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Detecting effects on soil moisture with Guerilla Sensing

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Abstract A soil moisture monitoring system (SMOS) is presented to support the microclover project in determining effects of soil cover on soil moisture. It is built as a project-specific adaptation of the environmental information system (EIS) Guerilla Sensing. We describe the adaptation process step by step to provide a blueprint for easy use of Guerilla Sensing in similar future projects.

Keywords environmental information system, soil moisture measurement, soil cover, plant cultivation

1 Introduction

Climate change and the resulting increase in temperature and drought periods challenge mankind with rising frequency. Routine economic processes must be put on trial, searching for more resource-conserving and efficient alternatives. Nursery industry is challenged from two sides. First, the lack of predictable precipitation and water availability causes pressure to reduce water consumption. Second, increasing energy prices and consequently more expensive fertilizers increased studies on how nitrogen-fixing legumes may reduce the dependency on artificial fertilizers. Legumes have consequently been used previously in a number of crops as living mulch [1]. The advantages are crop-specific and depend on cultivation practices [2]. The effect of living mulch, therefore, needs to be investigated separately for any cropping system. So far, experience with pot-based cultivation in horticultural nurseries is lacking.

The project “microclover” funded by the Agricultural European Innovation Partnership “Productivity and Sustainability in agriculture” investigates how soil cover by different clover types on nursery pots may help to *improve soil moisture*, *provide nitrogen* to the soil and even *suppress weeds*. Legumes are specifically suited as living mulch since they are able to fix nitrogen from the air through their symbiosis with rhizobial bacteria in root nodules. Low growing types of clover like micro-varieties of white clover (*Trifolium repens* L.) should therefore not compete with nursery plants. They do not shade them, but complement them by providing extra nitrogen and suppressing weeds by shading.

While soil nitrogen content and the biomass of the ornamental and weeds are easily measurable, the expected effect on soil moisture is not. As later highlighted in section 2, multiple soil moisture measurements must be taken and documented daily over a one-year period at two different measuring points on multiple outdoor plant pots. Furthermore, measurements shall not influence follow-up measurements, e.g. due to changes in the conditions at a measuring point resulting from measurement methodology. In addition, important parameters such as sampling rate of soil moisture and measurement accuracy are not fixed so far.

Measurement methodologies that determine soil moisture, by weight, by sticking instruments in and pulling them out, or by drying samples cannot be used. They would not measure soil moisture at defined points or would affect subsequent measurements by changing soil structure due to compression and incision of irrigation canals. In addition, the number of measurements throughout the day over a period of a year would result in large, repetitive, and monotonous efforts if done manually. Thus, a soil moisture observation system (SMOS) is required that automatically performs and documents soil moisture measurements at defined measuring points in pots without changing soil structure.
When developing the SMOS, it must be ensured that it can be operated in the measurement environment for a period of one year and that sufficient measurements are recorded to evaluate stated hypothesis. Components of the system must be designed to be resistant to environmental influences and mechanisms to monitor their functionality must be integrated. The former prevents downtimes and thus measurement loss, while the latter ensures still occuring downtimes will be detected and resolved. In addition, undetermined parameters such as the sampling rate of the soil moisture and the required measurement accuracy must be determined in order to ensure that measurements are performed adequately. Using an automated SMOS ensures performing the microclover experiment with limited effort. Beyond the microclover project, such a system could also be reused for experiments with similar conditions. Further experiments looking at effects on soil moisture could be automated with such a SMOS. Thus, the system's transferability should be taken into account as an important requirement.

After introducing the objective of the microclover project in section 1, the project challenges will be presented detailed in section 2. Related work that provide knowledge on sensor selection and the EIS Guerilla Sensing are presented in section 3. The concept for an adaption of Guerilla Sensing to SMOS is derived in section 4. To select appropriate sensors, various sensor types are evaluated in section 5 and their embedding in sensor nodes is presented in section 6. Within a formative evaluation in section 7 outstanding parameters like the sampling rate of the soil moisture and the required measurement accuracy as well as further system parameters that offer scaling possibilities are determined. Finally, section 8 summarizes and discusses the resulting SMOS.

Consider that results concerning the conceptualization and realization of the SMOS are presented here. Biological findings will be presented in a future paper, when an appropriate amount of data has been collected.

2 The microclover challenge

To evaluate the microclover project's hypothesis that soil cover with clover has a positive effect on soil moisture of plants in nursery pots, the change of soil moisture in pots must be monitored and compared. A positive effect on soil moisture is defined as a slower decrease of soil moisture in covered pots. Different combinations of clover species and ornamental plant species could lead to different magnitudes of effects. Interfering factors, such as differences by individual plants, local soil properties, environmental situations, and measuring errors must be taken into account in order to relate the effect to soil cover with clover. Detecting changes of soil moisture is achieved by repetitive, time-shifted measurements. Measurements must be done at least twice between two water inflow phases to determine falling soil moisture without influences of water inflow.

To investigate variations in magnitude of effects likely to occur depending on combination of plant species and clover species, microclover considers two different ornamental plant species in combination with two different clover species. Additionally, as a reference, each plant species is monitored without soil cover and with non-living mulch as cover. Taken together, eight different treatments are considered. In order to exclude effects of individual plants as far as possible, each treatment is tested on six individuals, leading to a setup with 48 pots.

Local properties of soil affects measurements due to different positions and compression. Just below surface, soil is more likely to be warmed by sunlight, so water is more likely to evaporate. In addition, gravity acts towards the bottom of pots, which will cause more water to accumulate there. To account local effects, two measurement points are selected, one near the top and one near the bottom of a pot, resulting in 96 measuring points. Fixed measuring points minimize influences due to compression, as only local changes have to be considered and changes due to variation in locality can be excluded.

To ensure transfering the projects results to economically managed nurseries, measurements must be carried out under real conditions. Changing temperatures, solar activities, rainfall, day and night cycles, and seasonal changes affect soil moisture. Therefore, soil moisture measurements have to be performed multiple times a day over a period of one year on ornamental plants supplied outdoors at a nursery. Due to the project duration and multiple measurements a day, it is likely that all relevant environmental factors will occur multiple times and can be considered accordingly. The care of ornamental plants by a nursery allows the results to be applied to real situations. But it must be noted that in this way uncontrolled water inflow may occur, for example, due to rain.

Depending on selected measuring equipment, errors occur during each measurement. Therefore, suitable measuring devices must be selected according to measurement project requirements and potential errors must be taken into account during evaluation. In order to measure the desired effect in the microclover project, the measurement error must be smaller than the smallest difference of soil moisture measurements to be considered. Only then effects assigned to measuring errors can be excluded. However, if repeated measurements of adequate quantity show that soil moisture decreases more slowly over time in clover-covered plants compared to control groups, the hypothesized effect can still be concluded based on a large number of observations. It is unlikely that measurement errors will occur repeatedly in sufficient quantity to support the hypothesis.

In summary, soil moisture must be measured several times a day over a period of one year in a realistic environment without affecting follow up measurements at 96 measuring points and documented for evaluation in a separable manner depending on measuring point and time. Thereby, the exact sampling rate of soil moisture and the required measurement accuracy is undetermined so far.

3 Related work

As the effects of soil cover with clover on soil moisture are to be determined, it is necessary to measure the changes in soil moisture over time. Other related projects are dedicated or have been dedicated to similar challenges.

Predictive Plant Production The project Predictive Plant Production tries to optimize environmental parameters like temperature, soil moisture and soil conductivity to match plants' needs [3]. This way, the project aims to increase plant growth while only as much resources are used as are necessary. A set of sensors is used to learn a model of plant growth and weather conditions. The model tries to predict the process of plant development and ease the scheduling in production.

As part of the Predictive Plant Production project, a wide variety of sensors from different manufacturers were compared and evaluated using a standardized procedure. Uniform soil is completely dried and then mixed with an amount of water that is tailored to the volume of the soil. The moistened soil is then filled into containers and compressed using a standardized process. Accordingly, the soil moisture of prepared soil is almost known. The soil moisture of the soil in containers is measured with different sensors. Difference between almost known and measured soil moisture is used to evaluate sensors.

The results vary over different sensors, as some delivered more accurate and repeatable results than others. Thereby, they differ in cost and durability. This suggest that sensors must be chosen project-specifically. Therefore, a study is performed in section 5 to make a microclover-specific sensor selection.

Guerilla Sensing In order to handle the microclover challenge and at the same time to support the intended sensor study with project-specific experiments, an adaptable EIS is needed. Here, the Guerrilla Sensing system [4] offers a solution. It is developed in an extensible way and allows automatic sensing and documentation of different environmental factors, which can be accessed via a web-based application. Sensor drivers can be defined in the Guerilla Sensing platform and firmware can be configured for situation-specific assembled sensor nodes, called G-Boxes. Various measurement projects, such as monitoring air quality near schools, radioactivity near castor transports and soil moisture measurements in forests[3] have already been realized with Guerilla Sensing.

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[3] https://www.guerilla-sensing.de/campaign/7

Due to the high degree of adaptability, a universal G-Box to which different soil moisture sensors can be connected is realized for the intended sensor study in section 5.2. Sensor drivers and parts of the universal G-Box are adopted to a microclover G-Box in section 6. With the web-based application, collected measurements in sensor experiments as well as in the microclover experiment can be remotly accessed at any time. Accordingly, missing measurements are noticed without travelling on site. Due to reuse of components and the generic approach of Guerilla Sensing, the effort to realize the required SMOS can be kept low. Here an instantiation of the Guerilla Sensing, shows its applicability to the problem at hand. For a detailed, general view on the systems architecture please refer to the paper "Environmental wellbeing through guerilla sensing" [4].

4 Guerilla Sensing as soil moisture observation system

Guerilla Sensing depicts with the three types of subsystems G-Client, G-Platform and G-Box the required functionalities and features to realize a SMOS in order to detect effects of soil cover on soil moisture. With the web-based G-Client, persisted measurements for multiple sensors can be screened simultaneously, visualized in line graphs, and exported to a file of comma separated values. Measurements can thus be viewed at any time and further processed with a variety of tools. The G-Platform persists measurements centrally and provides interfaces through which G-Clients can query measurements and G-Boxes can persist measurements. G-Boxes periodically request measurements from connected sensors and transfer them to the G-Platform. They can be designed project-specific, and the firmware for individual G-Boxes can be generated using the configurator in the G-Client via the G-Platform. The only requirement for a G-Box is that it supports the Arduino framework. In order to make project-specific sensors available via the configurator, their drivers must be implemented by extending a base-class and registered in the G-Platform.

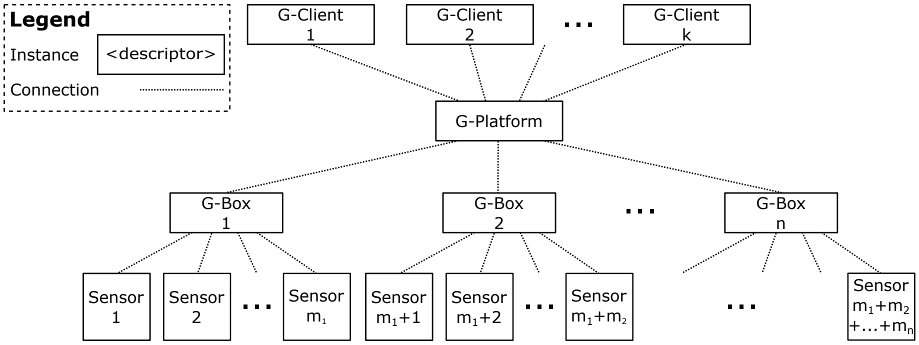

Fig. 1. Instances of Guerilla Sensing subsystems in order to observe effects in soil moisture.

As shown in Figure 1, k instances of G-Client can access the G-Platform. This allows stakeholders to access measurements simultaneously. Here, k can remain indeterminate, as the number of instances automatically adjusts according to requests of stakeholders. Stakeholders retrieve G-Client instances from the web server of the Guerilla Sensing system via web browser. The number of G-Box instances is also scalable with the Guerilla Sensing system. Thereby, Guerilla Sensing does not require that the number of G-Box instances n is predefined. Moreover, m_i sensor instances can be attached to a G-Box instance. The G-Box-specific number of sensor instances m_i must be known before the firmware is configured, but can easily be changed by configuring a new firmware.

By adjusting n and m_i, it is possible to scale between cost of G-Boxes and handleability of G-Boxes. When there are many G-Box instances, each connected to only a few sensor instances, the cost increases due to the large number of G-Box instances and the handleability also increases since there are only a few sensor instances connected to the G-Box instances. However, if few G-Box instances, each connected to many sensor instances, are used, the cost decreases due to the small number of G-Box instances but also the handleability decreases since many sensor instances are connected to one G-Box instance. For the microclover project, 96 soil moisture sensor instances are needed. The number of G-Box instances n and sensor instances m_i needs to be scaled accordingly.

The design of sensors and G-Boxes, as well as the number of G-Box instances n and the number of sensor instances per G-Box m_i have to be determined project-specifically, whereby decisions affect each other. In order to connect G-Boxes and sensors, G-Boxes must provide physical interfaces for sensors in an adequate number m_i. Which interfaces exactly are needed depends on sensors' choice. Only when sensors and G-Boxes are connected experience with the handleability can be made. Thus, m_i and n can be estimated in advance but have to be evaluated. To solve this problem, suitable sensors are first selected in section 5 and in section 6 G-Boxes are designed to handle more than an estimated number of sensor instances. In section 7 the handleability is evaluated.

5 Soil moisture sensor selection

In order to find suitable sensors to measure soil moisture in the microclover project, a project-specific sensor study was conducted, as highlighted in Section 3. This study is divided into two phases, where the first phase is lead by documentations to explore and select potential sensors for the second phase. The second phase is lead by experimental results to select a specific sensor. By reducing the number of sensors in the first phase, the effort for experiments in the second phase was reduced.

5.1 Sensor exploration

According the requirements discussed in section 2, sensors accuracy and durability have to be considered. Here, the required accuracy is unknown, but the

accuracy of sensors used must be known so that effects resulting from measurement errors can be taken into account. Regarding durability, the sensors must be able to operate outdoors for at least one year or it must be possible to replace sensors with respect to effort. Additionally, the documentation and connectivity of sensors will be considered in the first phase in order to use this information for the experiments in the second phase.
Based on the findings from the "Predictive Plant Production" project and experience with soil moisture sensors in previous Guerilla Sensing projects, a relationship between sensor cost and sensor characteristics like accuracy and durability can be seen. Therefore, sensors of different price categories are considered. Here, the selection is restricted to five sensors in a range from 20€ to 120€. Less expensive sensors are excluded based on the experiences with soil moisture sensors in previous Guerilla Sensing projects regarding their durability. More expensive sensors are excluded by limited projects funds. The considered range should be sufficiently covered by the five different sensors: Xiaomi Mi Flower Care Plant Sensor (∼20€), 3-prong sensor (∼25€), Tinovi Capacitive Soil Moisture sensor (∼30€) as well as the Trübner SMT50 (∼70€) and SMT100 (∼120€).

Xiaomi Mi Flower Care Plant Sensor This sensor is interesting for the project for its low cost of 20€ and communication via Bluetooth Low Energy (BLE). This will enable maximum flexibility for the setup, as no cables are needed and a single sensor node is suffice. This however comes with severe drawbacks. Firstly, the sensor is designed for indoor use, for monitoring soil moisture, light irradiation, and levels of fertilizer in the soil of house plants [5]. As a result, every single sensor have to be adapted with epoxy or similar materials to allow outdoor use. Also, the documentation is incomplete, so no data on the technology used or the accuracy can be found, which make intensive testing necessary.
3-prong Sensor For about 25€, the 3-prong sensor is a relatively inexpensive sensor that measures soil moisture via conductivity between the prongs. The accuracy of this sensor has a deviation of about ± 3-5% (higher deviation at higher moisture levels) [6]. The body of the sensor is made of epoxy, which should withstand the conditions. The prongs, however, are made of bare metal, which calls the long term durability into question. This sensor supports analog and RS485 communication. Unfortunately, the documentation of the sensor is limited to product descriptions.
Tinovi Capacitive Soil Moisture sensor The Tinovi Capacitive Soil Moisture Sensor is a dust and waterproof sensor that measures soil moisture via capacitance. No bare metal needs to be exposed for this measuring principle. It costs about 30€ and has a accuracy deviation of around ±5% [7]. The sensor supports I2C communication, but the cable length is very limited for I2C, which can be a problem depending on the distance between the pots. There is documentation provided by the manufacturer.
Trübner SMT50 The Trübner SMT50 is a more expensive option, priced at around 70€, but according to its documentation, it provides better quality data than the previous sensors, with a deviation of ±3% [8]. Its range of possible measurements, however, is limited to a volumetric water content of 50% or less.

The capacitive sensor is dust and waterproof, as it was made for outdoor use. The sensor is compatible with an analog communication protocol, and documentation is provided by the manufacturer.

Trübner SMT100 The Trübner SMT100 is the most expensive option, priced at around 120€, but it provides good accuracy with a deviation of ±2% (up to 50% volumentric water content) and ±3% (up to 100% volumentric water content) [9]. The capacitive sensor is dust and waterproof and is compatible with analog, RS485, and SDI-12 communication protocols. Documentation is provided by the manufacturer. Furthermore, the SMT100 has already been successfully used in comparable scientific projects [10][11].

The 3-prong sensor and the Xiaomi Mi Flower Care Plant Sensor are inadequately documented and their long-term performance under measurement environment conditions is questionable. Extensive arrangements must be made to operate the sensors as required. Alternative replacements of sensors in case of misbehavior would be imaginable due to the low prices, but the effect of operation in unsuitable environments on accuracy is unknown. This results in time- and money-consuming pre-experiments which the project budget does not cover. Consequently, these two sensors will not be considered any further.

In contrast, the Tinovi Capacitive Soil Moisture Sensor as well as the Trübner sensors SMT50 and SMT100 are well documented and built for outdoor use. It should be possible to operate all three sensors in the measurement environment without adjustments. The accuracy of all three sensors is well documented. Accordingly, this can be considered when analyzing measurements without determining the accuracy by own experiments. Based on these findings, the three sensors are candidates for further investigation in the subsequent second phase.

5.2 Sensor experiments

The remaining sensors were evaluated in more detail in three experiments to determine their fitness for the microclover project. In the first experiment, it is to be determined whether sensors work correctly and provide plausible values. The second experiment considers the continuity of sensors' measurements over an extended period of time. Experiment three will compare sensors to each other regarding their response to changes in soil moisture.

In order to efficiently perform experiments with the sensors, a universal G-Box was realized to which all sensors in question can be connected. The G-Box requests measurements from all sensors and sends them to the microclover G-Platform for later analysis. Developed drivers are accessible via G-Platform and therefore usable via the configurator in further progress.

Two samples of each sensor in question were obtained in each experiment to detect possible issues with individual samples. Here, the RS485 communication option was chosen for the SMT100. With an analog connection, measurements change depending on cable length due to different resistance values. Communication via SDI-12 would be suitable in principle as well, but RS485 has already been used in combination with G-Boxes, so corresponding experience is available.

Together, the universal G-Box requires at least two analog connections (Trübner SMT50), two I2C connections (Tinovi Capacitive Soil Moisture Sensor) and two RS485 connections (Trübner SMT100).

The universal G-Box is composed by an individual circuit board and off-the-shelf components, which can also been used to build the microclover G-Box.
In order to avoid influences caused by faulty contacts between used components, which can easily occur with breadboards, for example, a circuit board was designed and produced for the universal G-Box. The microclover measurements should also be protected against influences caused by faulty contacts. Therefore, during the development of the universal G-Box circuit board, care was taken to ensure that parts can be adopted to other circuit boards. Thus a microclover-specific circuit board can be easily realized by reusing parts of the universal G-Box circuit board. In addition, the board was designed to allow easy replacement of damaged components. For this purpose, pin header sockets have been placed on the board. Accordingly, components are chosen with the possibility of pin header connections. Furthermore, JST sockets were placed on the board to pass communication interfaces for sensors externally. This way, sensors can be connected simply and stable.
The firmware for G-Boxes requires support of the Arduino framework, which is given with ESP32 microcontrollers. Thereby, ESP32 microcontrollers can establish WiFi connections, providing a wireless way to connect to systems such as the G-Platform via an appropriate network structure. ESP32 developer boards, like the Firebeetle, offer the possibility to program integrated ESP32 microcontrollers easily via USB connection and are mountable via pin headers. Additionally, the 3.3 V output and the 5 V output of developer boards can be used to power remaining components, while developer boards are powered via USB. The Firebeetle has already been used successfully in several Guerilla Sensing projects and does not differ much from other ESP32 developer boards in terms of cost. Therefore, the Firebeetle ESP32 board is used here.
The Firebeetle has an analog-to-digital converter with 8-bit resolution. However, in order to capture soil moisture readings of the Trübner SMT50, which provides them as an analog signal with 8-bit resolved voltages, the resolution should be doubled to 16-bit due to synchronization issues. Accordingly, an external analog-to-digital converter with a 16-bit resolution is used. An ADS1115 board meets this criterion and can operate at least two SMT50 sensors simultaneously with four analog inputs. The board can be connected by pin headers, offers I2C communication, which is natively supported by the Firebeetle, and has been successfully used in Guerilla Sensing projects several times. Accordingly, an ADS1115 board was chosen to connect Trübner SMT50 sensors.
Connections via RS485 are not natively supported by the Firebeetle. But with a UART TTL to RS485 board the UART interface of the Firebeetle can be used to connect RS485 components. Also, such a board offers the possibility to be connected via pin headers. Since several components can be connected to one bus at the same time via RS485, a UART TTL to RS485 board is sufficient here to connect at least two Trüber SMT100 sensors.

As mentioned, the Firebeetle supports I2C communication. I2C is designed as a bus to which multiple components can be connected. Thus, at least two Tinovi Capacitive Soil Moisture sensors can be connected directly to the Firebeetle. However, I2C is only designed for short distance communication. Thus, according to the manufacturer's recommendation [7], pullup resistors have been placed on the board at appropriate lines to reduce interference at longer distances.

Two examples of each selected sensor can be connected to the universal G-Box via plugs. Also, the firmware of the G-Box can easily transferred via USB, enabling communication with sensors, thus making following experiments possible.

Experiment 1: The functionality of sensors with the universal G-Box was verified with known soil moisture conditions. Measurements were taken with sensors either in air or fully submerged in water. Soil moisture of 0% should correspond the former and soil moisture of 100% (or 50% for SMT50) to the latter.

All six sensor samples provided corresponding results and thus show plausible values for edge cases. Additionally, the sensors work with the universal G-Box.

Experiment 2: In the microclover project, soil moisture must be monitored over a period of one year. If possible, measurements from sensors should be provided whenever they are requested. Otherwise, it may not be possible to collect sufficient measurements to confirm or reject the microclover hypothesis. Therefore, the continuity of sensors is verified by taking measurements with the universal G-Box every five minutes over a week in a pot with soil. Whereby the measurement frequency of five minutes together with the measurement period of one week should be sufficient to conclude a longer operation.

The SMT50 as well as the SMT100 sensors delivered a measurement for every measurement request. However, the Tinovi sensors proved fairly unreliable. Multiple times, after previously establishing a functioning communication, sensors failed to transmit their measurements. This was attributed to I2C, which is optimized for shorter distances than what was intended for this component, which gets delivered with a four meter cable. Adjusment of the pull-up resistor improved this behavior, but did not completely eliminate interference.

Tinovi sensor cable lengths could be shortened at the expense of sensor deployment flexibility, but interferences in the project environment will be greater than those in this experiment. Based on that behavior and limited time for further stabilization actions, the Tinovi sensor was not considered any further.

Experiment 3: Since changes in soil moisture over time must be considered, the behavior of the SMT50 and the SMT100 sensors was observed in this regard. Sensors were placed in pots with soil and measurements were performed every minute. A comparatively high frequency of one measurement per minute was assumed to capture occuring effects. The pots were irrigated until water drained from them at varying time points. Soil moisture was expected to increase shortly after irrigation and then decrease until the next irrigation. Different intervals were chosen to look at the effect over different time spans. The soil was irrigated on the first, second, fourth, fifth, sixth, seventh, 11th, and 14th day.

The pots were located indoors and, thus, exposed to minor influences such as small temperature variations. Since there is no water consumer and tempera-

ture was moderate, rather slow decreases in soil moisture were expected. If such decreases can be detected, it is likely that decreases with consumers and higher temperatures can also be detected.
Based on the “Predictive Plant Production” project, it is known that the compression of soil influences measurements. Accordingly, the soil of all pots was initially moistened and mixed together in a container. Then, the soil was evenly distributed across the pots, with sensors placed in the center. The soil was loosely layered and gently pressed down after filling. However, irrigation of soil was expected to change the compression of the soil and thus influence measurements, for example, by increasing soil compression and thereby changing contact surface between sensor and soil. In weekly interpretations of recorded measurements by biologists, the running time of the experiment was adjusted. Finally, the experiment was performed for 22 days.

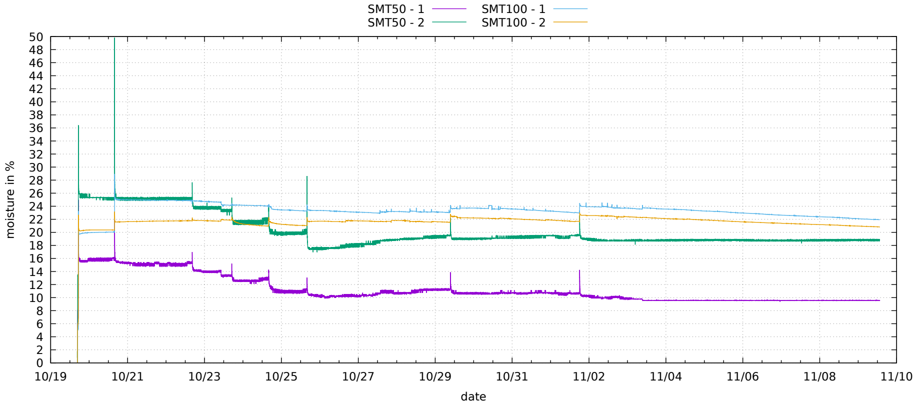

Fig. 2. Experiment 3 measurements overview

After each irrigation, there is a spike in soil moisture (Figure 2), which subsequently drops back. At the beginning of the experiment, the spikes are more intense and the drop to a lower level occurs more quickly. Measurements from the SMT50 show greater spikers and quicker drops compared to the SMT100. Between two irrigations there is in some cases an increase of measurements at the beginning of the experiment after reaching the lowest level. In early measurements, small increases in soil moisture content just before the next irrigation occured. This effect was stronger for the SMT50 and disappeard with the irrigation on the 11/01, detailed shown in Figure 3. The measurements of all sensors remain stable or decrease over the remaining runtime.
Compared to measurements of the SMT100, the strong spikes of the measurements of the SMT50 show that they are more sensitive to irrigation. In addition, measurements of the SMT50 drop very quickly to a low level, which can hardly be explained by evaporation. In contrast, the emasurements of the SMT100 increasingly behaved as expected as the experiment went on. Between irrigations,

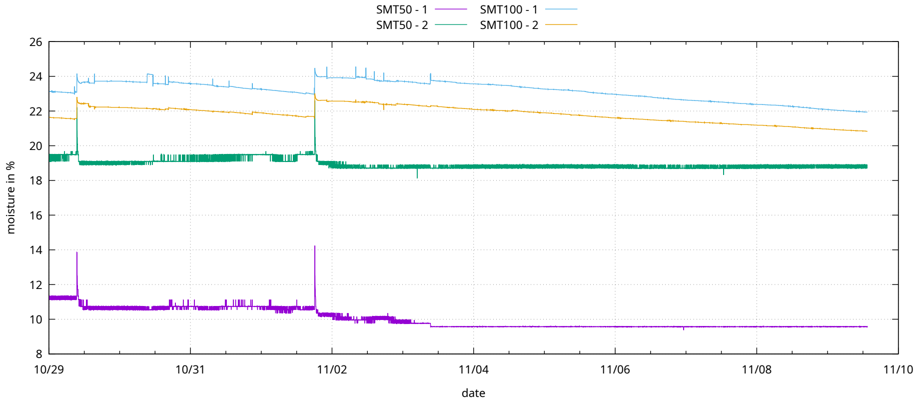

Fig. 3. Experiment 3 measurements after compression

the SMT50 and SMT100 show fluctuations as expected with measurement errors. The measurements from the SMT100 are more stable than the measurements from the SMT50. This can be attributed, at least in part, to the fact that the SMT100 take multiple measurements per measurement request and fuse them to provide one stabilized measurement. Increased measurements between two irrigations until the irrigation on 11/01 are interpreted as compression of soil through irrigation. Accordingly, only measurements after 11/01 are considered in the selection of sensors.

The SMT50 are not suitable for the microclover project due to the high spikes of measurements, the rapid drop in these and the hardly noticeable changes between irrigations. Evaporation effects are hardly reflected in measurements. In contrast, the SMT100 provide traceable measurements that show evaporation. Although they are more expensive, these sensors are the only ones considered here that are suitable for the microclover project. Accordingly, SMT100 are used to monitor soil moisture over time.

6 Microclover G-Boxes setup

As described in detail in section 2, the ornamental plants to be observed are placed and maintained outdoors in a nursery. Accordingly, G-Boxes must be protected against weather conditions and irrigation. Additionally, only one fixed power source and no Internet connection is present in the intended area. Former can be used as a power source for G-Boxes, but must be instrumentalized so that multiple G-Boxes can be operated. The latter must be established to allow connections to the G-Platform. G-Boxes and infrastructure needed for G-Boxes must be developed to match the microclover project conditions.

The G-Boxes are build to accomodate SMT100 sensor according to experience gained in the preliminary experiments. A microclover G-Box consists of an individual circuit board, a screw terminal, several JST sockets, several pin headers, a Firebeetle ESP32, and a UART TTL to RS485 board. Like with the universal G-Box, the individual circuit board offers advantages in terms of stable interconnection of components and sensors. SMT100 sensors are connected via JST sockets which gives flexibilty and stable connections. The microclover G-Box offers 12 sockets for SMT100 sensors. Whereby 12 sockets should be enough to cover eligible sensor instances m_i. The cost increased negligibly for the high number of connections. Connections that are not used do not have to be equipped with sockets, thus only the low costs for a possibly larger circuit board are incurred. Pin headers are used to connect the Firebeetle and the UART TTL to RS485 board to the circuit board in a stable but still replaceable way. Screw terminals on the circuit board are used to provide a central connection for power. In order to ensure that the microclover G-Box has the required weather resistance and is protected against irrigation, the circuit boards are installed in IP66-rated housings. To connect sensors and power sources, IP66 cable glands are mounted to the housings. Thus, all components are protected against dust and strong water streams. The exact number of cable glands for sensor instances m_i is determined in the context of parameterization in section 7.

While setting up the infrastructure, attention must be paid to the conditions of the measurement environment so that G-Boxes can be operated at least over the duration of the project. It should also be noted that the number of G-Box instances n is designed variable, allowing to scale between cost and handleability in the following. For this reason, the power supply and the Internet connection are set up in a tree-like structure starting from a central distribution box with IP66 protection class. Components, like 5 V power adapters and a mobile data router, are placed in the distribution box in a weatherproof and irrigation-proof manner. IP66 cable glands are used to lay cable lines to the G-Boxes. Via WiFi, the G-Boxes can establish connections to the router and thus to the Internet.

7 Microclover SMOS evaluation and parameterization

In order to evaluate the ability of the SMOS to support the microclover experiment and to determine outstanding parameters, a realistic experiment was performed. For this purpose, a microclover G-Box with six SMT100 sensors was used to detect changes in soil moisture at the surface between the roots of plants and at the bottom of pots between the 29th January 2023 and the 28th February 2023 for three pots planted with rhododendrons (Figure 4). Compared to experiment 3 in section 5.2, there are water consumers and two SMT100 sensors in each pot, as in the microclover project. By observing changes across three individual plants, a first impression regarding influences of individuals is indicated. The duration of the experiment is designed with more than a month so that drops in soil moisture can be observed several times and various influences such as compression due to irrigation can be registered. This should allow conclusions about the required measurement accuracy and the sampling rate of soil moisture. Additionally, the setup allows to evaluate the handleability for a fixed chosen number of sensor instances m_i. The initial number of sensor instances m_i

was set to six, because handling is subjectively given.
The plants were treated as normal plants by gardeners in the greenhouse of the botanical garden of the University of Oldenburg. The care of the plants indoors differs from the microclover project environment, but G-Boxes and sensors still need to be protected against irrigations. Accordingly, initial conclusions regarding irrigation resistance can be drawn.
Before starting the experiment, the plants were irrigated to compression by irrigation known from experiment 3 and the "Predictive Plant Production" project. Preliminary compression irrigation was monitored with a microclover G-Box and showed no noticeable effect after seven irrigations. Based on preparation, soil moisture is expected to increase rapidly after irrigation and then decrease slowly over time due to evaporation and water consumption.

Fig. 4. Microclover SMOS evaluation and parameterization experiment setup

In the experiment, the five irrigations performed during the period were recorded on 30th January, 9th February, 14th February, 22nd February, and 28th February. The soil moisture measurements for these are shown in Figure 5 and can be accessed via Guerilla Sensing[4]. After most irrigations, measurements rise rapidly and then slowly decrease to a lower level over time. Different local maxima and minima are reached between pots. The effect is more pronounced for sensors at the bottom of the pots. Recorded decreases in soil moisture ranged from about 0.5% to 16% in the lower region of the pots. Measurements from sensors in the upper area of the pots showed a slight increase between the second irrigation on 9th February and the fourth irrigation on 22nd February. The maximum drop in measurements at the top of the pots is about 1%. In some cases, such as after the second irrigation on 10th February, after the fourth irrigation

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[4] https://www.guerilla-sensing.de/measured-values?gboxes=[588]&from=1670949919000&to=1682696719000

on 24th February and after the fifth irrigation on 6th March, the measurements of sensors in the lower part of the pots drop abruptly by a maximum of 2.5%. The sampling rate of one minute was not met in all cases.

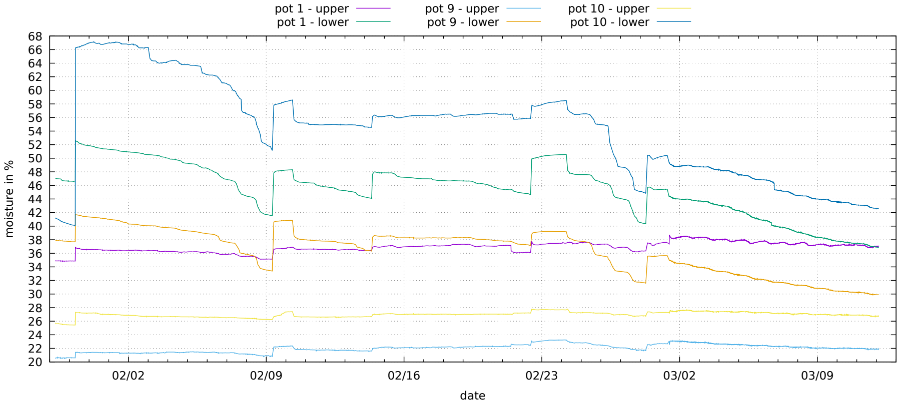

Fig. 5. Decrease between first and second irrigation

Different maxima and minima are explained by gardeners irrigation according to their sense. Therefore, there are also different intervals between irrigations. This irrigation behavior will not affect the microclover project because the focus is on soil moisture decrease and not absolute soil moisture levels.

The more pronounced effect in measurements of sensors in the lower area of the pots is contrary to the hypothesis made in section 2 that water evaporates more strongly in the upper area of the pots. Positioning of sensors between the roots probably has an effect here. Plants absorb water from the soil via their roots. Accordingly, sensors between roots are continuously surrounded by water in the roots and show relatively constant or even increasing soil moisture levels. In contrast, the water in the lower part of the pots is drained away by runoff, by water consumption and evaporation. Root growth over the microclover project period may cause the sensors in the lower area of the pots to be surrounded by roots as well. Further experiments need to be considered where biologists can examine the measurements in more detail and make conclusions.

In most cases, the decrease in soil moisture at the bottom of the pots due to the difference in levels can be attributed to drainage, evaporation and water consumption. The differences are more than double the measurement accuracy stated by the manufacturer for the SMT100. Other cases show smaller differences and are reasonable, but would need to be observed more frequently to exclude measurement errors as unlikely cause. This experiment was performed at low temperatures. Accordingly, evaporation effects should be lower than at summer times. With enough observations, the measurement accuracy of the SMT100 sensors should be sufficient to detect the considered effect. Thereby, the effect can be more pronounced by adjusting the delay between irrigations.

Suddenly occurring drops stay within the measurement accuracy of the SMT100 sensors and could be explained by measurement errors. However, it is noticeable that drops occur at the same time as missing measurements. The missing measurements could be related to interferences in the internet connection or to unreachable sensors. Between individual measurements, the microclover G-Box switches to idle mode. In this mode, the power supply of all sensors is interrupted to save energy. During previous experiments this did not lead to any disturbances, but in few cases it could occur as a result. It is therefore necessary to investigate whether drops are related to missing measurements and to clarify the cause of drops as well as missing measurements. A positive aspect is that the remotely accessible measurements enabled to detect missing measurements without traveling to the site.

Recorded soil moisture decreases are very slow and therefore a lower sampling rate can be assumed sufficient for the microclover project. Thus costs and energy can be saved during data transmission and measurements. But it should be noted that rain in the outdoor area can cause sudden water inflow. With a sampling rate of one measurement per hour, there should be enough decrease in soil moisture observable, even if sudden water inflows occur.

The initial decision to set the number of sensor instances m_i to six proved to be practical. Installing the G-Box with sensors went smoothly. Therefore, the number of sensors does not need to be reduced. But the number should also not be increased, because subsequently the assembly and installation of G-Boxes becomes disproportionately more difficult. Therefore, all m_i are assigned to six. Corresponding to 96 required sensors, this results in 16 G-Boxes.

8 Conclusion

The developed SMOS fulfills the requirements almost completely. Soil moisture measurements can be automatically performed and documented several times a day over a long period of time. Documented measurements can be accessed remotely. Evaluation and monitoring of measurements can thus be done without traveling to the site. Furthermore, reasonable parameter assignments for the required measurement accuracy and the sampling rate of soil moisture were found.

By scaling the experiment period to the intended period of the micro clover project, more measurements than needed were successfully obtained. Occurrences of missing measurements in the experiments do not carry weight. For future projects, occurrences of missing measurements can be attributed to the idle mode of G-Boxes or unstable internet connections. Both can be addressed by slight adjustments and extensions of the G-Box firmware.

Guerilla Sensing were used across all phases due to its adaptability and expandability. Functionalities such as remotely accessible documentation, visualisation, and export of measurements were used without adjustments. Developed components for initial experiments were reused to a large extent in the further course and thus reduced the development effort. Future projects will also benefit from components that have been implemented.

Further activities are planned to extend the visualization capabilities and to implement notifications in case of missing measurements. The line charts in Guerilla Sensing fully visualize all required information, but an aggregated display of project-relevant information would be clearer. For example, the average drop in soil moisture could be visualized grouped by treatment. This would allow biologists to see at a glance the current state of their experiment. Missing notifications will further reduce the effort required to detect missing measurements. Active monitoring will no longer be necessary.

In summary, based on Guerilla Sensing, a SMOS that allows to detect effects of soil cover with clover on soil moisture was developed. The described adaption-activities can be used as a blueprint for projects like the microclover project. Whether the SMOS will prove successful as expected remains to be seen. In approximately one year, the microclover project will be completed and final conclusions can be made.

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