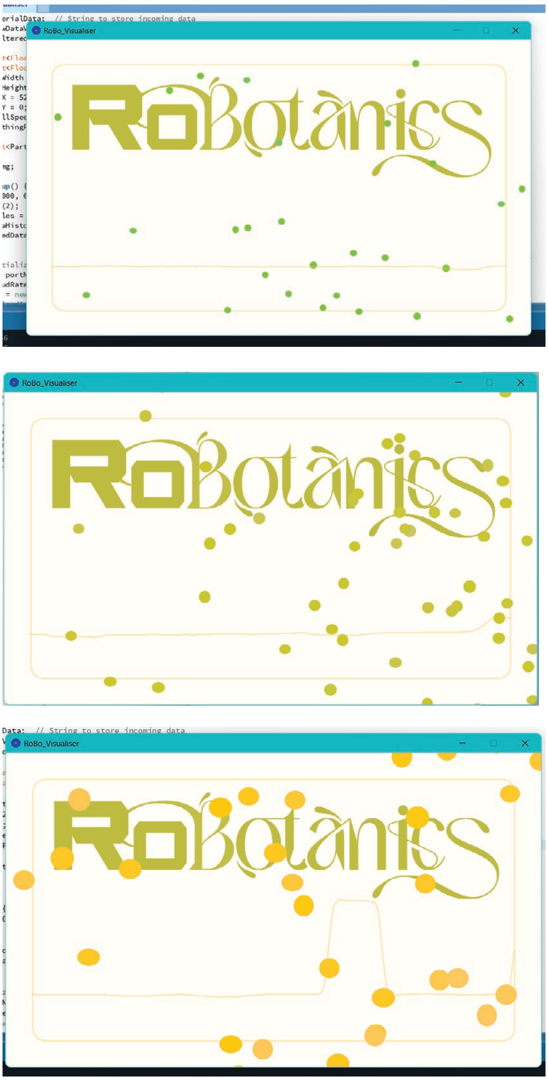


Figure 21. Prototype visualiser. Increasing values influence particle generation.

6.4 Additional

► **Simulation |** To have some impression of the bigger picture, a logistics simulation has been set up (see **Fig. 22**): The IDE faculty (top-view) with people and plants. Plant-sensors would pick up human activity, which then could be mapped out. Heatmap shows higher populations of people at designated areas. The swarm could use this information to navigate. This simulation is purely for visualisation purposes and is not powerd by an actual algorithm that carries out this proposal. Although it is very basic, it visualises what such a swarm would look like from above and what it could 'see' (human activity). In the simulation there are two agent groups, a human one and a plant one. Both have been given a set of rules. It should be noted that the rules given to the humans is extremely simplified and based on educated guesses, e.g. how many times people would move to the toilet or get coffee.

► **Combining Prototypes |** An attempt to combine the prototypes been done as well. This however presented issues that were out of scope for this project. More details about this experiment can be found in **Paragraph 8.4.3.**

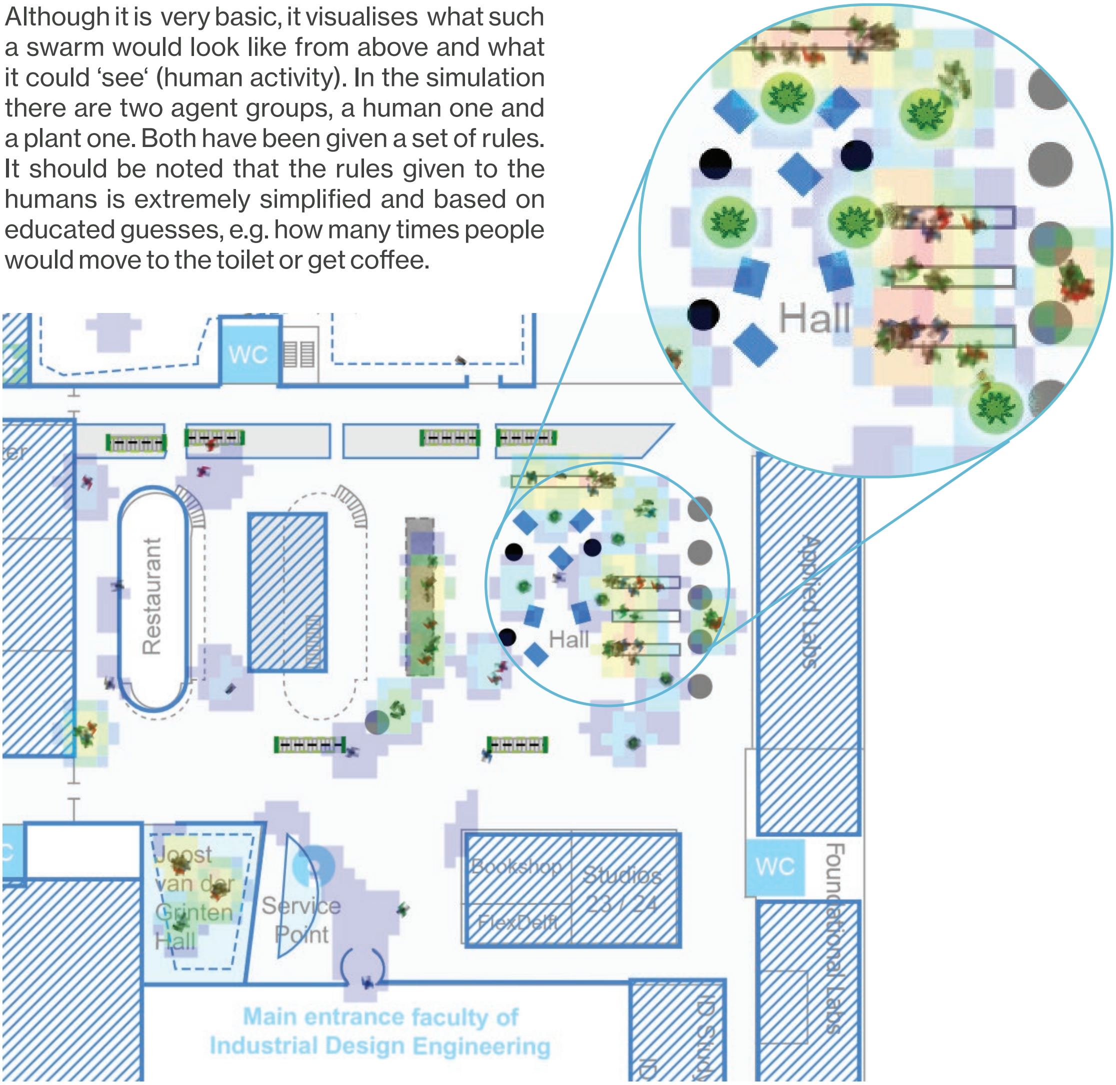


Figure 22. Screenshot of the simulation: The IDE faculty (top-view) with people and plants.

07. More Thoughts For Designers

Overview of observations on topics discussed in this section: **Creating RoBotanics.**

Plant as a Component

How might we prototype with plants as (touch) sensors? | Using plants as sensors presents an intriguing opportunity for designers. Although their setup is fairly simple, they do not provide exact measurements like traditional sensors do as mentioned in **Paragraph 6.3.2**. Instead, they work within ranges or thresholds, which adds some unpredictability and requires a lot of fine-tuning to get a fairly stable prototype. This requires patience. The inconsistency most likely occurs because of multiple factors such as the users' clothes, the plant's physiological state, contact with interfering materials etc. For now, this was resolved by manual adjustments and re-uploading the program to the microcontroller when the system is not optimal. For an ideal system, designers could perhaps explore live-finetuning by the end-user that allows the system to set a new threshold when it is required without touching the code. Or for example, look at the slope of the plot instead of the literal values, basing triggers on the steepness of change in values. Despite this challenge, using an **Arduino** microcontroller has been proven to be a valuable and relatively easy way to explore plant-hybrid technologies for beginners, and serve as an introduction to prototyping for plant-hybrid electronics.

What might happen if we see plants as any other hardware component? | Testing different plants produced various outcomes, showcasing the potential of seeing plants as interfaces. Similar to selecting e.g. specific game controllers for your concept, choosing different plants creates different HPI experiences. This approach echoes the research project 'Botanicus Interacticus' by Poupyrev et al. (2012), emphasising the flexibility in plant selection for design projects. Seeing plants as components is at the core of this project and evidently presents an opportunity for exploration and experimentation.

How might we intentionally use plant physiology? | Do not overlook the physiological characteristics of the plant, as observed during the prototyping and testing phase. Prior to building the prototype, there was an assumption that a plant-hybrid robot is only truly hybrid when it has direct integration of electronics. However, the prototype demonstrates that this does not always have to be the case when the specific plant choice clearly interacts and influences the overall system. For instance, the bouncy leaves of the ***Dypsis Lutescens*** exceeded expectations by responding to the actuators in unexpected ways, influencing the overall perception of the system. Variations in speed, turns, and other movements resulted into different responses from the plant, which shows that the plant itself became a crucial part within the system. Substituting it with a cactus, for instance, would result into a completely different effect, highlighting again how the chosen plant functions as a component rather than it being a randomly selected. Instead of looking at a specification sheet of hardware components, designers could look at physical properties of plants to satisfy their intended use.

Concept

How might we make ethical decisions in this field? | As designers who are interested in exploring plant-hybrid projects, it may be valuable to reflect on how we interact with plants, especially when incorporating them into technological systems. While the emotional experiences of plants remain uncertain, well-being should be considered in design choices. Although the debate on plant emotions is not our specialty, it is a valid concern. In this case, it became clear that some may question whether it is desirable to stimulate touch with plants, as people were worried ‘they will not like it‘, potentially resulting in stress for the plant.

How might we design for non-human entities? | An iteration of this concept involves the plant sensor not solely reacting to humans for amusement, but benefiting the plant’s system and algorithm in navigating as a swarm. This thought is connected to **Paragraph 5.2**, about Plant Intelligence. Instead of having a simple interaction where the human touches the plant and receives instant feedback, it uses the input for something beyond that. Human touch and proximity could influence where the swarm ‘wants’ to be, informing its peers on the other side of the hall to move a certain way. Besides the plant-touchsensor, humidity and light sensors could make this decision making algorithm even more complex, similar to how humans make daily decisions based on numerous factors. Ultimately, the communication serves the swarm itself rather than the human alone, satisfying the vision to restore the plant’s autonomy.

✲ SECTION III: Deploying the Robot

08. Experiments

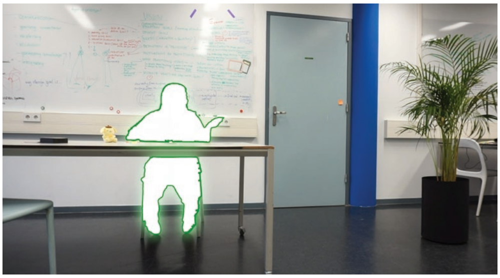
09. Wrap Up

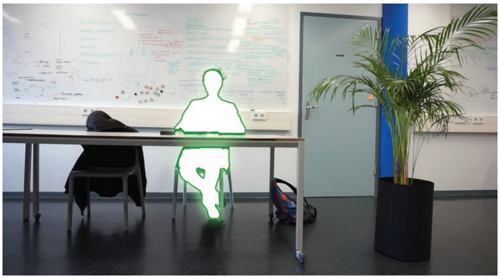
10. Final Thoughts for Designers












08. Experiments

This chapter summarises main observations from the experiments that were conducted during the project.

8.1. Overview

Within the project, several experiments have been conducted. One big one, the perception test - **Paragraph 8.2**, in which the slow movement is tested with 11 individuals. Secondly, some informal experiments through deployment of the robot in contexts - **Paragraph 8.3**, in which the robot is tested 'in the wild'. Lastly, some experiments with the plant sensor - **Paragraph 8.4**, in which the plant-sensing capabilities with the Arduino prototype is tested.

8.2 Perception Test

Prototype: Platform

Location: Lab

8.3 Deployment

Prototype: Platform

Location: Office/Context (public hall)

8.4 Plant -sensor feasability

Prototype: Sensor

Location: Lab

8.2 Perception Test

This experiment is conducted to gather insights on the perception of the movement of a slow moving mobile plant-hybrid robot.

8.2.1 Methodology

Introduction | Previous research states that design for swarm robotics motion should specifically focus on optimising the velocity of robots since that has the highest impact on human perception (Dietz et al., 2017). Therefore the focus of this experiment lies primarily on the velocity, rather than the location and direction of the movement. The test is conducted with a prototype moving at three predetermined constant speeds; Slow - **0.0005 m/s**, Medium - **0.005 m/s**, and Fast - **0.05 m/s** The slow speed is the slowest possible speed with the setup where the robot still drives smoothly, rather than with visible instances of steps. Afterwards, the speeds increase with a factor of 10 to have three distinctly different speeds. The highest speed is significantly higher than the slowest speed, but still much slower than a human. A previous study found that humans generally prefer slower robot speeds and states that an overtaking robot was considered to be less comfortable than passing the robot themselves (Neggers, 2022). Therefore it is desirable that the 'fast' tested speed is still much slower than the average walking speed, which has been measured at 1.0 - 1.5 m/s for adults (Levine & Norenzayan , 1999; Ali et al., 2018; Waters et al., 1988)

Through its slow movement, the concept aims to pull people back into the present while they are immersed and hyper fixated in their own 'personal bubble' (see **Fig. 23**). This means that the robot should be able to catch the humans' attention outside their focus gaze (**FG**). To verify this is possible at every tested speed, we observe when participants notice the movement of the plant while they are focused on a given task. In order to say something about how the speeds are experienced, cognitive perception is also considered.

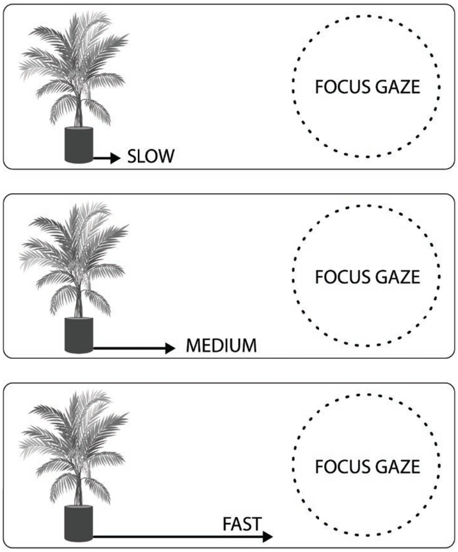


Figure 23. Moving towards FG in three speeds.

Set Up | The test will take place in a closed room. The participant will sit at a desk with a distraction activity in front of them (**Fig. 24**). This is to simulate a scenario where the participant's eyes stay within the FG. The participant is encouraged to 'think aloud', while they solve the puzzle. At an unannounced moment, the plant slowly moves around the room via the Wizard of Oz method. The plant starts at the border of the field of view (**FOV**) and slowly makes its way towards the FG. Once the participant takes note of the robot, the time (s) is noted down. Together with the known velocity, the displacement is determined too. After all speeds are evaluated, a post-task debriefing will take place to complete the session.

Additional Assumptions:

- FOV is about 200° wide (Klymenko et al., 1994).
- FG is about 20° wide while focused on a task (Tobii, n.d.).
- Human-Plant distance of the regular plants in the common hall is generally ~1.5m based on observation (educated guess).

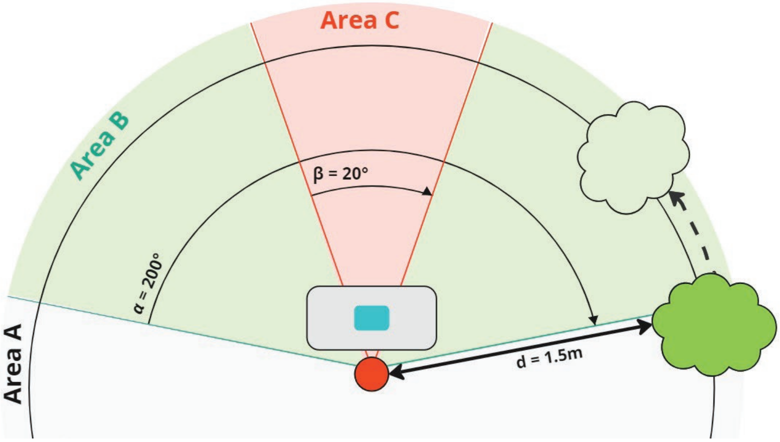


Figure 24. Setup Overview: Schematic top-view of the test setup (top), a photograph of the actual test setup in reality (middle) and the distraction activity (bottom).

d = human-plant distance.

Based on the common distance of plants in the IDE main hall (see **Assumptions**, p. 55).

Area A: Irrelevant Area

Space outside of max. FOV, so a wider angle than alpha, > 200° . Therefore this serves as a limit for the Perceptible area B.

Area B: Perceptible Area

Inside max. FOV, so < 200° & Outside focus area, so > 20°. Noticing the robot inside this area is a requirement, which should be verified. Hypothetically, different participants will notice the plant at different points within the perceptible area.

Area C: Focus Gaze Area

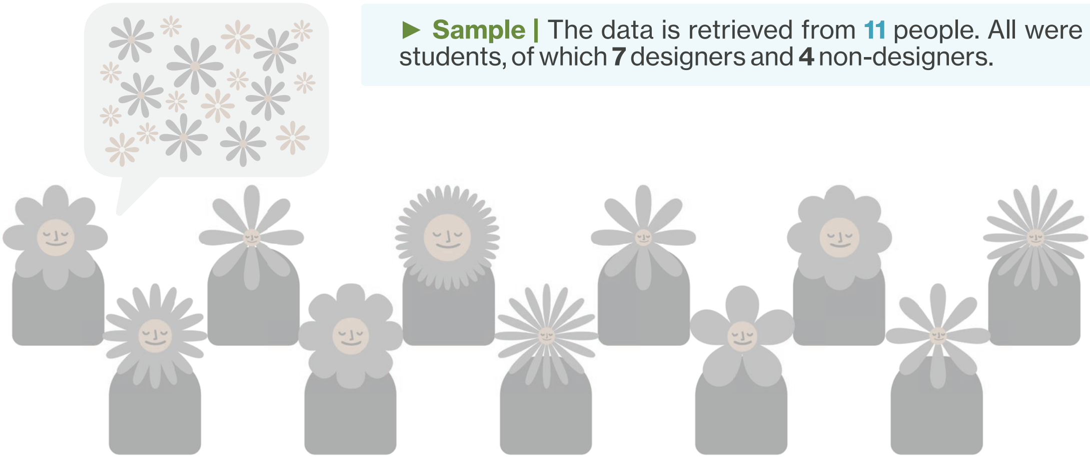
Since we keep our gaze inside of 20 degrees while focused on a task, it can be speculated that the plant will most certainly be noticed when it reaches this area. Therefore this serves as another limit for the Perceptible area B

8.2.2 Data Analysis

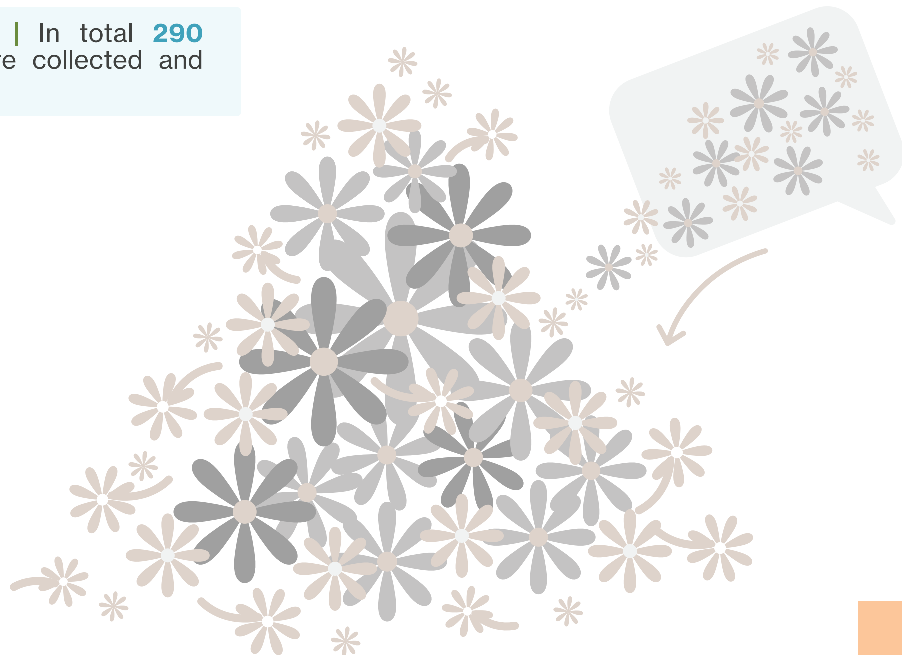
▶ **General Overview |** For the qualitative data analysis, the audio recordings were partly transcribed (excluding quotes about the distraction activity e.g. puzzle strategies) and organised in an Excel document. The transcribed data was then imported into Atlas.ti, a software used for qualitative data analysis. In Atlas.ti, the participant's quotes were carefully reviewed and sorted to find patterns and themes in what people actually said. Additionally, Atlas.ti helped make data visualisation, e.g. bar charts and word clouds, which visually demonstrate connections between ideas and highlight frequently mentioned words. This process allowed for an in-depth examination of the large amount of obtained data and provided meaningful insights.

For additional insights, the time (s) it took for participants to notice that plant has also been recorded. Lastly, the video footage provides extra information about non-verbal reactions.

▶ **Sample |** The data is retrieved from **11** people. All were students, of which **7** designers and **4** non-designers.



▶ **Quotes |** In total **290** quotes were collected and identified.



"I was wondering what it was doing, because I know it moves now, I was like mmm what are you waiting for?"

▶ **Making sense of it |** The quotes provide some impression of people's thoughts behind their reactions, but the amount made it quite overwhelming. That is why the data was clustered, categorised and analysed to make sense of a large amount of information.

"It feels weird to kind of look at a plant, in a paranoid way, whether it is moving."

really didn't realize you suddenly stood behind a plant. I was so into my game. Totally didn't notice, oops."

▶ **Overarching Groups |** Looking at the reviewed quotes and the nature of the test set-up, three main categories are identified:

✲ **Experience Reflection** | Quotes about how the participants experienced the experiment session.

▶ *"First one was **disturbing** the most because I think it moved the fastest."*

✲ **Perception Triggers** | Quotes about how the participants perceived the prototype through their senses, specifically visually and/or auditory.

▶ *"The **leaves are moving a lot**. Yeah you do notice that."*

✲ **Creative Interpretation** | Quotes about how the participants imagined and/or brainstormed about the concept.

▶ *"I feel like, yeah, **it might be a nice integration to** set like a certain tone in a certain area."*

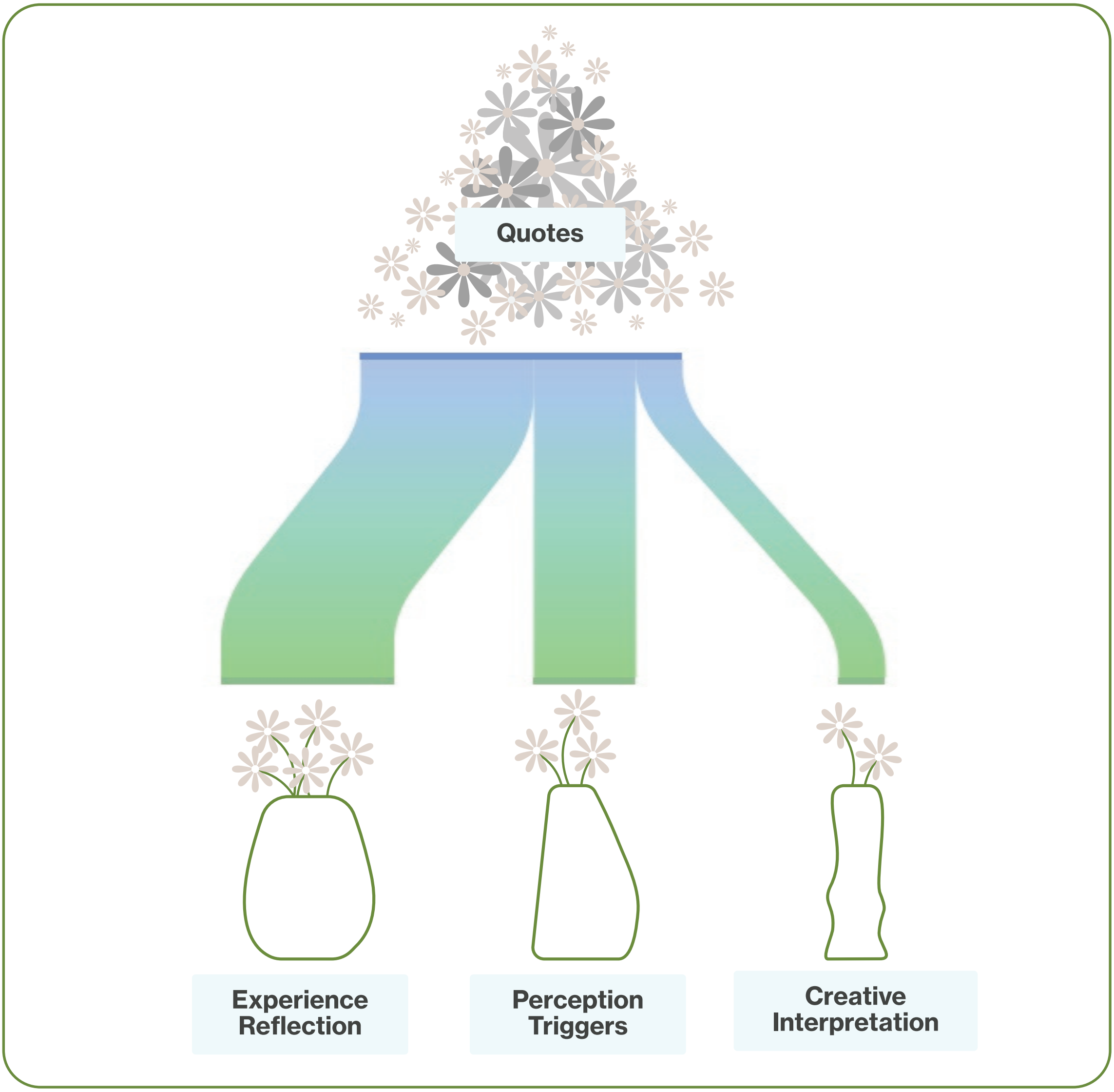


Figure 25. Visualisation showing the collected data categorised in groups. This demonstrates that in reality, most quotes were reflections on the participant's experience.

► **Combining Ideas |** Zooming in, these groups of quotes are further categorised into codes. **Figure 26** provides an overview of these codes and sub-codes. Given the amount of quotes, this allows us to get an even better understanding of what the qualitative data may indicate - motivations, values, concerns etc.

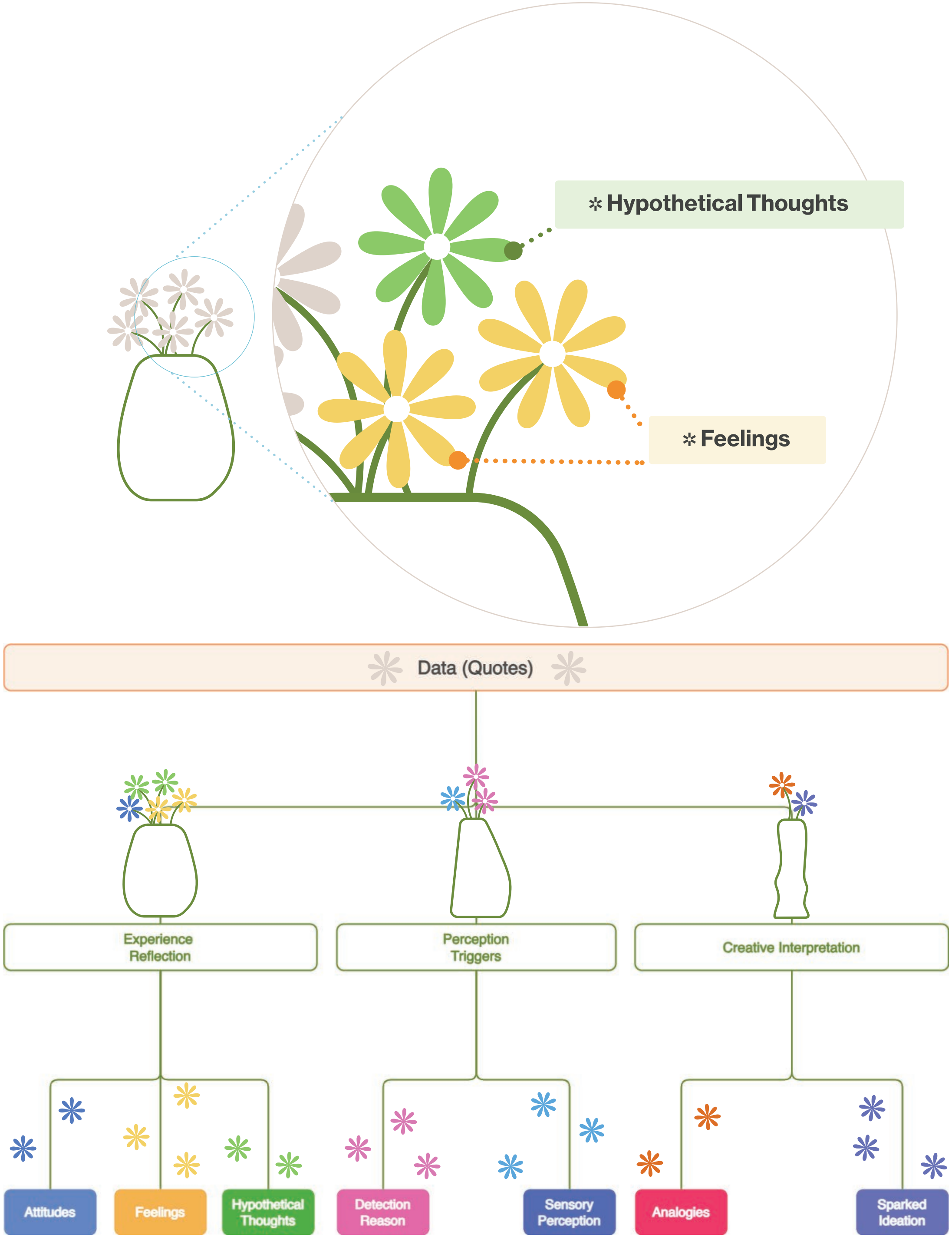


Figure 26. Diagram showing the collected data categorised in codes.

► **Sub-codes |** The last iteration; Identifying overlapping topics within codes. These are often very specific, but provide even more nuance to the data.

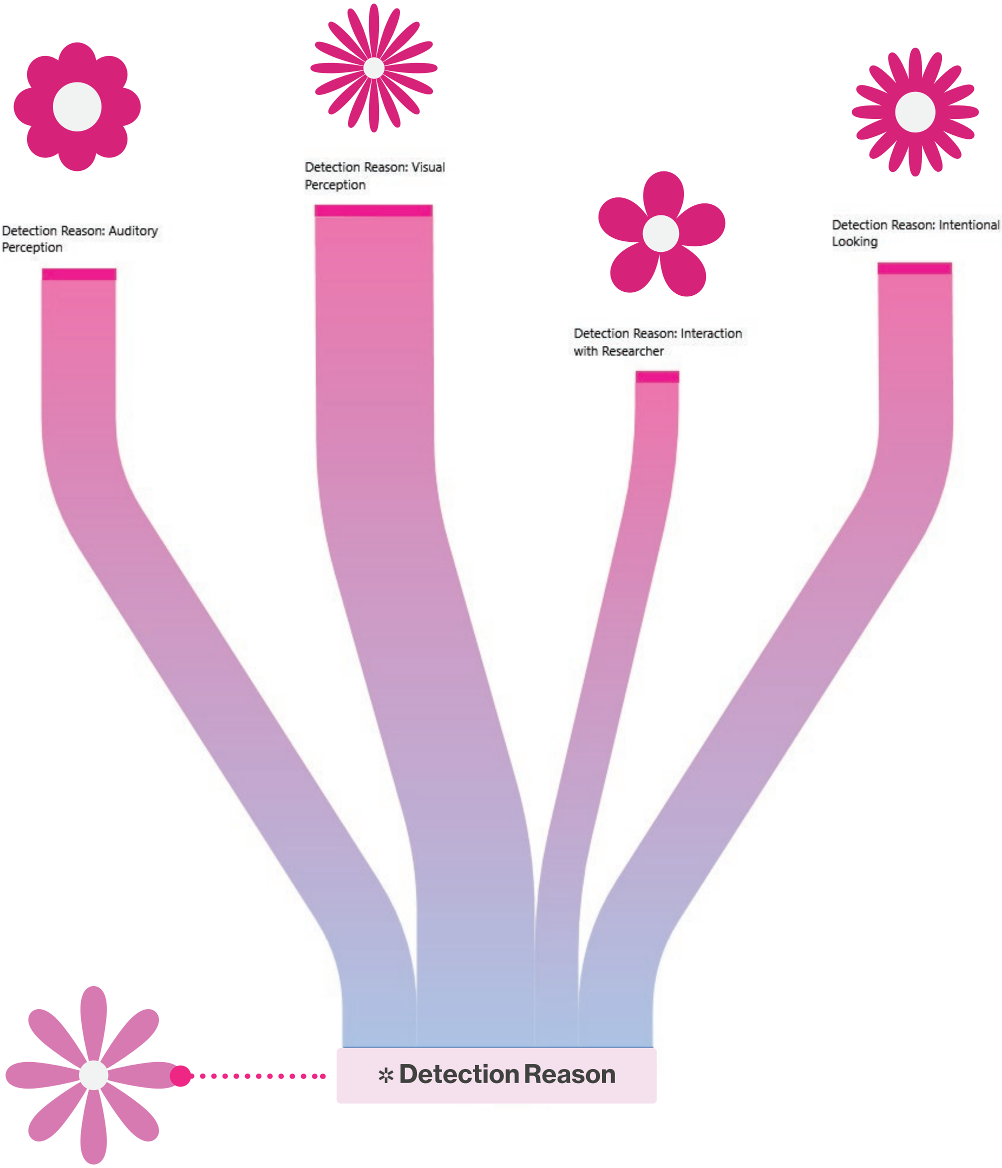


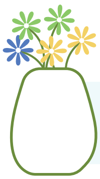
Figure 27. Diagram showing an example of how each code is further broken down to sub-codes: the 'Detection Reason' codeded quotes categorised into 1. Auditory Perception, 2. Visual Perception, 3. Interaction with Researcher, 4. Intentional Observation.

8.2.3 Interpretation

Observation statements | This paragraph elaborates on the interpretation of the data retrieved from the perception test, in which every **[A#]** code refers to a statement. This name system is used to reference the statements in the remainder of this document in the following manner:

(Observ. **A1**, **B1**, **C1** ...)

Overview



A. Experience Reflection | The following insights are about what participants expressed regarding their feelings towards the concept and prototype.

A1. Most people found the experience to be funny.	(p. 63)
A2. Negative feelings were often expressed in a hypothetical way.	(p. 63)
A3. People consciously want to keep an eye on the plant.	(p. 64)
A4. Designers are genuinely more accepting of the concept.	(p. 64)
A5. People perceived the distinct movements more than the actual speed.	(p. 65)
A6. People generally dislike the fast speed.	(p. 65)

B. Perception Triggers | The following insights are about what participants did or expressed following sensory triggers (visual, auditory).

B1. Time measurement does not say much.	(p. 66)
B2. Inattentional blindness is very prevalent.	(p. 66)
B3. People did not notice displacement for the slowest speed, but rather acknowledged the leaf movement	(p. 67)
B4. People had speed specific reasons why they detected the plant.	(p. 67)

C. Creative Interpretation | The following insights are about creative interpretations of participants about the concept; Analogies, Creative

C1. People associate the plant's movement with wind / outside nature.	(p. 68)
C2. People have similar ideas.	(p. 69)
C3. People also have unique ideas.	(p. 69)
C4. People have creative concerns.	(p. 70)

A. Experience Reflection | The following insights are about what participants expressed regarding their feelings towards the concept and prototype.

Overall Feelings

A1. Most people found the experience to be funny | The word 'funny' was mentioned **21** times by 7 out of 11 participants to describe their feelings towards the plant-hybrid robot.

A2. Negative feelings were often expressed in a hypothetical way | All 11 participants expressed concerns and/or imagined an experience outside the lab setting. For example: *"If it moves like really slow, I would be scared that someone would bump into it by accident".* These quotes are not about the experiment itself, but about what could be the case. Therefore it can only be seen as speculation, yet it does indicate certain values people have, in this case public safety.

> *"I would think it's distracting,* ***but I'm clearly not distracted****. I didn't notice it at all, but maybe with a task that I didn't like as much. Because* ***I can imagine it being distracting****."*

> *"I wouldn't mind, but I can imagine that* ***other people might think****, why is it there then? if it serves no purpose."*

A3. People consciously want to keep an eye on the plant | 9 out of 11 participants expressed that they either intentionally looked or had the urge to check on the plant. This conscious thought seems to be true for most people. Having this urge did not always mean, however, that the participant actually looked up. It does show that it is a common feeling that the majority shared. It should however also be noted that one person also expressed concerns since it may potentially distract them from their task.

Figure 27. Diagram showing 9 out of 11 expressed their anticipatory awareness of the moving plant while being engaged in their distraction activity.

A4. Designers are genuinely more accepting of the concept | Looking at the distribution of acceptance over designers and non-designers, the stereotype that designers may be more open to unusual ideas seems to be confirmed. Again, the small group is too small to claim this with confidence. It should also be noted that even in this small group, four people show that they do not fit this stereotype. Looking at the entire group, the data shows that the majority of the participants were accepting of the concept, while some were a bit more sceptical.

Figure 28. Diagram showing the difference in attitudes between designers and non-designers.

Speeds

A5. People perceived the distinct movements more than the actual speed | While the test setup is based on the three different 'speeds', participant experienced it more as three different 'movements'. This shows that the movements, as a result of a certain speed, says more about their experience with the plant than the actual velocity. Consequently, people rarely called the different modes 'the fast speed' or 'the slow one', but used other adjectives to describe the movements:

> *"**Smooth** is better for sure than **shaky**. Not only because of sound but because of the movement. It feels more natural."*

> *"So I would say the second one was more **Zen** compared to the first one because the first one was **just running around**"*

In the example above a participant called the medium speed the 'smooth' one and the fast one the 'shaky' one, using adjectives they visually perceived. In the second example, another participant describes the different speeds by how they **experienced** the movement.

A6. People generally dislike the fast speed. | Most negative feelings towards the speeds were expressed towards the fast speed. The motivations behind this were primarily the sound and the 'dramatic' movement, which would be too disturbing. The fast speed made the leaves of the chosen plant bounce the most and therefore also made the most sound. One could argue that it does not necessarily have to be negative since this could instead be used intentionally, in order to get attention.

> *"Okay but now I'm hearing it move. And it's pretty loud. **That was annoying**. I mean, I can tolerate it, but no."*

> *"It is **kind of disturbing**, because then it does not move smoothly. It just moves a bit in an icky way, so then I don't like it"*

B. Perception Triggers | The following insights are about what participants did or expressed following sensory triggers (visual, auditory).

Detection

B1. Time measurement does not say much | Looking at the recorded detection times (**Figure 29**), it is not possible to draw a solid conclusion given the small sample size and the large deviations.

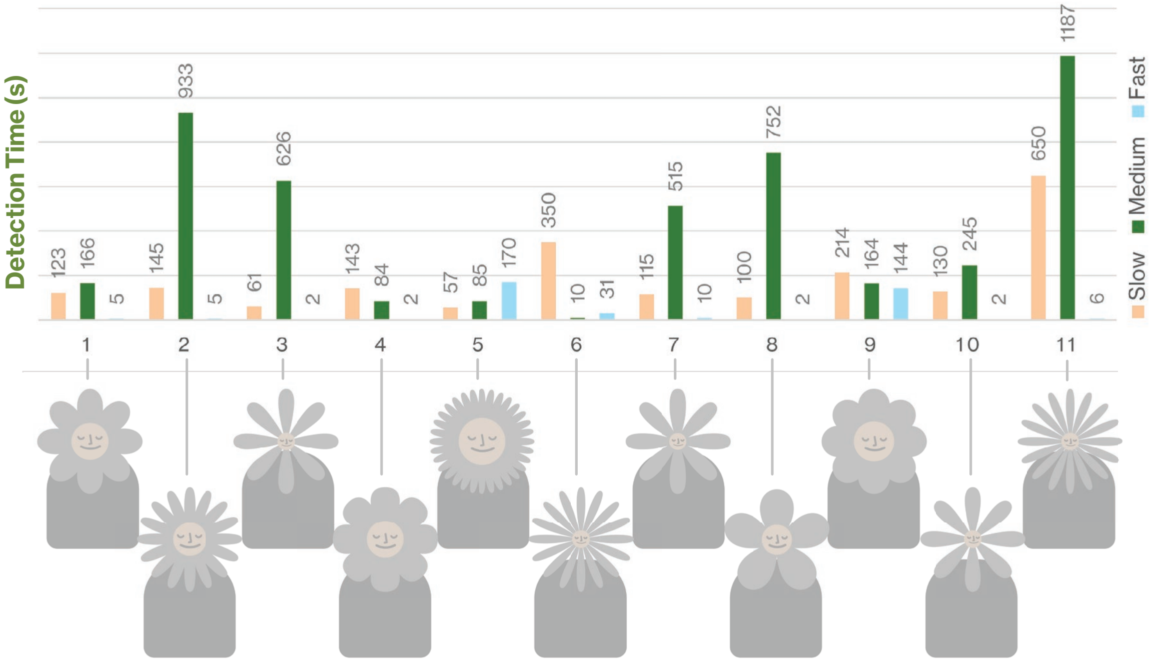


Figure 29. Bar chart showing measured detection times (s) at three speeds for each participant.

B2. Inattentional blindness is prevalent | One thing that could explain the deviation mentioned in **B1**, is that **6 out of 11** participants did not notice the plant moved closer to them, up until it reached the space in between them and the researcher. While some noticed slightly on the side of their field of view, there were **4 out of 11** cases in which it was fully in between the participant and the researcher (see **Figure 29**). In some instances, participants even looked up at the researcher, and continued with the activity, proving they genuinely did not register that the plant had entered their field of view. Although some inattentional blindness was anticipated, the working prototype was more effective than expected. For those people that experienced this, the detection times differ significantly from the others.

Figure 29. Example of a case where the participant did not notice the plant had moved in front.

Speeds

B3. People did not notice displacement for the slowest speed, but rather acknowledged the leaf movement | The slowest speed was noticed relatively early, while it should in principal be hardest to notice. Only for 3 out of 11, this was the longest recorded time (see **Fig. 29,** #4, #6 and #9). This is most likely due to the fact that it was never done first and therefore, participants were more inclined to intentionally check the plant due to prior knowledge (Observ. **A3**) and consequently noticed the plant's subtle movement. The movement was not seen as a displacement, but rather as a movement on its place, since the leaf displacement (bouncing) was bigger than the overall displacement over the floor.

> *"I saw the leaves just- In the corner of my eye I saw the leaves just vibrating a bit. But I think- (...) Is there like a vibrating motor in there?"*

> *"**It's shaking**. Or is that the wind? (...) didn't notice at all. It's shaking? what? okay, funny."*

> *"Not really moving to be honest, like not just changing place but **moving in its place**."*

B4. People had speed specific reasons why they detected the plant | People had different reasons to look up and notice the plant, but some seem to be speed specific. The chart below shows the distribution of the sub-codes describing the plant detection reasons (see **Fig. 31**). For example, auditory perception was only high for the fastest speed. This can be explained because the fast speed caused some noise of the mechanism (platform) and leaves rustling in a way that was unique to that speed. For the sub-code **Intentional Looking**, the result is most likely influenced again because of the order in which participants experienced the different modes (see **Observ. B3**). In order to intentionally look, prior knowledge is required. Therefore this one is not necessarily speed specific.

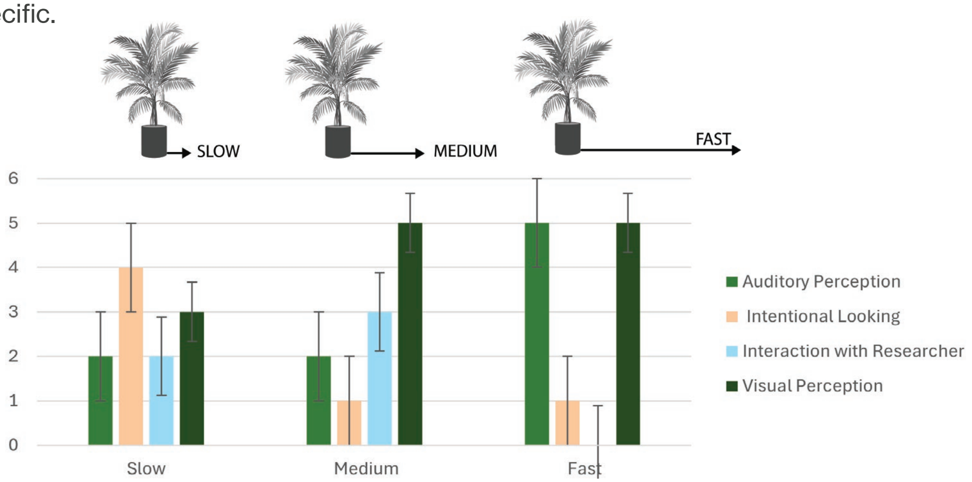
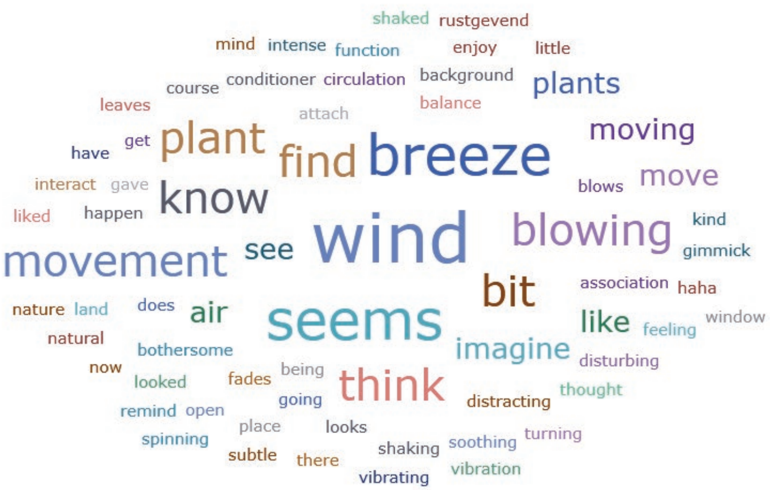


Figure 31. Barchart showing large differences between the conditions: Slow, Medium and Fast.

C. Creative Interpretation | The following insights are about creative interpretations of participants about the concept; Analogies, Creative

Analogies

C1. People associate the plant's movement with wind | The subtle movement of the plant's leaves made people think of the wind. Of all participants, 7 out of 11 people made this comparison. One person also mentioned the similarity with AC air flow on indoor plants.



"It's like ***when you open the window****, the wind blows through the plant. That gave me that kind of feeling."*

"That might also be a nice thing also in like indoor environments like if you see the leaves moving it might give like a feeling of wind. ***From plants outside, from trees outside****. So that might also bring some more ambiance to the environment, to the room."*

Creative Ideas

C2. People have similar ideas | Looking at the data (**Figure 32**), top three mentioned concepts were: 1. Environment Enhancement. 2. Creating Spaces. 3. Companionship. Further elaboration in **Chapter 9**.

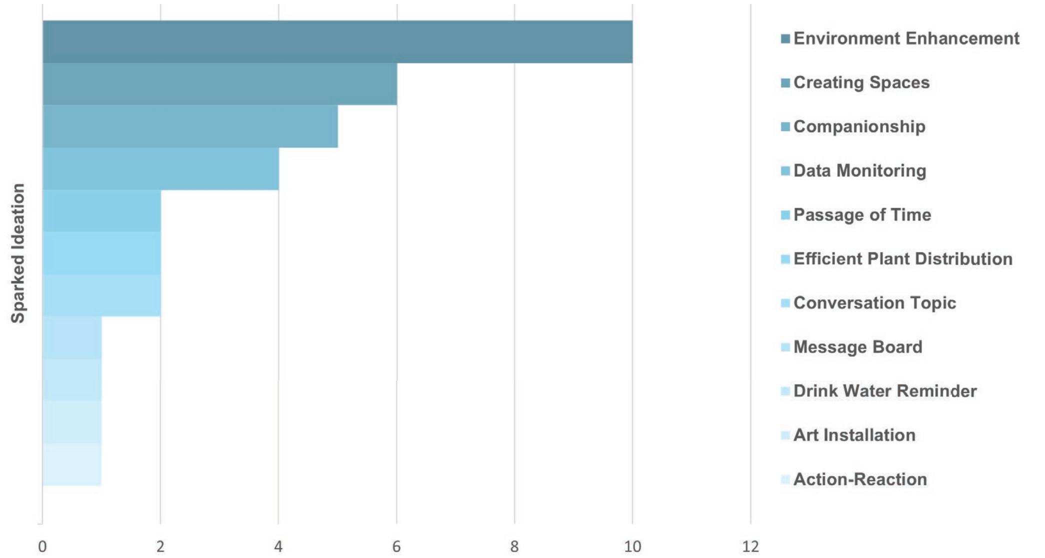


Figure 32. Barchart showing the frequency of mentioned ideas.

C3. People have unique ideas | Next to the overlapping ideas, there were a number of unique or relatively unique ideas that came up (**Figure 33**). The diagram above show the idea output per participant, showing overlap with other participants, but also unique outputs. This ranged from more psychological based concepts to more practical based concepts. Further elaboration in **Chapter 9**.

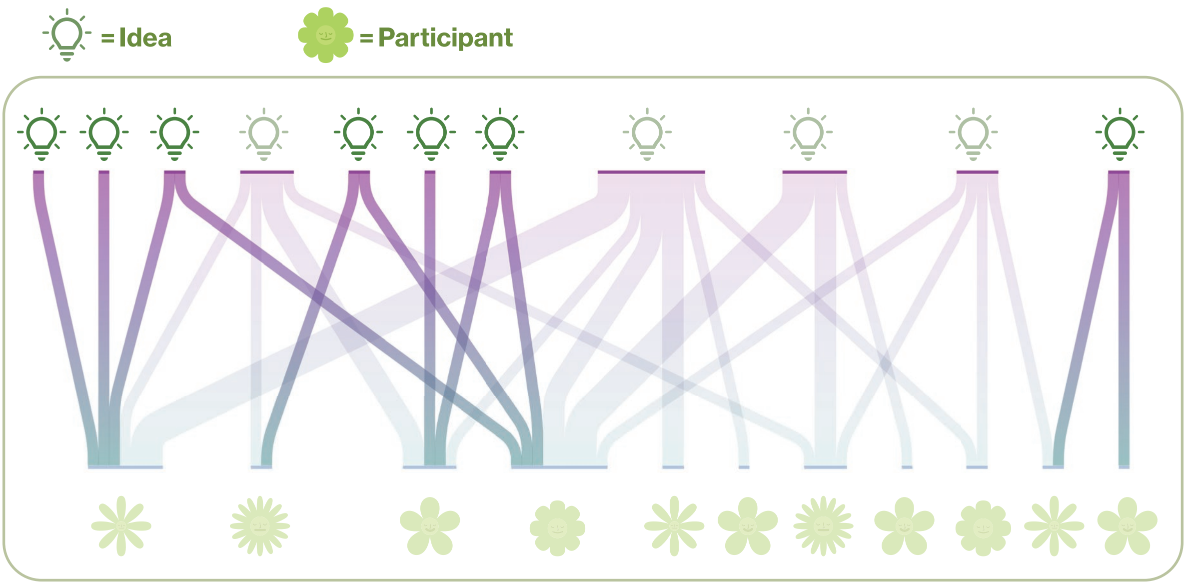


Figure 31. Diagram showing the flow of ideation ouput of the participants, showing that there were some ideas that overlapped (**Observ. C2**), while 7 of 11 ideas were (relatively) unique.

C4. People have creative concerns | Connected to point **A2** about negative hypothetical thinking, people were also creative in what concerns they brought up. Below some examples of unique quotes.

> *"When there is an* ***earthquake*** *I expect the plants to go [like that]"; "what if it traumatises someone who thinks it's an actual earthquake.."*

> *"I'm also thinking, like to the extremes, like might people see this as like a sort of* ***mind control?*** *Because it's so non-intrusive, but it's still- Yeah, like if this can be used to move people around,* **it's like using a shepherd dog to like herd people** *through the city. So what might people think of that?"*

> *"I can imagine* ***feeling watched,*** *because a drifting plant feels like you're being pranked. Like there's a camera somewhere."*

8.2.4 Discussion

There are several discussion points that should be improved for further research:

✲ **Sample |** The size was fairly small, the project's potential could benefit from more test with a more diverse sample.

✲ **Controlled Environment |** The researcher approached the experiments in a casual way, which might have influenced the results. For example, the humorous nature of the experiment triggered the researcher to audibly laugh at times were it could have been more controlled. This might have signalled to the participants that something was happening. Furthermore, the 'lab' was not clutter free and silent, which might have influenced and/or distracted the participants. For example, people talking on the hallway made one person look up and consequently notice the moving plant.

✲ **Interpretation |** The researcher attempted to approach the data analysis in a somewhat systematic way, but still acknowledges the personal interpretation of qualitative data. Additionally, four transcripts were translated to English from Dutch. This means some quotes might have lost some nuance in translation. For further studies this should be more consistent, or assisted by a professional translator.

✲ **Prototype |** There were some instances where the prototype did not work smoothly, such as a small sound when the motors start moving from a static state. Additionally, the tight testing schedule also caused an empty battery, which influenced part of the experiment. This was however more a planning issue from the researcher, who should have planned enough charging time in between sessions. Although it unfortunately influenced the detection aspects, it also brought some insights: Even with an exhausted battery, which causes the prototype to make a noticeable sound, the participant did not immediately assume the sound was coming from the plant.

These points could be improved for further research, but did not make the results unusable. The results may serve as indicators or assumptions for other experiments.

8.3 Deployment

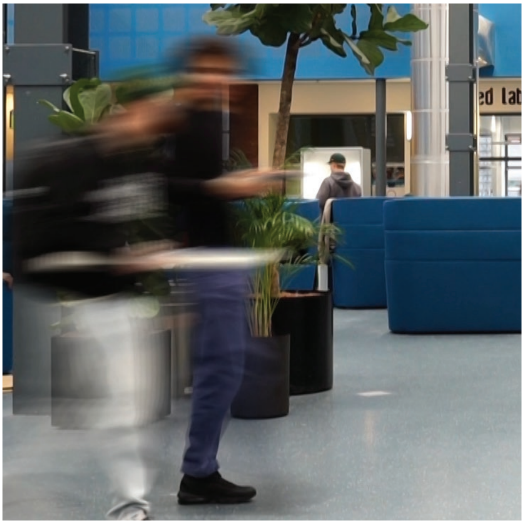
This section highlights two of the spontaneous experiments that were not setup in a systematic way.

8.3.1 In the office

► **Battery Life |** This experiment provided unexpected insights that were later confirmed in the perception test (**Paragraph 8.2**). The initial goal was to let the prototype drive at a constant speed in the lab with a full battery to track how long the battery life is. This was done in a office like setting in the shared working space of the researcher. The prototype started moving at the researcher's own desk in a straight line, as long as possible. In the meantime the researcher continued to work on other stuff, while occasionally keeping an eye on the robot. **Result:** The battery life turned out to be about 1.5 hours before the system stopped behaving properly. Although this was valuable information for the perception test, it was not the most surprising one. During the run, no one noticed that the plant had moved in a straight line (about **9** meters).

► **Parallels |** This was an early sign that the prototype is extremely subtle, which has also been observed in the perception test. It should be noted that people in the lab were primarily focused on their work and did not know the prototype was working. Some people also walked past the prototype and did not mention it. It is however not clear whether they really did not notice it or simply did not want to say anything about it. After asking someone in close proximity of where the plant ended up, it was clear that this person had not noticed it at all.

► **Watching |** Another observation is that the only person that was 'pulled back into reality' by the plant, was the researcher who had knowledge of the plant's active movement and had to make sure it would not run into something. From the researcher's perspective, it felt like watching a child or pet to make sure it does not put itself in danger. Again, this parallels the behaviour that was observed in the perception test, where prior knowledge of the plant was one of the detection reasons.



8.3.2 In the hall

► **Time-lapse |** This experiment's initial goal was to record a time-lapse in the envisioned environment, the faculty hall. For this time-lapse, the prototype was transported to the hall and placed among the plants that are always there.

► **Seamless |** The prototype blended into its environment, which was an objective mentioned in **Paragraph 3.2**. The deployment in its intended context shows that the prototype seamlessly fits in its environment.

► **Object Detection |** Another observation was that, as expected, people did not walk into the plant robot and simply avoided the object themselves. This indicates that the assumption that extreme slow movement could be a way to avoid collision between humans and robots is realistic. It also shows that the concerns regarding human-plant collision, which some participants had in the perception test, may not be realistic.

8.4 Plant-Sensor Feasibility

This section highlights experiments with the plant-sensor prototype.

8.4.1 Early experiments

► **Turning on a LED |** In the early stages of the plant sensor experiments, the focus was on establishing a basic system where the touch of a leaf would trigger the activation of the LED bar. This initial setup proved to be fairly stable, although it required fine-tuning to determine the appropriate threshold for its sensitivity. Through multiple trials involving different individuals interacting with the plant, the system consistently responded as envisioned (see **Fig. 32**). Additionally, the sensor also works as it interacts with other plants.

► **Conversation Starter |** The prototype was a good conversation starter. Letting people interact with the plant-sensor often made people brainstorm about ideas after learning the possibility of HPI.

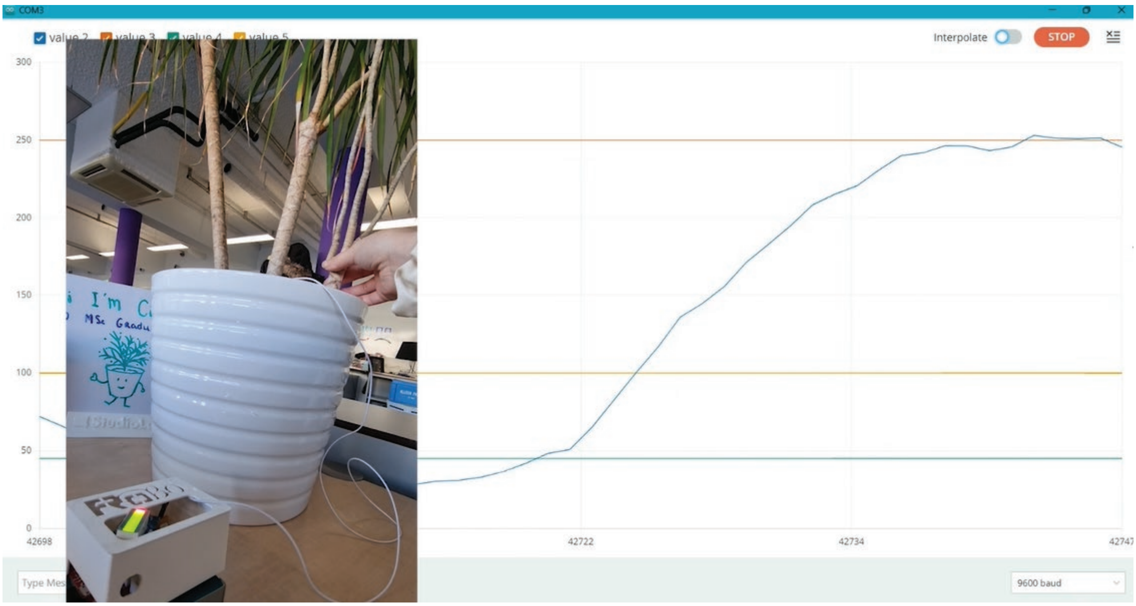


Figure 32. Arduino serial plotter, showing the sensor value. The horizontal lines are constants, set by the researcher to indicate the approximate value of different interactions, the highest red line being touch (as seen in this example). These constants also serve as thresholds to trigger feedback.

8.4.2 Exploring Proximity

► **Increasing Ohm |** On the Arduino Playground page of the CapactiveSensor library used in the code, it is stated that the resistor size influences the sensitivity of the system (Badger, 2008). **Figure 33** shows an overview of a small experiment of the sensor at different distances by replacing the originally 1MOhm resister with one of **3.3 MOhm**. Other resistors were tested as well but did not deliver the same stability. The sensor was tested at different differences, showing that the sensor hits the thresholds for each distance. This means that, if optimised, it may be possible for the plant-sensor to accurately determine at what distance the human or plant is located.

► **Concept Iteration |** Finding out that the plant is able to sense proximity, resulted in a crucial concept iteration. Instead of solely touch, proximity became another possibility and a tool for the swarm to use. This changed the system architecture in **Paragraph 5.1.2**, since it could now rely on humans simply being close by a plant.

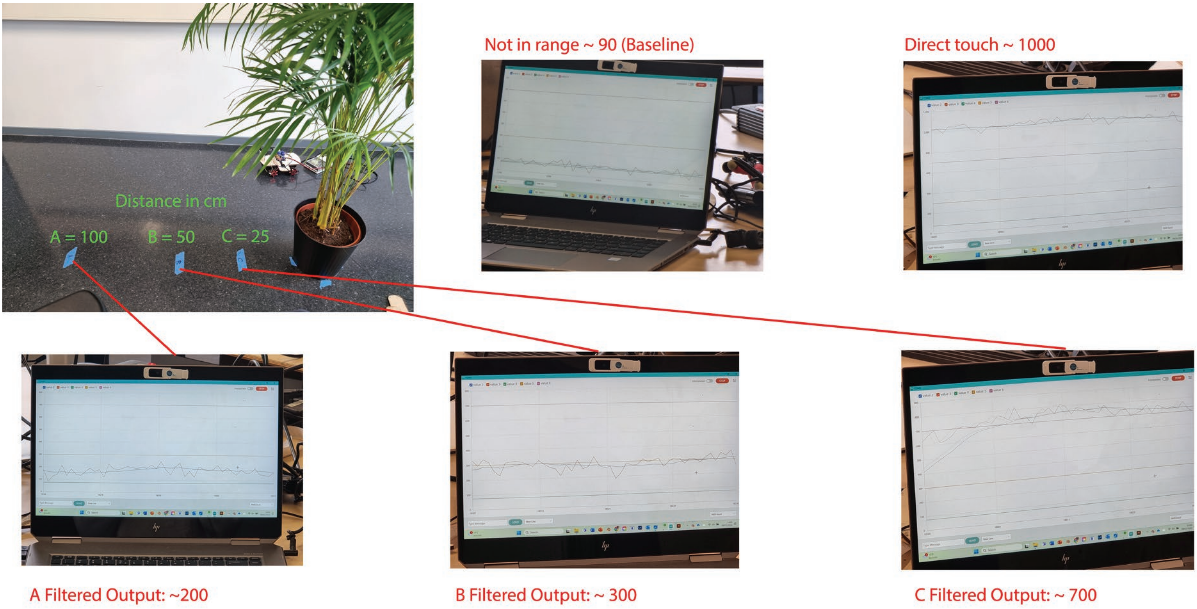


Figure 33. Setup and experiment output overview: Serial plotters showing that the sensor hits the thresholds at different distances.

►**Demo Prototype |** In an informal testing session, the prototype discussed in **Paragraph 8.3.3** was tested (see **Fig. 34**). For 4 out of 5 people the prototype behaved as intended, showcasing its stability as a sensor. For one person the 'heavy touch' feedback was not triggered. After a reset of the microcontroller, this improved. The cause for this occurence is not determined.

Since it is a demo prototype, there was room for interpretation on what the feedback actually means. The LED lights simple indicated the size of the sensed data. This presented opportunities to explore other usecases for a sensor such as this. Partcipants brainstormed about ideas for what input and output the system could have. For example, one person suggested that it could also have a speaker in it, playing different sounds from nature depending on the input.

One concern that was confirmed, is that people have the urge to keep touching the prototype:

> "Because of the particles it makes me want to constantly interact with it. Like, you see that you can influence something so ***you keep touching it.***"

As mentioned in **Paragraph 5.3**, this might not be the best for the plant, since most plants generally do not like to be touched a lot. This is why designers should consider not making applications that provide instant satisfaction for the human. Alternatively, if instant feedback is necessary, one could choose a specific plant species that does not mind touch, e.g. Peace Lily (Spathiphyllum), Jade Plant (Crassula ovata) or Aloe Vera (Yarden, 2022).

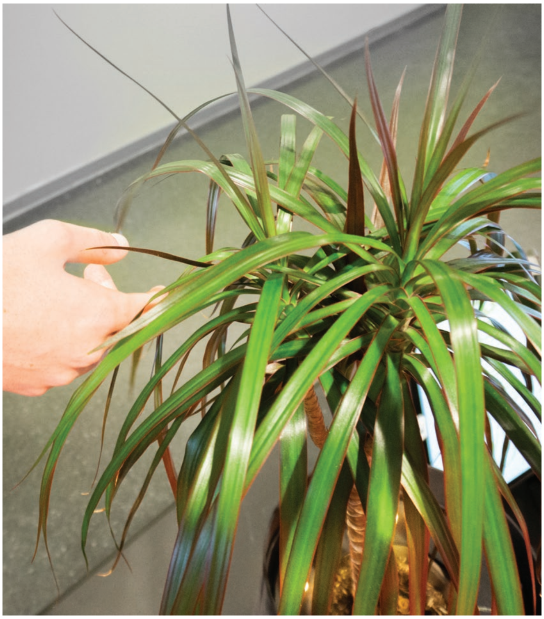


Figure 34. Participant testing the sensor. The prototype is equipped with RGB LED lights and connected to a data visualiser, generating particles based on sensed values (**Par. 6.3.3.**).

► **Feasibility Issues |** Combining the sensor prototype with the drive platform did not provide a stable result, because of several issues that unfortunately became out of scope for this project to solve at this time:

✲ **Interference of the platform prototype |** It was clear that while the researcher moved the plant with the controller, the active electronics impacted the sensor data.

✲ **Grounding |** The author of the code library (Badger, 2008), emphasizes the significance of proper grounding for capacitive sensing with Arduino boards. This lack of proper grounding of the prototype mostlikely contributes to the unstable result.

✲ **Configuration |** Furthermore, combining the prototypes not ideal due to their own configurations, with each their own power supply for example. In a future iteration, the prototype should be designed to be integrated.

Further elaboration on this topic in **Appendix F**.

09. Wrap Up

This chapter proposes a final iteration and also serves as a design freeze for this project. References to **Paragraph 8.2.3**, refer to the interpretation section of the perception test, in which every **[Observ. A#]** code refers to an observed statement.

9.1 Further Possibilities for Iteration

► **Adjusted System Architecture |** After the experiments it became clear that the system architecture of the prototype might be a combination of two that were defined in HPI framework (**Par. 2.2.2: Fig. 11**). From the perception test, we can conclude that the actuator influenced the plant system's movement significantly, making people experience the plant's movement act as if it has different physical 'behaviours' (Observ. **A5, B4**). Thus, the an iteration of the architecture may look more like the one in **Figure 35**. As envisioned, the sensing method made it fit within the **Embedded Direct Integration** category. However, since the actuator also had an effect again on the psychological state of the plant system, it is now updated by combining it with **Proxy Integration**.

► **Determine More Behaviours |** The experiments demonstrated some indication of what effect different speeds had on people(Observe. **A5, A6, B3, B4**). The prototypes showed that the actuation affects the plants physiological state in different ways, triggering distinct responses, which could be used intentionally to achieve specific goals - giving the plant a way to convey a message and communicate in a non-verbal way (e.g. fast movement to ask for attention). This observation also made clear how all these different behaviours could be used, instead of choosing one 'ideal speed'. Instead it could for example also be combined, or the effect of other speeds could be explored to find new meanings that could be used depending on what kind of behaviour it wants to execute.

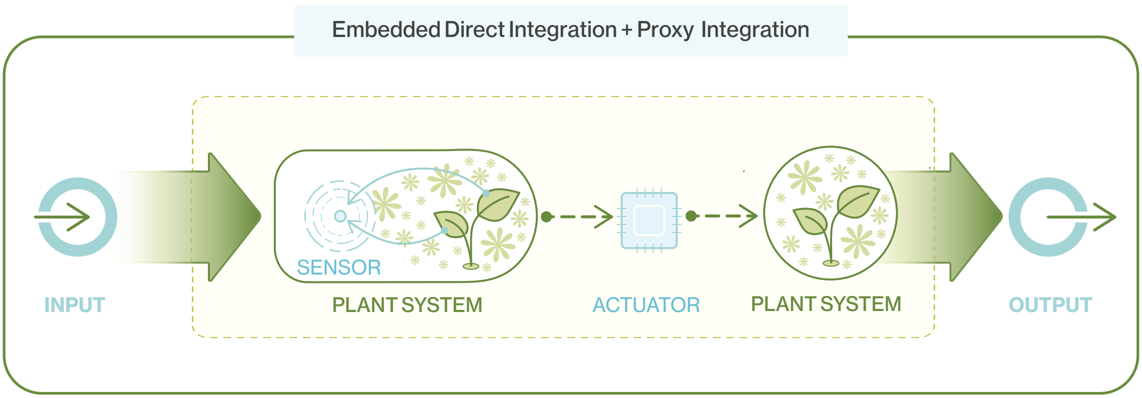


Figure 35. Updated system architecture after experiments.

► **Roles within a swarm |** Although the sensor issues that are mentioned in **Paragraph 8.4.2**, can most likely be solved after some more development, an alternative option that was inspired by this issue is to give the plants different roles. This could be that the swarm relies on both moving and static agents that collaborate. Similar to how an ant colony has its queen, drones, workers, and alates or reproductives with each their own task (Terminix, 2023). Likewise, some plants within the swarm could be (static) sensing plants, that sense and/or react to humans that surround them. This information could then be communicated to the moving plants, who carry out actions based on these sensing plants.

► **Using Movement Awareness |** From the experiments it was clear that the knowledge of the moving plants might be enough to reach the envisioned effect (Observ. **A3**). This supports the working principle of the concept that aims make people aware of the passing of time.

► **Bringing Liveliness |** The prototype demonstrated that the subtle movement of the plant reminds people of outdoor plants, mimicking the presence of wind (Observ. **C1**). This brought people an enhanced sense of understanding and purpose of the concept. Therefore it is a valuable analogy that could be used as a tool to explain the concept. Although bringing more liveliness and dynamic aspects to the environment was already an envisioned effect, it could be used even more intentionally. With this finding, the concept aims to enhance the environment by bringing more of this liveliness to indoor plants. Furthermore, the conceptual idea behind aims to nudge humans to pay attention to their surroundings in a closed space, encouraging them to be aware of the passage of time.

One participant also commented on this, saying that after a the time on the clock are just numbers and sometimes is difficult to . This way one can ‘experience‘ time as opposed to dismissing changing numbers on a display.

► **Plant type |** Further exploration could include experimentation with more types of plants with each their own unique properties. For example; what would happen with a cactus?

9.2 Challenges

► **Plant Sensor |** Fully integrating the plant sensor with the mobile prototype would be the next step for this project. This is however a step that is expected to be particularly challenging (for designers) due to its technical complexity.

► **Prototyping Swarms |** A crucial missing prototype to explore would be the algorithm that determines the plant's navigation and movement. This prototype would demonstrate the decision-making strategies of the swarm based on plant-sensor data, other external sensors and potentially also time of day. Next to that, it should be investigated how to prototype multiple of these plants physically. One plant was manageable for one researcher, but scaling up to multiple will most likely present new challenges. This may require the involvement of a larger team or the development of control systems to manage and coordinate multiple robots effectively.

► **Long-term effects |** A big limitation of the experiment was that it was only an introduction to the concept. Since the concept is meant to be a longer term installation for a public space, effects on a longer time-scale should also be investigated. Given that the knowledge of the plant's presence seemed to have an effect, it would be a great challenge to see how this possibly changes over time. Perhaps this effect gets stronger since people might learn how to make use of this knowledge, or maybe it gets weaker since people do not care about it anymore. These are all speculations that could be true.

9.3 Design Directions

This section reflects on design directions that as a result of the project as a whole, illustrated by the ideation from test participants (**Observ. C2, C3**). It suggests different approaches to design directions for future variations of RoBotanics, giving an idea on how we might design further with plants.

► **1. Exploring Symbiotic Relationships between Humans and Plant entities |** Focus on understanding the mutual benefits between humans and plants.

1a. Focus on Plant Well-being | An example from the participants: let people around the plant know how to take care of it, telling people it needs water.

This design direction is common in many related works, for example: PotPet (Kawakami et al., 2010), a plant on wheels moves automatically to sunny places or approaches people when it requires water.

1b. Focus on Human Well-being | An example of an idea mentioned by one of the participants involves plants reminding humans to drink water by spraying water onto themselves, reversing the traditional notion of humans caring for plants by watering them (**Fig. 36**).

Using the plant to raise awareness have also been inspirations in projects such as Infotropism by Holstius et al. (2004), where the plant is used as a 'display' to raise awareness for recycling trash and influence recycling behaviour.

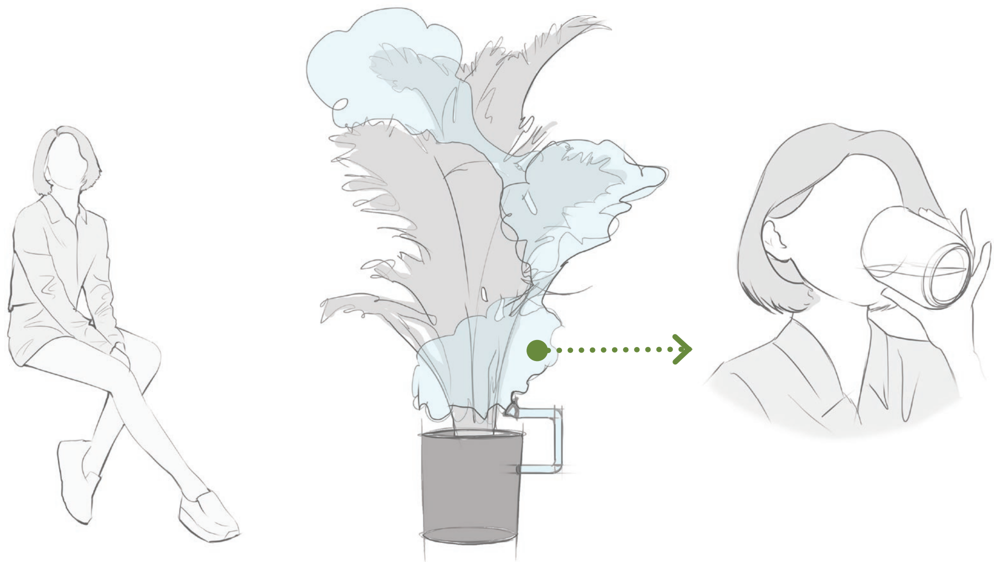


Figure 36. Sketch of a plant that encourages people to drink water, leading by example.

► **2. Exploring Shared Space |** Ideas on the robot moving in space.

2a. Guiding Crowds | One aspect of slow moving robots is that it offers an opportunity to subtly influence crowds. Similar to bushes showing the border of gardens or plant pots dividing roads from pavements, these robots could subtly influence human movement within the space (see **Fig. 37**). Instead of those plant being static, it could transform the space over time in a subtle matter. Think of syncing this up with the time of day, creating space in rush-hours and distributing vegetation during quiet hours. This subliminal control could shape the flow of people without their awareness, subtly guiding their paths.

Figure 37. Plants creating a walkway (Jcomp, 2019).

2b. Custom Barrier Formation | Alternatively, the movement of plant-robots could serve as dynamic space dividers controlled **by human command**. This idea was mentioned by 3 participants. In contrast with the slow moving concept, this use case would involve more human control over the robots and relies on instant satisfaction. For example, these plant-robots could create private spaces for events or meetings when it is needed, offering modular flexibility in space utilisation.

2c. Equal Vegetation | In the perception test, 2 participants brought up that it has potential economic benefits, as fewer plants would be needed to create the sense of greenery in large areas. By strategically distributing the plant-robots throughout the space, they could fulfil this desire without overcrowding and overwhelming the environment (see **Fig. 38**). Envisioning a scenario where plant-robots dynamically navigate through human-populated areas in order to satisfy the vegetation levels regardless of where humans are sitting or standing.

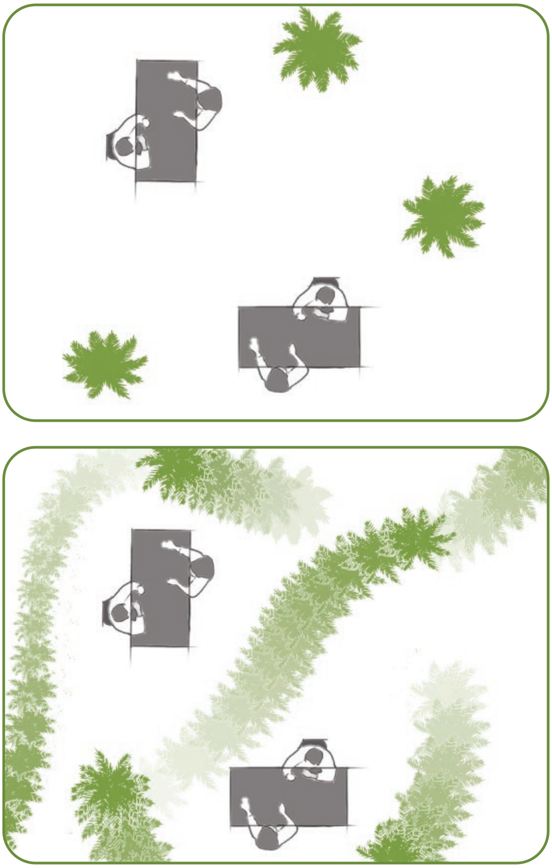


Figure 38. Distribution of regular plants (top) vs. Distribution if plant robots move over time (bottom).

► **3. Exploring plants as social beings |** Ideas on giving the plants personality and a sense of autonomy.

3a. Companionship | Personification of plants, equipping them with human-like qualities, brining a sense of companionship and connection. This anthropomorphism gives human characteristics to plants, making them feel like company, creating the feeling as if the plants are visiting or greeting you.

3b. Plant Communication | Ways to communicate with plant entities. In Project Florence (Steiner et al., 2017), researchers created a plant 'translator', converting plant data into words.

However, this does not have to be verbal communication. Knowing that taps can be observed, designers may think of non-verbal languages such as counting the taps for specific answers similar to conventional method, for example: one short tap means go, two taps stop, long tap means rotate until release etc. (see **Fig. 39**). For this to work, more research on human-plant touch should be conducted as well to ensure that the plant's health remains stable.

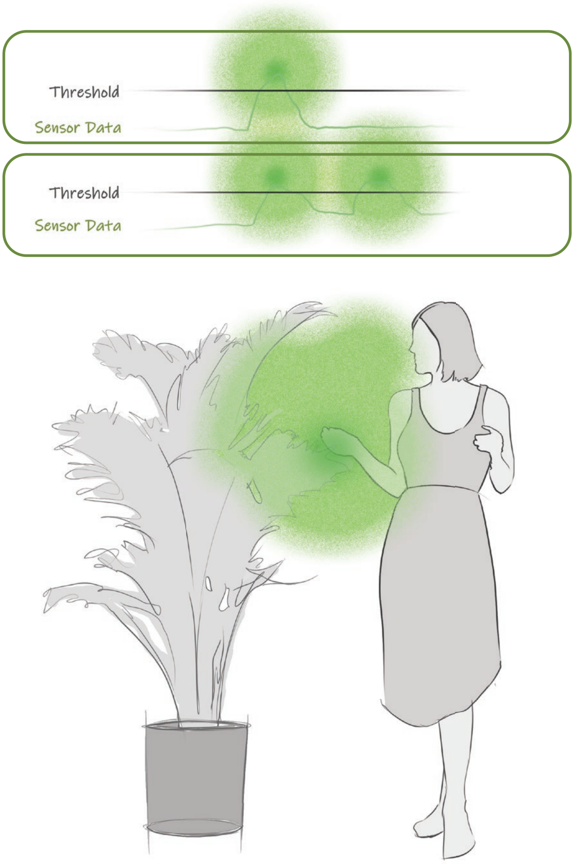


Figure 39. Envisioning HPI through non-verbal communication.

► **4. Exploring Prototyping Practices |** Next to conceptualisation of HPI systems, the practical side of HPI prototyping is an area that could be explored. The focus is on understanding how to design with plants and how to integrate them in practice.

4a. Stable data gathering | This direction includes ideas that use the plant to collect environment data in their system architecture. For example, monitoring air quality, or following sunlight (also see point **1a**). Developing stable sensors and implementing systems that ensure this stability in the long run.

4b. Plant Interfaces in Products | Finding ways to integrate plant interfaces in products. As seen in Bioo Lux (Arkyne Technologies-Bioo, 2023), where the plant is integrated as a simple switch mechanism; if you touch the plant, the lamp turns on. Designers could think of different kinds of input-output systems that are feasible within a marketable product.

4c. Exploring Design Methodology | This final direction is all about developing design methodology for HPI as discussed in **Chapter 4**. For designers who are new in this field, this could be a valuable direction as it helps navigate in a very broad scope.

10. Final Thoughts For Designers

Overview of recommendations related to this section: **Deploying the Robot**.

Plant-Hybrid Technology

Sparked Creativity | The project was not only inspiring for the researcher/designer, but also for the experiment participants. People, including non-designers, came up with out-of-the-box ideas. Design with plant-hybrid applications is a novel design space and might confuse some people at first, but people are generally able to adapt to this reality quickly. Although there was some resistance from a more pragmatic perspective, this did not hold back people from brainstorming.

Limitations & Further Research

Feasibility | Although prototyping and experimenting was challenging, and at several times uncertain, it was not impossible to design with it. In contrary, limitations also stimulated new ideas, as discussed in **Paragraph 9.1**. Furthermore, the field could benefit from more research in design that attempts to prototype with these technologies in order to develop new feasible methods for prototyping.

Plant-Sensor on a Mobile Robot | Designers need to be aware of issues like grounding problems and potential interference from nearby electronics, as observed in the platform prototype. At this state of the project, it was not possible to create a stable sensor on a mobile robot platform. This could however be a challenge for designers that want to explore this possibility and improve its feasibility.

Long-term Effects | As the concept aims for a more long-term presence in a public space, it becomes crucial to explore its effects over a longer period. Considering that knowledge of the plant's presence appeared to influence outcomes through anticipatory awareness, investigating how this dynamic evolves over time is required to verify its effectiveness. The limited time frame of the project made it impossible to cover this aspect for now.

Project Reflection

The study aimed to explore the use of mobile plant-hybrid robots in public spaces, aiming to bring liveliness into indoor environments. The concept promotes living in the present moment, as it subtly tries to express the passage of time. It creates a symbiotic relationship between a group of plants and a group of humans, living alongside each other, and being able to perceive each other's dynamic presence.

Through an iterative design process, functional prototypes were created, featuring extremely slow movement and plant-sensing capabilities. Testing these prototypes revealed interesting findings: initial surprise at the robots' movements was followed by acceptance and appreciation for their presence. Some questioned its purpose, while others brainstormed about new purposes. The subliminally moving plant robot proposes a way in which a plant-robots could coexist alongside humans in public space and demonstrated that inattentional blindess might be an effective tool. Moreover, the prototypes showed that the actuation affects the plants physiological state in different ways, triggering distinct responses, which could be used intentionally to achieve specific goals. Looking forward, there are numerous ways for further exploration within product/ interaction design, allowing more designers to become part of a movement towards the fusion of design, technology and nature.

How might **you** design with living plants as **ROBOT** components?

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Appendices

A. Initial Project Brief

B. Platform Prototype BOM

C. Prototype Arduino Code: Platform

D. Prototype Arduino Code: Sensor

E. Prototype Processing Code: Sensor

F. Sensor Experiments Issues

G. Copyright Disclaimer

Appendix A. Initial Project Brief

TU Delft

Swarm Robotics Integration for Human Navigation

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date - 09 - 2023 - 03 - 2024 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

In short:
This project is research on the potential of swarm robotics in public spaces and explores the embodiment design of such robots to optimize human-(swarm)robot interaction. To make the project more specific, the public space in question could be the IDE faculty as it is a complex building that may benefit from assistance in navigation and/or building maintenance. In emergency context, a complex building also means that it requires efficient crowd management to control the situation. This project will explore and evaluate the value of swarm robotics in these settings.

Project Stakeholders:
For this project, the main stakeholders would be building managers (and owners), safety departments, and (non-) frequent visitors of the building. In the case of IDE, this involves the TUD staff, students, and the municipality of Delft (indirectly). Regardless of why one may be in the building, a common value is that the building is safe and provides the facilities that are needed to perform work.

Other potential stakeholders:
In other settings, these systems could also be valuable for other complex public buildings that frequently welcome visitors (and therefore are not familiar with the building) such as museums, big supermarkets/shops, hospitals, event halls, public libraries etc.

Opportunities: New technologies in an this field gives us a lot of room for research opportunities (TRL 4-6); Designing human-robot interactions in Industry 4.0 and beyond; User testing on perception of robots in a public space; Applying design methods and practices in the robotics field, providing a different perspective (Fig. 1, p.4).

Limitations: New technologies also mean that it may stay conceptual, although a working MVP or prototype should be feasible. The big scale of the project forces it to require some simulated experiences, since not all can be explored. The depth and form of these simulations should be determined carefully and stay relevant to the master study objectives, since another limitation is the lack of (programming) knoweledge. For example, the simulation on the next page may be too advanced (Fig. 2, p.4), but a simulation showing expected trajectories of a specific context could be manually visualised in a 3D environment instead of a real-time algorithm.

space available for images / figures on next page

introduction (continued): space for images

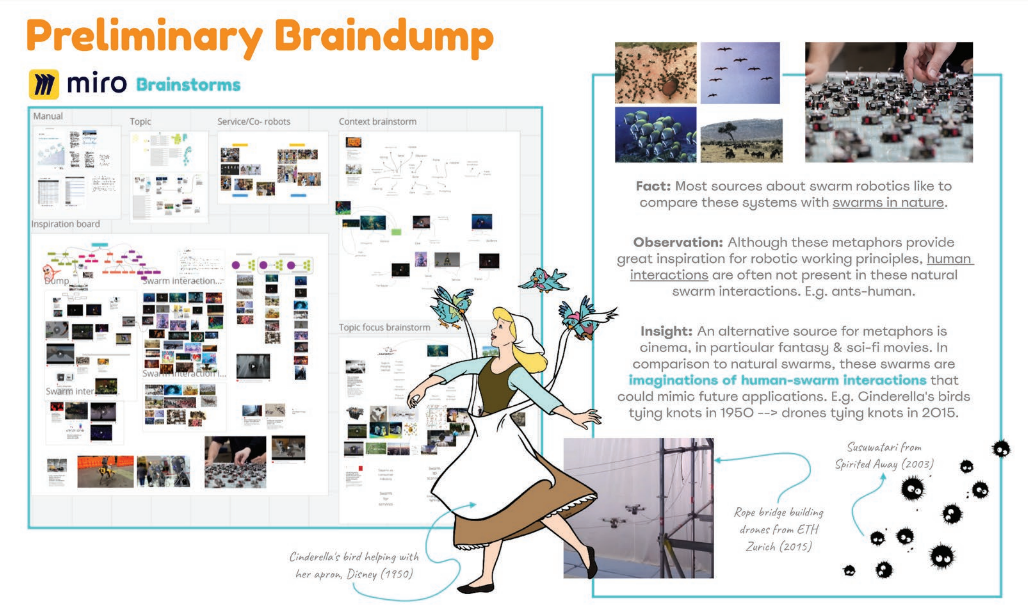


image / figure 1: Initial topic exploration and introduction to swarm robotics related to human interaction.

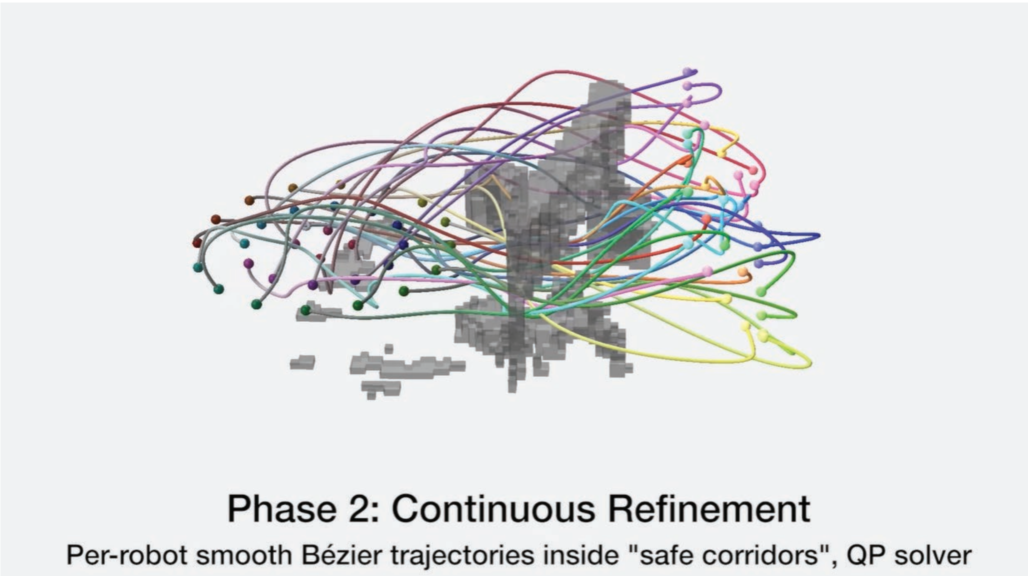


image / figure 2: Hönig, Wolfgang et al. (2018). "Trajectory Planning for Quadrotor Swarms."

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Challenge: Navigating through big complex buildings can be challenging. In an emergency setting, this is even true for frequent visitors when certain paths can be obstructed or panic becomes overwhelming.

Solutionspace: Although different solutions are possible, the only hard requirement for this project is to explore solutions that apply swarm robotics.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

A design for elements within an integrated multi-robot or swarm robot ecosystem for complex public buildings that aid in various ways, including: guidance, crowd management, maintenance inspection and more to be explored.

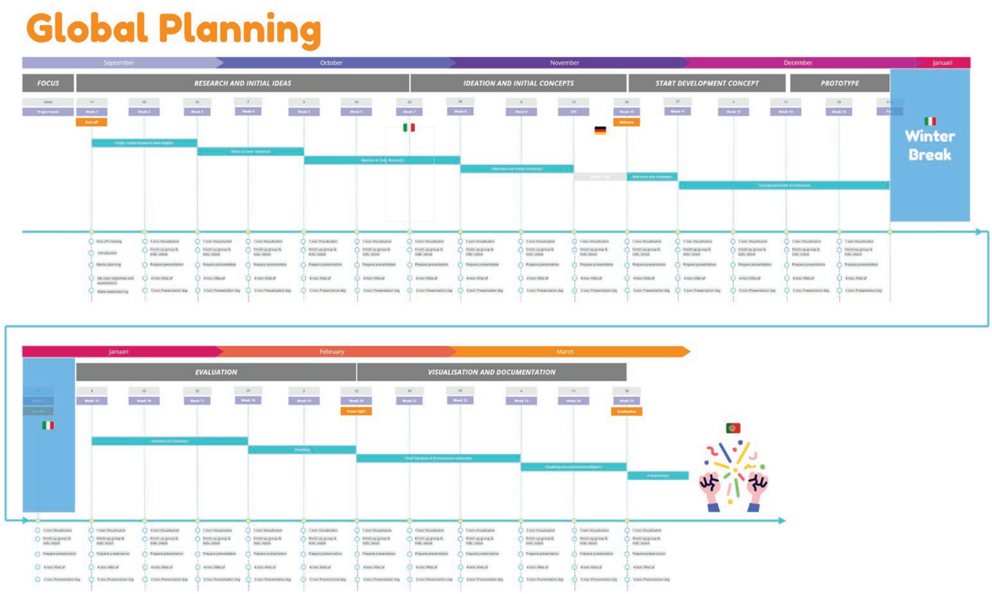
Deliverables:
Envisioned robot ecosystem, illustrated by visual and simulated experiences, a (working) prototype and embodiment design proposal for at least one main component within the system.

Other gained insights;
Cognitive ergonomics of robot-to-human feedback and the other way around; Perception on the product and interaction; Aesthetics of the robots; Logistics of the robots (including charging).

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date - 9 - 2023 | - 3 - 2024 end date



The planning above is edittable in Miro and will be adjusted along the way. The grey bulletpoints under each week serve as placeholders for future tasks.

Initial project distribution (budget):

Determine applications and narrow down scope (±10 days)
Conceptualizing/Embodiment design (± 60 days)
Evaluating concept and detailing (±20 days)
Final phase: Report/Presentation (±10 days)

s & Name C.Y. Chang Student number 4854942

Title of Project Swarm Robotics Integration for Human Navigation

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

I approached Jordan because I was interested in a graduation project about social robotics. I was looking for something that was exciting and outside my comfort zone since it is my last university project.
I have not worked on a robotics project before, but it's something I am extremely excited about and something I can do best while I am still at university, in my opinion. After several brainstorms with Jordan over the summer period (Figure 1, p.4), we came to the conclusion that a project around embodiment design of path generating swarm systems within buildings excites us both and allows me to explore apply skills related to the IPD programme.

Inspiration for the field:
- Personal interest in new tech. When I think of the future I, and I believe most people, think of robots. In a world where fear of implementation is overwhelming, I want to advocate for design within this field to ensure that implementation does not have to be feared. I believe design is essential to make the future vision more human and less dystopian.

- Elective: AI & Society. This elective course really inspired me to think about introductions of new smart technologies within society and which implications those have.

- I work for a company that is within automation manufacturing industry. Therefore I am surrounded by people who are constantly discussing topics within the robotics industry.

Personal ambitions:
- Improve understanding of common coding languages (e.g. Python).
- Advanced prototyping (and CAD modelling).
- Setting up a multi-agent simulation (Using e.g. Gazebo, MatLab, Unity).
- Applying design knowledge to robotics.
- Investigating the value of AI in my personal design process.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Appendix B. Platform Prototype BOM

#	Part	Qt.	Type
1	Mecanum Wheels	4	Fingertech Robotics, 54x34 mm
2	Cooling Fan	1	Reused, 5V
3	Stepper Motors	4	NEMA17
4	Arduino Board (Microcontroller)	1	Arduino Uno WiFi Rev2
5	Powerbank	1	5V, to power Arduino board
6	CNC shield	1	CNC Shield V3
7	Stepper Drivers	4	TMC 2208
8	Rechargable Battery	1	ACS110, NiMH/NiCd 1.2-12V
9	Stepper Motor Brackets	4	90° , metal
10	Laser-cut Platform (Wood)	1	Custom, 5mm
11	Standoffs	8	40 mm

Appendix C. Prototype Arduino Code: Platform

```
=========================================❀Title❀=========================================
// “RoBo V2.2” by Cin Yie Chang, TU Delft, January 2024


// ======================================❀References❀======================================
// Bluetooth code based on: “Controller”, Copyright 2021 - 2023, Ricardo Quesada

// Steppermotor basics code based on: “Using an Arduino CNC Shield V3”, (2023) by Xukyo at www.aranacorp.com
// Steppermotor basics code based on: “1. Continuous rotation example code” (2019) by Benne de Bakker at www.makerguides.com
// Steppermotor mecanum wheel directions based on: “Radio control with NRF24L01” (2019) by Dejan at www.HowToMechatronics.com

// Library: AccelStepper.h - http://www.airspayce.com/mikem/arduino/AccelStepper/index.html, Copyright (C) 2010-2021, Mike McCauley
// Library: Bluepad32.h - https://github.com/ricardoquesada/bluepad32-arduino, Copyright (C) 2021 - 2023, Ricardo Quesada


// ==================================❀Initialization(Setup)❀==================================
#include <AccelStepper.h>
#include <Bluepad32.h>
ControllerPtr myControllers[BP32_MAX_CONTROLLERS];


const int enPin=8;
const int stepXPin = 2; // X.STEP
const int dirXPin = 5; // X.DIR
const int stepYPin = 3; // Y.STEP
const int dirYPin = 6; // Y.DIR
const int stepZPin = 4; // Z.STEP
const int dirZPin = 7; // Z.DIR
const int stepAPin = 12; // A.STEP
const int dirAPin = 13; // A.DIR


//(Type:driver, STEP, DIR, EN)
AccelStepper LeftFrontWheel(1, stepXPin, dirXPin, enPin);
AccelStepper LeftBackWheel(1, stepZPin, dirZPin, enPin);
AccelStepper RightFrontWheel(1, stepYPin, dirYPin, enPin);
AccelStepper RightBackWheel(1, stepAPin, dirAPin, enPin);


int wheelSpeed = 5;
int SpeedState = 0;


void setup() {
  Serial.begin(9600);
    while (!Serial) {
    // Wait for serial port to connect.You don’t have to do this in your game.
    //This is only for debugging purposes, so that you can see the output in the serial console.
    ;
  }


  Serial.println(F(“CNC Shield Initialized”));


  String fv = BP32.firmwareVersion();
  Serial.print(“Firmware version installed: “);
  Serial.println(fv);

  // To get the BD Address (MAC address) call:
  const uint8_t* addr = BP32.localBdAddress();
  Serial.print(“BD Address: “);
  for (int i = 0; i < 6; i++) {
    Serial.print(addr[i], HEX);
    if (i < 5)
      Serial.print(“:”);
    else
      Serial.println();
  }


  // BP32.pinMode(27, OUTPUT);
  // BP32.digitalWrite(27, 0);


  // This call is mandatory. It sets up Bluepad32 and creates the callbacks.
  BP32.setup(&onConnectedController, &onDisconnectedController);


  // “forgetBluetoothKeys()” should be called when the user performs a “device factory reset”, or similar.
  // Calling “forgetBluetoothKeys” in setup() just as an example.
  // Forgetting Bluetooth keys prevents “paired” gamepads to reconnect.
  // But it might also fix some connection / re-connection issues.
  BP32.forgetBluetoothKeys();
```

```
  //Initial speed & Acceleration
  LeftFrontWheel.setMaxSpeed(500);
  LeftBackWheel.setMaxSpeed(500);
  RightFrontWheel.setMaxSpeed(500);
  RightBackWheel.setMaxSpeed(500);


  //Declare pins
  pinMode(enPin, OUTPUT);
  digitalWrite(enPin, LOW);
}


// ==================================❀Bluetooth Connection❀==================================
// This callback gets called any time a new gamepad is connected.
// Up to 4 gamepads can be connected at the same time.
void onConnectedController(ControllerPtr ctl) {
  bool foundEmptySlot = false;
  for (int i = 0; i < BP32_MAX_GAMEPADS; i++) {
    if (myControllers[i] == nullptr) {
      Serial.print("CALLBACK: Controller is connected, index=");
      Serial.println(i);
      myControllers[i] = ctl;
      foundEmptySlot = true;
    }
    break;
  }


  if (!foundEmptySlot) {
    Serial.println(
        "CALLBACK: Controller connected, but could not found empty slot");
  }
}


void onDisconnectedController(ControllerPtr ctl) {
  bool foundGamepad = false;


  for (int i = 0; i < BP32_MAX_GAMEPADS; i++) {
    if (myControllers[i] == ctl) {
      Serial.print("CALLBACK: Controller is disconnected from index=");
      Serial.println(i);
      myControllers[i] = nullptr;
      foundGamepad = true;
      break;
    }
  }


  if (!foundGamepad) {
    Serial.println(
        "CALLBACK: Controller disconnected, but not found in myControllers");
  }
}


// ==================================❀Button Detection❀==================================
  void processGamepad(ControllerPtr gamepad) {
    if (gamepad->axisRX() < 0  & gamepad->axisRY() == 0) {
    moveSidewaysLeft();
    //Serial.println("Robot goes Left");
    }
   else if (gamepad->axisRX() > 0 & gamepad->axisRY() == 0) {
    moveSidewaysRight();
    //Serial.println("Robot goes Right");
    }
    else if (gamepad->axisRX() == 0 & gamepad->axisRY() < 0 ) {
    moveForward();
    //Serial.println("Robot goes Forward");
    }
    else if (gamepad->axisRX() == 0 & gamepad->axisRY() > 0) {
    moveBackward();
    //Serial.println("Robot goes Back");
    }
    else if (gamepad->axisRX() > 0 & gamepad->axisRY() < 0) {
    moveRightForward();
    //Serial.println("Robot goes Right Forward");
    }
    else if (gamepad->axisRX() < 0 & gamepad->axisRY() < 0) {
    moveLeftForward();
```

```
    //Serial.println("Robot goes Left Forward");
    }
    else if (gamepad->axisRX() > 0 & gamepad->axisRY() > 0) {
    moveRightBackward();
    //Serial.println("Robot goes Right Back");
    }
    else if (gamepad->axisRX() < 0 & gamepad->axisRY() > 0) {
    moveLeftBackward();
    //Serial.println("Robot goes Left Back");
    }
    else if (gamepad->b()) {
    rotateRight();
    //Serial.println("Robot rotates Right");
    }
    else if (gamepad->a()) {
    rotateLeft();
    //Serial.println("Robot rotates Left");
    }
    else{
    //stopMoving();
    stopMoving();
    };


    if (gamepad->dpad() == 1){
      SpeedState++;
      Serial.println (SpeedState);
      delay(500);
    }
    else if(gamepad->dpad() == 2){
      SpeedState--;
      Serial.println (SpeedState);
      delay(500);
      };

  }


// ======================================❀Loop❀==========================================
void loop() {
  // This call fetches all the controller info from the NINA (ESP32) module.
  // Call this function in your main loop.
  // The controllers' pointer (the ones received in the callbacks) gets updated automatically.
  BP32.update();


  // It is safe to always do this before using the controller API.
  // This guarantees that the controller is valid and connected.
  for (int i = 0; i < BP32_MAX_CONTROLLERS; i++) {
    ControllerPtr myController = myControllers[i];
    if (myController && myController->isConnected())
    {
      if (myController->isGamepad())
        processGamepad(myController);
    }
  }


  //SpeedState

  if (SpeedState == 1){
    wheelSpeed = 50; //medium
  }
  else if (SpeedState == 0){
    wheelSpeed = 5; //superslow
  }
  else if (SpeedState == 2){
    wheelSpeed = 500; //fast
  }
  else if (SpeedState == 3){
    SpeedState = 2;
  }
    else if (SpeedState == -1){
    SpeedState = 0;
  }


  // Execute the steps
  LeftFrontWheel.runSpeed();
  LeftBackWheel.runSpeed();
  RightFrontWheel.runSpeed();
  RightBackWheel.runSpeed();

}
```

```
// ================================❀Drive Direction Functions❀==================================
void moveForward() {
  LeftFrontWheel.setSpeed(-wheelSpeed);
  LeftBackWheel.setSpeed(-wheelSpeed);
  RightFrontWheel.setSpeed(wheelSpeed);
  RightBackWheel.setSpeed(wheelSpeed);
}
void moveBackward() {
  LeftFrontWheel.setSpeed(wheelSpeed);
  LeftBackWheel.setSpeed(wheelSpeed);
  RightFrontWheel.setSpeed(-wheelSpeed);
  RightBackWheel.setSpeed(-wheelSpeed);
}
void moveSidewaysRight() {
  LeftFrontWheel.setSpeed(-wheelSpeed);
  LeftBackWheel.setSpeed(wheelSpeed);
  RightFrontWheel.setSpeed(-wheelSpeed);
  RightBackWheel.setSpeed(wheelSpeed);
}
void moveSidewaysLeft() {
  LeftFrontWheel.setSpeed(wheelSpeed);
  LeftBackWheel.setSpeed(-wheelSpeed);
  RightFrontWheel.setSpeed(wheelSpeed);
  RightBackWheel.setSpeed(-wheelSpeed);
}
void rotateLeft() {
  LeftFrontWheel.setSpeed(wheelSpeed);
  LeftBackWheel.setSpeed(wheelSpeed);
  RightFrontWheel.setSpeed(wheelSpeed);
  RightBackWheel.setSpeed(wheelSpeed);
}
void rotateRight() {
  LeftFrontWheel.setSpeed(-wheelSpeed);
  LeftBackWheel.setSpeed(-wheelSpeed);
  RightFrontWheel.setSpeed(-wheelSpeed);
  RightBackWheel.setSpeed(-wheelSpeed);
}
void moveRightForward() {
  LeftFrontWheel.setSpeed(-wheelSpeed);
  LeftBackWheel.setSpeed(0);
  RightFrontWheel.setSpeed(0);
  RightBackWheel.setSpeed(wheelSpeed);
}
void moveRightBackward() {
  LeftFrontWheel.setSpeed(0);
  LeftBackWheel.setSpeed(wheelSpeed);
  RightFrontWheel.setSpeed(-wheelSpeed);
  RightBackWheel.setSpeed(0);
}
void moveLeftForward() {
  LeftFrontWheel.setSpeed(0);
  LeftBackWheel.setSpeed(-wheelSpeed);
  RightFrontWheel.setSpeed(wheelSpeed);
  RightBackWheel.setSpeed(0);
}
void moveLeftBackward() {
  LeftFrontWheel.setSpeed(wheelSpeed);
  LeftBackWheel.setSpeed(0);
  RightFrontWheel.setSpeed(0);
  RightBackWheel.setSpeed(-wheelSpeed);
}
void stopMoving() {
  LeftFrontWheel.setSpeed(0);
  LeftBackWheel.setSpeed(0);
  RightFrontWheel.setSpeed(0);
  RightBackWheel.setSpeed(0);
}
```

[END OF CODE]

Appendix D. Prototype Arduino Code: Sensor

```
//=========================================❀Title❀===========================================
// "Plant Sensor V2" by Cin Yie Chang, TU Delft, February 2024

//======================================❀References❀=========================================
// Plant Touch Sensor based on "Touch Sensitive Color Changing Plants using Arduino and RGB LEDs", (2020) by RAJESH at www.circuitdigest.
com
// Average data based on "Filter", (2021) by Ian Carey.
// Grove LED Bar green->red based on "Level", (2010) by Frankie Chu (Seeed Studio).

// Library: CapacitiveSensor.h - https://github.com/PaulStoffregen/CapacitiveSensor Copyright (C),2008, Paul Badger & Paul Stoffregen.
// Library: Grove_LED_Bar.h -  https://github.com/Seeed-Studio/Grove_LED_Bar/tree/master Copyright (C), 2010, Seeed Studio// Library:
MovingAverage.h - https://github.com/careyi3/MovingAverage, Copyright (C), 2021, Ian Carey

//=================================❀Initialization(Setup)❀====================================
#include <CapacitiveSensor.h>
#include <Grove_LED_Bar.h>
#include <MovingAverage.h>

double filteredOutput1;
MovingAverage filter(15);

CapacitiveSensor capSensor = CapacitiveSensor(4, 2);

int threshold1 = 75; //baseline
int threshold2 = 150; //close distance
int threshold3 = 210; //touch distance
const int ledPin = 6;
const int VibPin = 4;
Grove_LED_Bar bar(7, 6, 0);
int i = 1;

void setup() {
  Serial.begin(9600);
  pinMode (VibPin, OUTPUT);
}

// ======================================❀Loop❀==================================== ========
void loop() {
  long sensorValue = capSensor.capacitiveSensor(13);
  filteredOutput1 = filter.addSample(sensorValue);

  Serial.print(sensorValue);
  Serial.print(",");
  Serial.print(filteredOutput1);
  Serial.print(",");
  Serial.print(threshold1); // treshold1 - baseline
  Serial.print(",");
  Serial.print(threshold2); // treshold2 - close distance
  Serial.print(",");
  Serial.println(threshold3); // treshold2 - touch distance
  Serial.print(",");

  // LED bar
  if (filteredOutput1 >= threshold3){
    i = 10;
    }
    else if (filteredOutput1 >= threshold2 && filteredOutput1 <= threshold3){
    i=5;
    }
    else{
      i=1;
    }

  bar.setLevel(i);

  delay(50); // Readability
}
```

[END OF CODE]

Appendix E. Processing Code: Sensor Visualiser

```
import processing.serial.*;

Serial myPort;  // Serial port object
String serialData;  // String to store incoming data
float rawDataValue;  // Parsed raw data value
float filteredDataValue;  // Parsed filtered data value

ArrayList<Float> rawDataHistory; // Store historical raw data for plotting
ArrayList<Float> filteredDataHistory; // Store historical filtered data for plotting
int plotWidth = 1800; // Width of the plot area
int plotHeight = 900; // Height of the plot area
int plotX = 56; // X-coordinate of the plot area
int plotY = 0; // Y-coordinate of the plot area
int scrollSpeed = 2; // Speed of scrolling
int smoothingFactor = 50; // Smoothing factor for moving average filter

ArrayList<Particle> particles;  // ArrayList to store particles

PImage img;

void setup() {
  fullScreen();
  smooth(1);  // Enable smooth drawing
  particles = new ArrayList<Particle>();  // Initialize particle array list
  rawDataHistory = new ArrayList<Float>(); // Initialize historical raw data array list
  filteredDataHistory = new ArrayList<Float>(); // Initialize historical filtered data array list


  // Initialize serial communication with Arduino
  String portName = "COM3";  // Change this to match your port
  int baudRate = 9600;  // Match this to your Arduino's baud rate
  myPort = new Serial(this, portName, baudRate);
  img = loadImage("Logo-01.png");
}

void draw() {
  // Draw broken white background
  background(255,255,245);
  rect(50, 50, 1800, 1000, 28);
  image(img, 50, 50,1800,500);
  // Read data from serial port if available
  while (myPort.available() > 0) {
    serialData = myPort.readStringUntil('\n');
    if (serialData != null) {
      serialData = serialData.trim();  // Remove whitespace
      rawDataValue = float(serialData);   // Convert string to float

      // Add raw data to history
      rawDataHistory.add(rawDataValue);

      // Limit raw data history to plot width
      if (rawDataHistory.size() > plotWidth) {
        rawDataHistory.remove(0);
      }

      // Apply moving average filter to raw data
      if (rawDataHistory.size() >= smoothingFactor) {
        float sum = 0;
        for (int i = rawDataHistory.size() - smoothingFactor; i < rawDataHistory.size(); i++) {
          sum += rawDataHistory.get(i);
        }
        filteredDataValue = sum / smoothingFactor;
        filteredDataHistory.add(filteredDataValue);
      }

      // Limit filtered data history to plot width
      if (filteredDataHistory.size() > plotWidth) {
        filteredDataHistory.remove(0);
      }

      // Add or remove particles based on filtered data value
      int diff = int(filteredDataValue) - particles.size();
      if (diff > 0) {
        for (int i = 0; i < diff; i++) {
          particles.add(new Particle(filteredDataValue+random(0,1800), filteredDataValue+random(0,1000), filteredDataValue));  /
  }
      } else if (diff < 0) {
        for (int i = 0; i < -diff; i++) {
          particles.remove(particles.size() - 1);  // Remove last particle
        }
      }
    }
  }

  // Update and display particles
  for (int i = particles.size()-1; i >= 0; i--) {
```

```
    Particle p = particles.get(i);
    p.update();
    p.display();
  }

  // Draw raw data plot line
  drawPlot(filteredDataHistory, color(255,200, 100, 100)); // Hot pink color

  // Draw filtered data plot line
//  drawPlot(rawDataHistory, color(150, 200, 100, 102)); // Yellow color
}

// Function to draw plot line
void drawPlot(ArrayList<Float> data, color plotColor) {
  noFill();
  stroke(plotColor);
  strokeWeight(5);
  beginShape();
  for (int i = 0; i < data.size(); i++) {
    float x = plotX + i - scrollSpeed;
    float y = plotY + plotHeight - map(data.get(i), 0, 500, 0, plotHeight);
    vertex(x, y);
  }
  endShape();
}


// Particle class
class Particle {
  float x, y;
  float speedX, speedY;
  float maxParticles;
  float intensity;
  color particleColor;

  Particle(float x, float y, float maxParticles) {
    this.x = x;
    this.y = y;
    speedX = random(-1, 1);
    speedY = random(-1, 1);
    this.maxParticles = maxParticles;
    intensity = 0; // Initial intensity
  }

  void update() {
    intensity = filteredDataValue*0.08; // Increase intensity over time
    float distance = map(intensity, 0, maxParticles, 0, 300); // Map intensity to distance
    x += speedX * distance;
    y += speedY * distance;
  }

  void display() {
     // Randomize particle color between turquoise blue and bright green
    particleColor = color(intensity*50, 200, random(0,150));
    println (intensity);
    noStroke();
    fill(particleColor);

    ellipse(x, y, intensity * random(5,6), intensity * random(4.5, 6)); // Adjust particle size based on intensity
  }
}
```

[END OF CODE]

Appendix F. Sensor Experiment Issues

Sensor Issues

Combining Prototypes | Since the components cannot fully integrate, some attempts have been done to prove the feasibility of the plant sensor on the platform since this is the envisioned concept. This however presented multiple issues that were not solved within this project:

✲ **Interference of the platform prototype |** It was clear that while the researcher moved the platform with the controller, it impacted the sensor data. Although this fluctuation was often not bigger than the capactive difference that occurs while touching the plant, it does make the proximity sensing impossible at this stage since it relies on subtle changes in value. The touch sensing still seems somewhat feasible since it generally overtakes these fluctuations .

✲ **Grounding Issues |** The author of the code library, Paul Badger, emphasizes the significance of proper grounding for capacitive sensing with Arduino boards (2008). This mostlikely contributes to the unstable result. This was also demonstrated by the fact that the sensor was more stable when powered by a charging laptop. A potential approach that Badger mentions involves connecting the Arduino ground to an earth ground, such as a water pipe. This was however not tested.

✲ **Seperate powersupplies |** Since each prototype has its own board and powersupplies, combining the two made it challenging to find a good configuration and mostlikely also contributed to the unstable sensor since it presumably changes the capacitance.

Sparked Inspiration | Thus, at this state of the project it was not possible to create a stable sensor on a mobile robot platform. With a static application however, it still demonstrated stable results; behaving as intended and delivering the desired output while interacting with the plant. This should however not limit the concept as it is a technical issue that should be solvable. Additionally, this limit also inspired a concept that involves plants with different tasks, e.g. static feelers working togetehr with mobile plants without feelers.

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