Horizon 2020

flora robotica

Societies of Symbiotic Robot-Plant Bio-Hybrids as Social Architectural Artifacts

Deliverable D1.1

Investigation of current mechatronics systems as a basis for the robotic symbiont

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Name:	**Investigation of current mechatronics systems as a basis for the robotic symbiont**
Description:	We describe the mechatronics concept which is a combination of modular robot mechanics, actuators, and electronic sensor modules for detecting the state of plants tied together with open-source single-board computers. We outline the current concept itself and the background for the concept.

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Contents

1 Introduction

The mechatronics basis of the *flora robotica* project put forward in the Description of Work is a combination of modular robot mechanics, actuators, and electronic sensor modules for detecting the state of plants tied together with open-source single-board computers such as BeagleBone Black or Raspberry Pi.

The consortium has since iterated on the mechatronics concept to better align it with the use case of using *flora robotica* hybrid organisms for architectural purposes. Below we outline some of the background for the current concept and the concept itself. The concept is still under development and as such should be considered preliminary. However, the concept gives a good indication of the kind of technologies that may become relevant as the project progresses and giving and overview of these technologies is the main point of this deliverable.

2 Design Goals

The *flora robotica* project's primary goal is to create a bio-hybrid robot-plant system where the robotic and the plant elements develop in a symbiotic relationship. The next step is to take *flora robotica* and apply it in a social and architectural context. Let us look at these two elements in more detail.

If we leave the specific plant-robot hybrid behind and consider the more general class of bio-hybrids, the state of the art describes them as a combination of closely interacting biological and technological elements [9]. An aspect of which as mentioned above is the symbiosis between living organisms and programmable autonomous robots. There are several goals targeted by biohybrids. One of them is to provide adaptability, plasticity and self-healing properties for such systems. In addition, integrating biological entities into existing engineering or IT infrastructure allows balancing a coexistence of fast-growing human ecosystems with natural ecosystems. Thereby a sustainability of natural ecosystems is emphasised. The topic of the biological entity controlling the robot is also an important topic, appearing in medical autonomous prostheses or human-robot interfaces. Many kinds of microorganisms and plants are superior in sensing environmental, pathogenic or unconventional impact factors. Such biohybrids, denoted as smart bio-sensors or phyto-sensors, are used in traditional technological devices and systems [16].

Let us take a step further and consider bio-hybrids in the form of *flora robotica* in an architectural context and look at how the plant symbiont may contribute to the creation of architectural

Plant growth	Conventional construction
Pros	**Cons**
"free"	Expensive (material, labor, transportation)
"No" energy consumption	High energy consumption
Adaptable	Pre-determined
Biodegradable	None biodegradable
Inherent aesthetic qualities	Designed to be aesthetic
Self-repair / renewal	High maintenance
Cons	**Pros**
Slow	Fast
Uncontrolled	Controlled

Table 1: A comparison of plant growth as a construction method compared to conventional construction.

structures. One way to do this is to compare plant growth to conventional construction as we have done in Table 1. It is clear that plant growth has many advantages over conventional construction when it comes to addressing modern societal challenges such as reducing energy consumption and environmental impact while providing functionality not possible with none-living matter such as self-renewal and adaptation. However, there is a big 'if' and that is if it is possible to handle the disadvantages of plant growth, such as being slow and uncontrolled. Increasing the rate of growth of plants is not in the scope of this project, but is potentially something that can be investigated separately. However, the question of controllability is a significant part of *flora robotica*. This is where the robotic symbiont comes in as being able to interact with the plant for the whole *flora robotica* system to grow into desired morphologies. However, the robotic symbiont is of limited usefulness if it invalidates the potential advantages of using plants for growing structures. Hence, if we aim to design a robotic symbiont it should optimally have the following characteristics although clearly not all are possible with current technology.

Energy neutral. Since the electronics will use energy, the robotic symbiont will have to collect its own energy in order to continue to work for long periods of time together with the plant symbiont.

Adaptable. The mechanical structure of the robotic symbionts should be adaptable both to changes in the task and the environment and in particular in response to its plant symbionts.

Biodegradable. The mechatronics should be biodegradable.

Self-repairable. The robotic symbiont should be able to repair itself or use the plant symbiont to repair itself.

Controllable. This is the specific functionality that the robotic symbiont adds to the plant-robot hybrid. It should be able to interact with the plant to achieve desired outcomes.

Fast. The plant is inherently slow but the robotic structure can be deployed quickly and provide functionality until the plant symbiont catches up.

3 Design Concept

As mentioned we cannot hope to realize all the desirable characteristics of the robotic symbiont discussed in the previous section. However, through a productive concept development phase we have designed a concept that gets relatively close. This architectural concept is illustrated in Figure 1. The basis of this concept is a purely technical construction kit made from nodes and rods that allows a user to build intricate geometrical structures. This mechanical structure as well as the plant symbiont can be instrumented with, what we call, *electronic fruit*. Electronic fruits are characterised by being easy to attach to and detach from the mechanical structure or the plant symbiont if it has sufficient structural strength to support the weight of the fruit. A fruit can also be carried over a long distance and hence can, conceptually speaking, seed other *flora robotica* structures with information gathered at the original site. In the envisioned system there are many types of electronic fruit providing different functionality such as sensing of the plant symbionts and the environment, actuators for influencing the plant or the mechanical scaffold, or for interacting with the human user (see Section 5.6 for a priliminary discussion of the technical implementation of sensor fruits). The electronic fruits are expected to have two modes of operation. In deployed mode they are in low-power mode and employ distributed control based on local communication and if possible harvest energy locally. In addition to

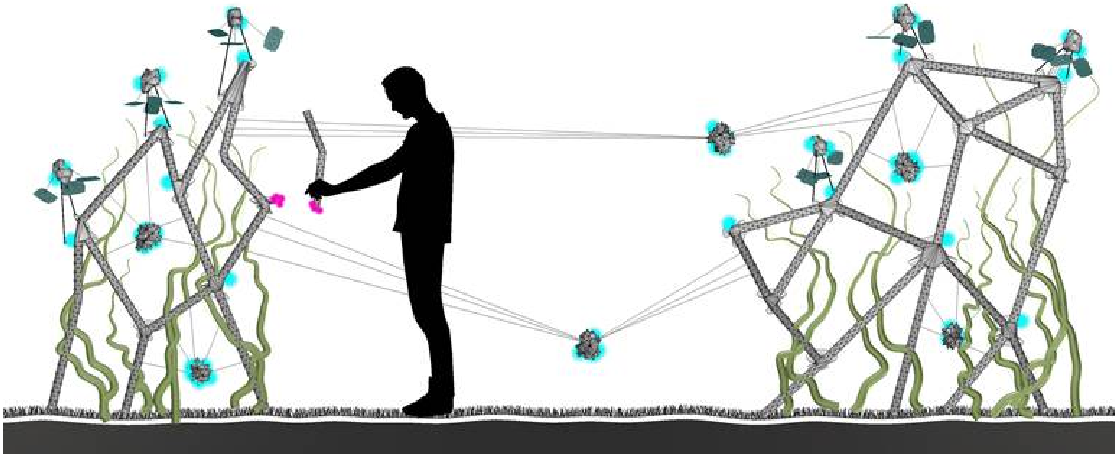

Figure 1: An illustration of a preliminary *flora robotica* concept. The concept includes a scaffold structure built from rods and nodes (gray), electronic modules attached to the scaffold or suspended between elements, and the plant symbionts. Some electronic modules have solar panels attached indicated by the small squares. The human user interacts with an electronic module maybe to inform the *flora robotica* system that growth is desired in this direction.

the functionality of the deployed mode, they provide all relevant data in experimental mode to a central host for recording of the experiment and to support general software development, deployment and debugging work. In experimental mode the robotic symbionts rely on external power or batteries. Following is a discussion of how this concept takes steps towards reaching the desired characteristics of the robotic symbiont.

Energy neutral. Energy can be harvested to make the system energy neutral in deployed mode.

Adaptable. The rod-and-node design makes it possible to add and remove elements from the system as needed and reinforce the structure as it becomes bigger.

Biodegradable. Electronics cannot be made biodegradable at this point, but using the concept of electronic fruits they can be detached and reused. The rods and nodes on the other hand can be made of bio-degradable material. A potential concept is that the mechanical robotic symbiont initially can provide structural strength to the system—a responsibility which over time is transferred to the plant as it grows bigger while the mechanical parts degrade.

Self-repairable. None of the deployed mechatronics components are self-repairable. However, what we can provide is a system that is easy to repair by making electronics and mechanics easily replaceable and let the plant symbiont play a potentially larger structural role over time.

Controlable. A key challenge of the project is to control the growth of plants into desired shapes. Here various options are available as outlined in coming sections.

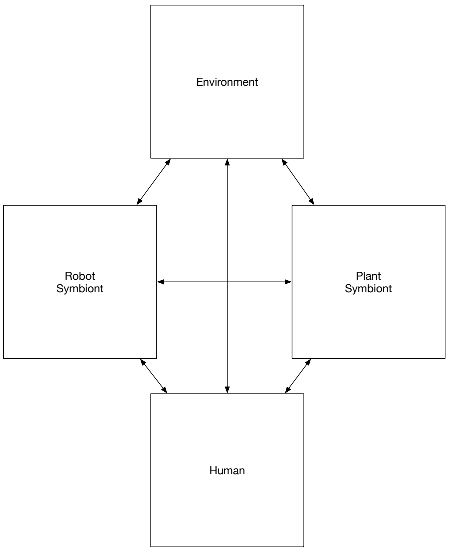

Figure 2: Simplified overview of interactions between plant, robot, human, and environment.

Fast. Robotics elements can quickly be snapped together to form a prototype structure that anticipates the growth of the plant symbiont.

Above we have outlined the characteristics of a robotic symbiont that is compatible with the plant symbiont to the degree that is possible. However, we have not touch upon the interactions. An overview of the interactions can be seen in Figure 2. The figure, however, is deceptively simple. In its most simple form the robot symbiont can sense the physiological state of the plant and influence the physiological state of the plant through actuation. This can be the basis for a homeostatic feedback loop where the robot can take care of the plant symbiont or drive it to desired goal states (this mode of interaction is illustrated in Figure 3, top). Similarly, from the plant symbiont's perspective there is a control loop where it senses the physical manifestation of the robot as well as the actuation stimuli created by the robot and then reacts to those. These two control loops are the basis for a symbiotic relationship between the two and is represented by the double arrow going from robot symbiont to plant symbiont in Figure 2. However, the two symbionts are also both embedded in an environment they both can sense and influence directly. If we look at all these four control loops it is clear that there are higher level control loops as well. It may be that the plant physiologically reacts to a stimuli from the environment which the robot can sense as illustrated in Figure 3 (bottom). This is a case of using the plant as a sensor and is called phyto-sensing. The final aspect is the interaction with the human who clearly can sense and act on all elements both consciously and subconsciously (e.g., through exchange of gases).

The possible interactions to explore are truly staggering. However, for this deliverable we are focused on the mechatronic basis of *flora robotica* and hence we only discuss the electronic sensors and actuators of the robotic symbiont that are relevant for the concept and potential interaction described above.

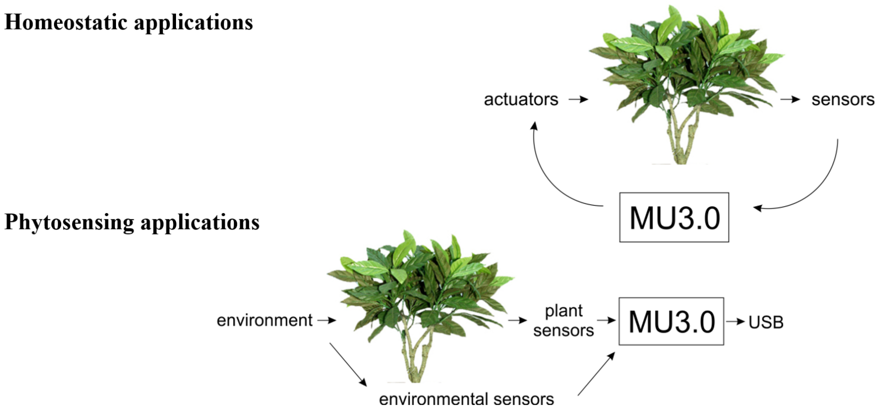

Figure 3: Closed-loop control and homeostatic system with plant sensors and plant actuators, from [3].

4 Related Systems

In this section we provide an overview of related systems to the envisioned *flora robotica* system.

4.1 Modular Robotics

Modules of modular robots typically contain integrated mechanics and electronics that allow the modules to be put together in a plug'n'play fashion [20]. While this plug'n'play feature is desirable also from a *flora robotica* perspective the negative consequences are serious. The use of integrated mechatronics make the individual module large and heavy. This is a problem if we are to build structures on an architectural scale because just maintaining the structural integrity of robotic symbionts would be a major challenge. Another consequence is that the modules become costly due to the complex integrated mechatronics. Again, this becomes problematic if we are to scale to architectural relevant sizes. Finally, the integration of electronics in every module means that there is electronics distributed throughout the system which is a significant waste of resources as it is likely that electronics is only needed in specific parts of the structure (e.g., at the frontier of growth). This background was know at the time of writing the Description of Work and therefore we proposed an alternative design strategy. The idea behind this strategy is that the mechanics is separated from the electronics such that the mechanics can be assembled first and the later electronics can be added where necessary. This concept is used in the LocoKit robot construction kit that partner ITU developed in the past [10]. However, while the concept applies equally to *flora robotica* the specific technical implementation does not. The LocoKit electronics is geared towards high-powered fast locomotion and for *flora robotica* we are more focused on low-power, slow actuation. Hence, many of the ideas and experiences from the field of modular robotics are carried into the project, but the existing mechatronics implementation are not a good match for the requirements of *flora robotica*.

4.2 Plant-Control Systems

Almost all existing plant-control systems are developed in the context of agricultural and horticultural production. The goal is therefore to optimize and control CO2, light and irrigation (CLI control), to optimize the productivity of plants. One of the oldest implementations of such systems was developed in the 1980s in Kishinev (Academy of Science of Moldavian SSR) [11]. The system had 14 different plant sensors and about 7 plant actuators, systematic changes of environmental parameters (through plant actuators) were done by computers. For an example see Figure 4. This system was the first that implemented a full closed-loop-cycle of plant control.

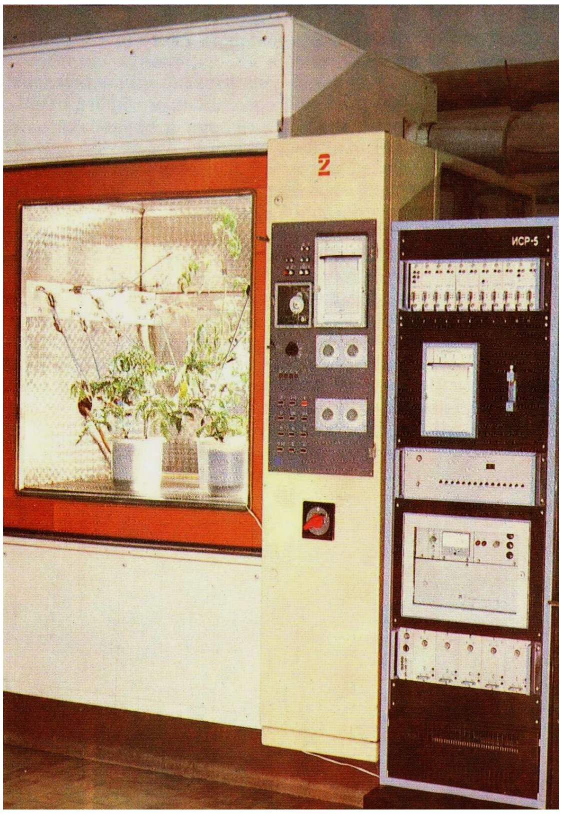

Figure 4: One module of the BIOTRON system: an example of a plant chamber.

A large number of further developments in scientific and commercial areas arose from this system, among them the phyto-sensor group (bio-instruments S.R.L.)[1], Daletown Company Ltd and others. Well-known companies such as Gardena[2] that produces automatic solutions for water control operate on the European market. Currently, we can also find a large number of different systems, especially from Asian companies, that offer half-automatic controllers of CO2, light and irrigation. Fully Automatic CLI control is not frequently used in large agricultural and horticultural companies. Primarily for reasons of responsibility and insurance, the human operator is involved in the control loop.

In the context of flora robotica, CLI control can be implemented by the robotic symbiont to guarantee a homeostatic regulation of plants. However, the task is different from conventional CLI control because *flora robotica* systems are not only to be deployed in completely controllable environments such as green houses. However, many of the sensors and actuators are still relevant.

[1] http://www.phyto-sensor.com
[2] http://www.gardena.com

4.3 Conclusion

It is clear that the existing systems, both on the conventional plant control side and on the modular robotics side, are not good matches for a realisation of the *flora robotica* concept. However, this does not mean we have to design the *flora robotica* hardware from scratch. In the following section we list the most relevant technologies that could find their use in *flora robotica*.

5 Technological Background

In the following sections we describe the technological background for the robotic symbiont in terms of specific components or technologies that may become part of the *flora robotica* implementation.

5.1 Sensor Nodes

In the Description of Work we mention motes as a basis for a distributed sensor system deployed throughout the structure of *flora robotica*. The number of different sensor motes available is staggering. Wikipedia lists more than a hundred systems of various levels of maturity and functionality (see https://en.wikipedia.org/wiki/List_of_wireless_sensor_nodes). It is beyond the scope of this document to go through them all. However, what is clear is that for sensor nodes the consortium is likely to be able to use existing technology. Three potential candidates are:

MU: a low-power, low-noise sensor system, developed by Cybertronica Research (CYB, *flora robotica* partner). It supports all standard sensors with voltage, current or frequency output and can supply a voltage between 1.8 and 40 volts. The core is based on flexible PSoC technology allowing a fast adaptation of the systems to the project requirements. As an example of sensor nodes for different types "sensor fruits," the systems MU2.0 and MU3.0 are to be mentioned, see Figure 5. The electronics possesses several MOSFET and full-bridge PWM drivers and thus is suitable for plant actuation as well.

Waspmote: low-power consumption (15mA if on), add-on boards available for most wireless communication technologies, add-on boards available with 100+ types of sensors, add-on boards available for integrating own sensors, prepared to be power by solar cells, core board is open-source, a mature software architecture and API available. The core board is about 100 Euros. (http://www.libelium.com/products/waspmote/hardware/)

Multi-standard SensorTag: low power consumption, range of sensors integrated (magnet, microphone, motion, humidity, ambient light, pressure), wireless communication, mature software development environment available, open-source hardware, extendible, tag costs 25 Euros. (http://www.ti.com/ww/en/wireless_connectivity/sensortag2015/tearDown.html)

The last two nodes are supported by large companies with significant support and documentation. While these modes are similar in several ways the Waspmote system has a much wider range of sensors available and also sensors that can be mounted outside of the mote itself, for example, on a plant or a robot. On the other hand, the Multi-Standard SensorTag has all sensors integrated onboard and is thus a more integrated platform. The MU3.0 system allows for a flexible way to connect different sensors and has the advantage that it can be tailored to the specific needs of *flora robotica* because the producer is a partner.

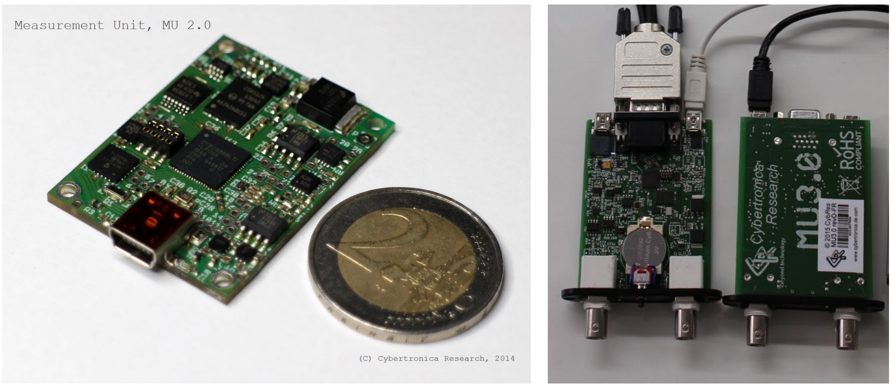

Figure 5: Example of electronic nodes for "sensor fruits": MU20 (size of electronic board 30×40mm) and MU30 (size of electronic board 40×60mm).

An important aspect of the *flora robotica* sensor node is that it is desirable to establish local communication between nodes where there is a relation between the distance between nodes and the quality of the signal. The underlying point is to be able to exploit, at an algorithmic level, that only neighbouring modules receive specific signals. This is not possible with all address- or ID-based communication technologies. Hence, the sensor nodes above have to be extended with a means for local communication. This could be in the form of an infrared transceiver ring organised with transceivers organised to provide acceptable coverage.

5.2 Single-Board Computers for Instrumentation

While sensor motes are likely to be able to handle the run-time of the system they are limited in terms of computation power, storage, and energy. Hence for more demanding tasks we plan to use a single-board computer. The responsibility of this computer would be to collect data from all motes and potentially facilitate communication between nodes (which is needed in a bluetooth setup with one master and many slaves). It can log the data both as a documentation of a research result and as debugging. Furthermore, the single-board computer would have a Linux operating system allowing us to work very efficiently by using standard software libraries. There are many choices of cheap single-board computers, also many that appeared since the Description of Work has been written. Wikipedia provides a comprehensive list of options (`https://en.wikipedia.org/wiki/Comparison_of_single-board_computers`). Usually, the older systems are preferable as they have a large user base and hence documentation and hardware support is well developed. For *flora robotica* the deciding factor is likely to be connectivity. If USB, SPI and I2C is enough this is supported by all boards and hence older systems will be favoured, for example, Raspberry Pi. However, if more advanced communication is required (as discussed in the following section) it might be useful to look at alternative boards that include Wi-Fi as well as Bluetooth (e.g., Banana Pi).

5.3 Communication Technologies

Wireless communication makes the development and installation of the modules easier. There are no electrical connectors and it allows to update the firmware wirelessly, which is useful for re-programming and debugging purposes. Nevertheless, most wireless protocols are based on heterogeneous devices having different roles in the network. This can affect the power consumption in some technologies and usually creates single point failures. Although there are a lot of different wireless protocols, none specificially has all the requested features for *flora robotica*: homogeneous devices (no coordinators or masters), self-healing, low power, low cost, etc. An overview of different options of wireless communication protocols is given below and we will select the protocol based on partners' feedback.

Bluetooth low energy: It has a star topology where a master device periodically talks with its devices. It is widespread and it is very easy to implement the over-the-air programming feature. Connection interval can be set to values ranging from 7.25ms to 4s. Furthermore, the slave may skip some of the connection events such that the maximum effective connection interval is 32s. The drawback is that we have to implement routing mechanisms in the master to distribute the messages between the devices. As the power consumption in the master node will be significantly higher than in slave devices, we should also implement a mechanism to switch the master role periodically.

Ant: This is similar to Bluetooth low energy but allows more network topologies. Its maximum connection interval is 2 seconds but this feature can be changed at runtime. It is based on a channel concept, where each channel has at least one master and one or several slaves. Each device can have up to 8 independent channels, so for up to eight devices it would be straightforward to build a network. Each device would have a master channel to send its data and seven (or less) slave channels to receive data from other devices. If more devices are needed, we should implement a switching role and routing mechanisms as proposed for BT low energy.

6lowPAN (Contiki): This protocol has encapsulation and header compression mechanisms that allow IPv6 packets to be sent and received over IEEE 802.15.4 based networks. This means that is possible to communicate with a low powered device from a computer using standard protocols such as HTTP, UDP or TCP. 6lowPAN is implemented in the Contiki operating system (`http://www.contiki-os.org/`) and can be used with CC2650 integrated devices. The main drawback is that one node in the network has to be an edge router (with or without internet access) to allow the routing of the messages, causing a single point of failure. Switching this role at runtime is not easy as one has to compile the code used by all nodes asynchronously.

Zigbee: It provides a mesh network with three different types of roles: coordinators, routers and end devices. Usually, implementations are based on non-beacon mode where coordinators and routers must be powered on all the time. Nevertheless, Texas Instruments has a Zigbee Stack able to work in beacon mode. Using this approach all routers and the coordinator can sleep a fixed period of time to save power. Connection interval can be set up to several minutes but is fixed. Nevertheless, the coordinator would be a single point of failure and we should implement strategies to recover the network in the case of problems. This error could be common due to the coordinator wasting more energy than other devices, as it has to route all messages. Over the air programming is not supported in this implementation.

Digimesh: Proprietary protocol made by Digi where all nodes are homogeneous, can route messages and can sleep cyclically. There is no over the air programming and it uses Digi devices which can increase the cost significantly.

Thread: This is a self-healing and IP-addressable network. The specifications are still under development and, probably, routers need permanent power. Currently, only Freescale has a Thread Beta Development Program able to external developers.

MyriaNed or MyriaWise: "The MyriaWise nodes do not need any infrastructure, they just organize themselves and become a fully meshed network which is the infrastructure in itself. The protocol runs on the Nordic BLE chip. Via one gateway one can get the data from all network nodes in one's backoffice. With MyriaWise as your IoT network you are able to create a self-organising network with 10.000 nodes or more. They last for over 5 years on a single battery and without a single point of failure. An important differentiator of MyriaWise is the support of network programming: the behaviour of the network can be changed without updating individual nodes." It seems perfect for our application but there is not too much information available. There is a webshop selling some prototypes and a kit with development software and MyriaNed library (`https://myriamodem.vanmierlo.com/`). But it seems that they are commercialising this technology (`http://chess.nl/wireless-by-nordic/`).

While some of the newer technologies are interesting from the perspective of *flora robotica*, the choice is likely to be made based on compatibility with the single-board computer. Then Bluetooth seems the obvious choice as it is widely supported by many devices including tablets which may be relevant later in the project in connection with the social garden.

5.4 Phyto-sensors

A phyto-sensor can also be defined as a device that can either detect, record, or transmit information related to a physiological change in a plant [18, 17]. The electrophysiology of a plant is widely used in phyto-sensing because mechanical, chemical, and other influences affect the electrical action potentials throughout the plant. The most commonly used methods for plant electrophysiology evaluation are patch clamps, electrochemical impedance measurement, and charge stimulation. The charge stimulation method was introduced in [17]. It delivers the electrical charge from a capacitor to the plant and disconnects the plant from the stimulus generation system. This was made in order to estimate the plant response after stimulation and make sure that the stimulation generator does not trigger changes or impact the plant responses after stimulation. Bioelectrical impulses in the plant travel from the root to the stem and vice versa. The speed of propagation of these impulses is influenced by chemical treatment, intensity of the irritation, mechanical wounding, previous excitations, temperature, and other irritants [19]. Plants are continuously interacting with the external environment in order to maintain homeostasis. A large number of works [15, 8, 7, 13, 6] investigated and mentioned that electrical activity of a plant depends on environment characteristics (temperature, lighting, irrigation of the plant, etc.) and moreover it is possible to detect the correlation of plant electrical activity with the circadian cycle. Thus is is important to measure all relevant environmental parameters in parallel to phyto-sensing.

5.5 Plant, Robot and Environment Sensing

Plant sensing is directly related to obtaining and recording physiological data from plants and represents a significant challenge. Currently three approaches seem to be of interest. One of them is based on plant tropisms. Tropisms are directional movement responses that occur in response to a directional stimulus. The relative inclination can be sensed by small 3D accelerometer and a 3D magnetometer, for example, installed on the leafs or the stem. The movement in term of displacement can be be sensed by IR-based (proximity sensing) and camera-based approaches. However they have disadvantages of requiring either a global view on a plant or additional sensors for detecting the movement direction. The displacement of specific points on a plant can also be measured in a wireless way by installing active or passive elements (like RFID chips) on plants and sensing the intensity of responses. There are works indicating a usage of electric fields [4, 1, 2] for biomass sensing, see Figure 6. In particular, this approach can be used for estimating the parameters of plant growth.

The second approach for plant sensing is based on electrophysiology. Here, either the potential between several points of a plant, see Figure 8, or a current between two points is measured. Both approaches have a number of well documented physiological effects of electrical signals in plants (see Figure 7). The European project "PLEASED" was dealing with the potential measurement and mapping stimuli to responses [14].

Environmental sensing includes a number of standard sensors for temperature and air humidity measurement, soil moisture, light, and CO2. These sensors are commercially available, attention should only be paid to the accuracy of measurements, linearity, and the the level of noise in the data acquisition module. An example of environmental sensors connected to a MU3.0 node is shown in Figure 11.

Robot sensors installed on a mechatronic platform can include different standard proprioceptive sensors, like 3D accelerometers/3D magnetometers, infra-red proximity sensors, and others. Their selection will be finalised after the first design of a mechatronic platform.

5.6 Preliminary Considerations Regarding "Sensor Fruits"

At this point in the project we are supposed to deliver the technological basis for *flora robotica*. In the following we already speculate regarding the implementation of so-called "electronic fruits" given the technologies described above.

The concept of "sensor fruits" requires different kinds of electronic modules that differ in terms of size/weight, energy consumption (thus require wiring for power supply), and connected sensors. Several considerations regarding the selection of electronic modules are shown in Table 2.

Level	Example of used technology	Wiring	Energy requirement
main controller	RASBRERRY PI2	required	high
sensor/actuator node (large "electronic fruit")	MU3.0	required	high
sensor node (small "sensor fruit")	MU2.0	wireless is possible	low
sensors (very small "sensor fruit")	only sensors	required	very low

Table 2: Several examples for different "electronic fruits".

The tested setup with different electronic components is shown in Figure 9. The main board can be connected to many (max. 127) sensor nodes, see Figure 10. An example of environmental sensors (very small "sensor fruits") connected to MU3.0 is shown in Figure 11.

5.7 Actuators

In the Description of Work actuators are seen as a way to deform the lattice structure of the robot symbiont to adapt it to the growth of plants. This view is not currently favoured because we envision that the plant is intertwined with the lattice structure of the robot and hence any large scale actuation is likely to tear the plant apart. Practically speaking, the plant, although flexible, cannot be stretched. Hence, it is not possible to have a plant connected to a scaffold structure that is elongating due to actuation. If the chosen species of plant symbionts is flexible, such as beans, it is possible to bend it.

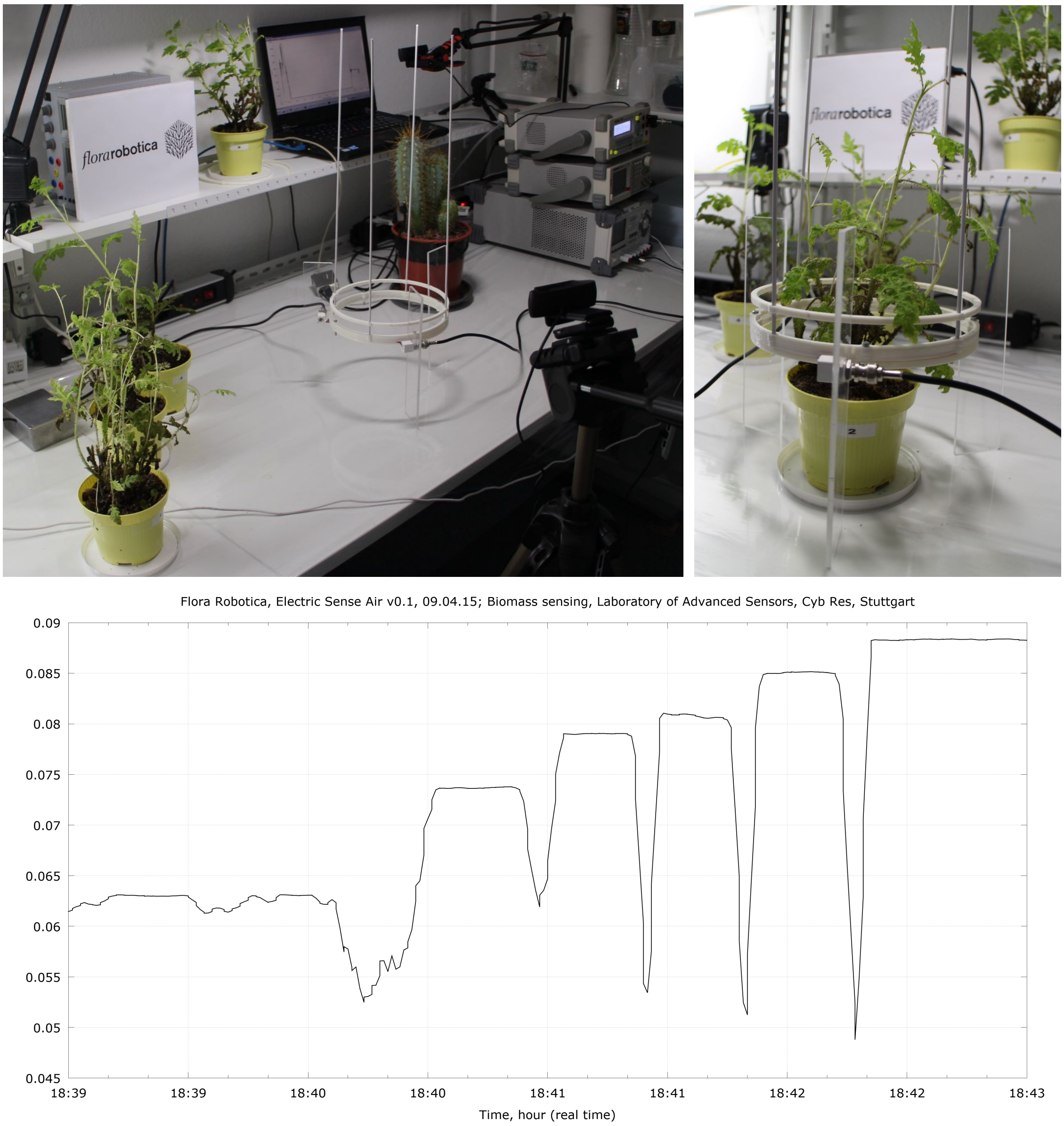

Figure 6: Test of biomass sensing by using electric fields.

Stimulus	Signal	Plant	Physiological effect	Reference(s)
Mechanical	AP	*Dionaea*	Trap closure Release of digestive enzymes	Sibaoka 1969
Mechanical	AP	*Drosera*	Tentacle movement to wrap around the insect	Williams & Pickard 1972a,b
Cold shock, mechanical	AP	*Mimosa*	Regulation of leaf movement	Fromm & Eschrich 1988a,b,c; Sibaoka 1966, 1969
Electrical	AP	*Chara*	Cessation of cytoplasmic streaming	Hayama, Shimmen & Tazawa 1979
Electrical	AP	*Conocephalum*	Increase in respiration	Dziubinska *et al*. 1989
Pollination	AP	*Incarvilea, Hibiscus*	Increase in respiration	Sinyukhin & Britikov 1967; Fromm Hajirezaei & Wilke 1995
Re-irrigation	AP	*Zea*	Increase in gas exchange	Fromm & Fei 1998
Cold shock	AP	*Zea*	Reduction in phloem transport	Fromm & Bauer 1994
Electrical, cooling	AP	*Luffa*	Decrease of elongation growth of the stem	Shiina & Tazawa 1986
Electrical	AP	*Lycopersicon*	Induction of *pin2* gene expression	Stankovic & Davies 1996
Heating	VP			
Heating	VP	*Vicia*	Increase in respiration	Filek & Koscielniak 1997
Heating	VP	*Solanum*	Induction of jasmonic acid biosynthesis and *pin2* gene expression	Fisahn *et al*. 2004
Wounding	VP	*Pisum*	Inhibition of protein synthesis, formation of polysomes	Davies, Ramaiah & Abe 1986; Davies & Stankovic 2006
Heating	VP	*Mimosa, Populus*	Transient reduction of photosynthesis	Koziolek *et al*. 2004; Lautner *et al*. 2005

Figure 7: Examples of well documented physiological effects of electrical signals in plants, from [5].

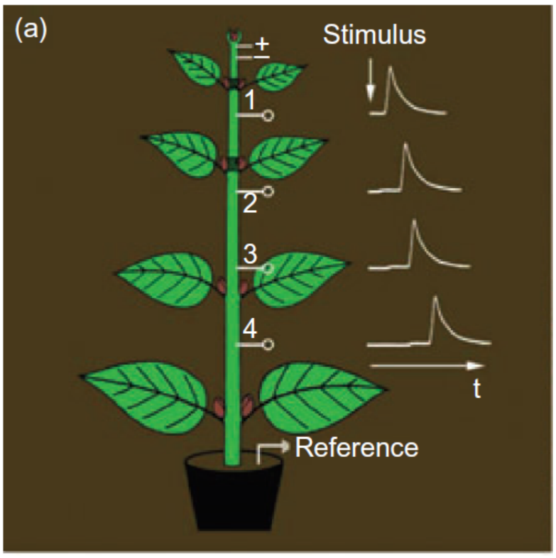

Figure 8: An illustration of how a potential could be measured, from [5].

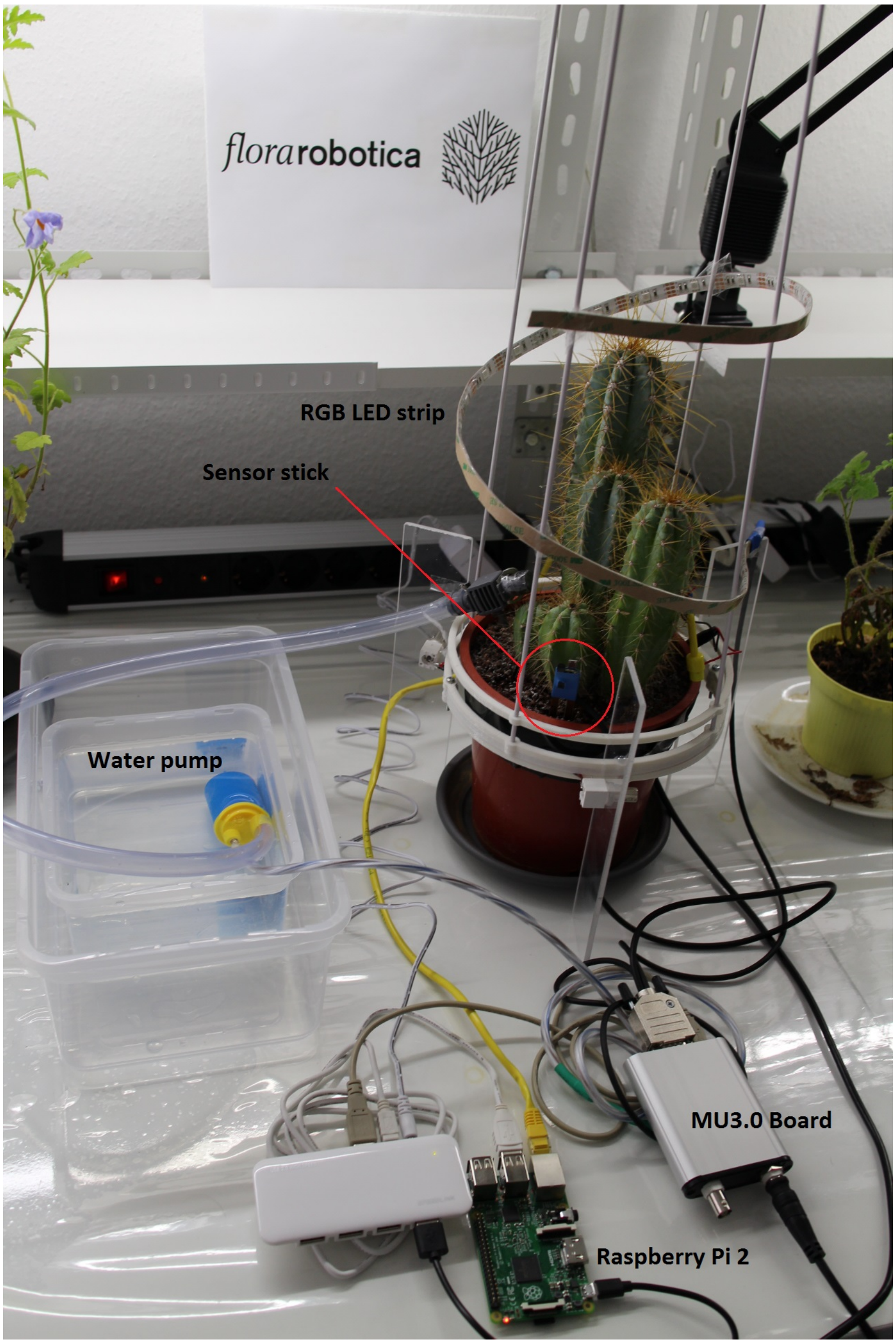

Figure 9: Example system with the main board Raspberry Pi2, the sensor/actuator node (large "electronic fruit") with MU3.0 and several environmental sensors/actuators.

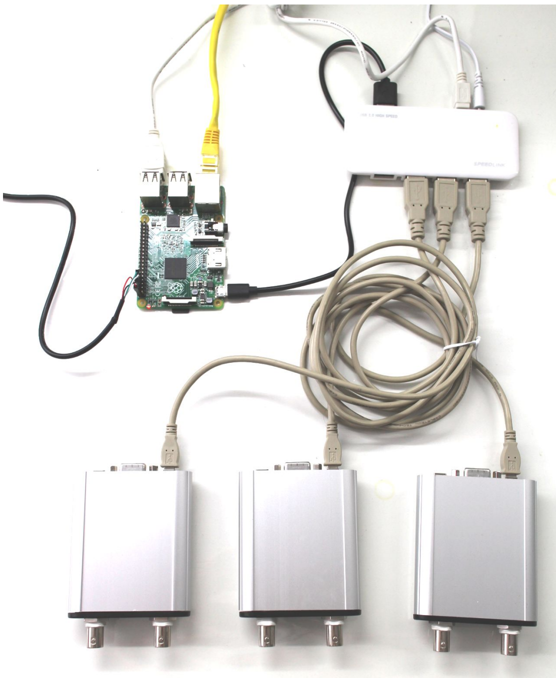

Figure 10: Connection between the main board and several sensor/actuator nodes.

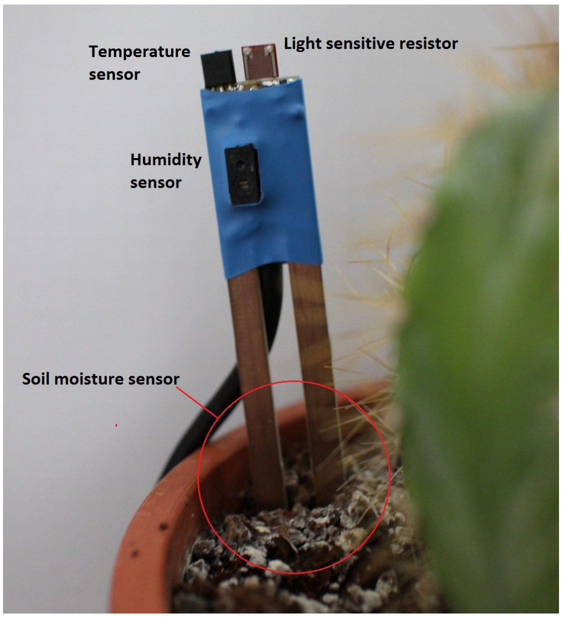

Figure 11: Examples of environmental sensors (very small "sensor fruit").

The second concern about actuation is that it is the goal to make the online part of the *flora robotica* hardware power-neutral or at least very low powered. Actuators are high-powered, typically using two orders of magnitude more power than basic electronics. Hence, any actuator employed can only operate rarely and in short intervals. In particular, any actuation that requires power to maintain position is not appropriate. The approach to handling this challenge is to make sure that the chosen gearing mechanisms are not back-drivable. For specific choice of motors there is a wide range available from the simple to control servo motors to more efficient, but difficult to control brushless dc motors. The specific choice of actuator technology depends on further investigation of torque requirements of the system which then should be balance against the power available to find a useful frequency of action.

5.8 Plant Actuators

The actuator discussion above is geared towards large scale mechanical actuation of the robotic or plant symbionts. It is, however, also possible to influence the growth of the plant symbiont through different forms of actuation. An obvious choice is to use RGB LEDs to exploit the plants' natural phototaxis and morphism although competing with natural light will be a significant challenge so it may be best to direct and control the natural light as opposed to powering LEDs.

Possible plant actuators are also CO2 devices (and in general ions-activated air [14]) and electric stimulation (by current and by electric field). Vibration motors are available off-the-shelf and may also be interesting for use either on the plant or robotic symbiont. The vibration may be able to stress the plant in specific parts and thus reduce growth rate. It may also be possible to detect the vibration and to use it as a means for local communication or even to signal to human beings.

Releasing hormones on the plant may also yield benefits for the *flora robotica* system and will thus be considered, but a high priority is to consider any associated health risks and the technology will in case of health risks not be used.

5.9 Energy Harvesting

A core aspect of *flora robotica* is to investigate whether it can be made energy neutral by collecting the necessary energy from the surrounding environment. An obvious choice are solar cells as light will be needed to keep the plant symbiont alive anyway. For solar cells there are various options primarily split between cells that are more efficient at converting direct sunlight as opposed to others that are better at converting indirect light. The latter is most often used in northern Europe.

An alternative is to harvest the energy from wind moving the branches of either the plant or the robotic symbiont. One option here is to use piezoelectric elements that convert strain into electricity for which successful experiments have already been reported [12]. However, the amount of generated current is very small compared to solar cells.

More experimental is the potential of harvesting energy directly from the metabolism of the tree as demonstrated by VolTree[3]. Project partner CYB has explored energy production through a potentiometer approach with bi-metal electrodes. This approach can also be tested in further development in *flora robotica*.

[3] http://voltreepower.com/index.html

6 Conclusion

In this deliverable we have covered the potential mechatronic basis of the robotic symbiont of *flora robotica*. For mechanics the consortium is focused on lattice structures that can be assembled by a human user. The electronics infrastructure of the robotic symbiont covers many available choices in sensing and actuator technologies. There are also many options in terms of communication technologies for connecting elements of the *flora robotica* system together and many choices of single-board computers for use in development and in recording of experiments. Finally, some more high risk possibilities have been outlined that relate to phyto-sensing and energy harvesting.

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