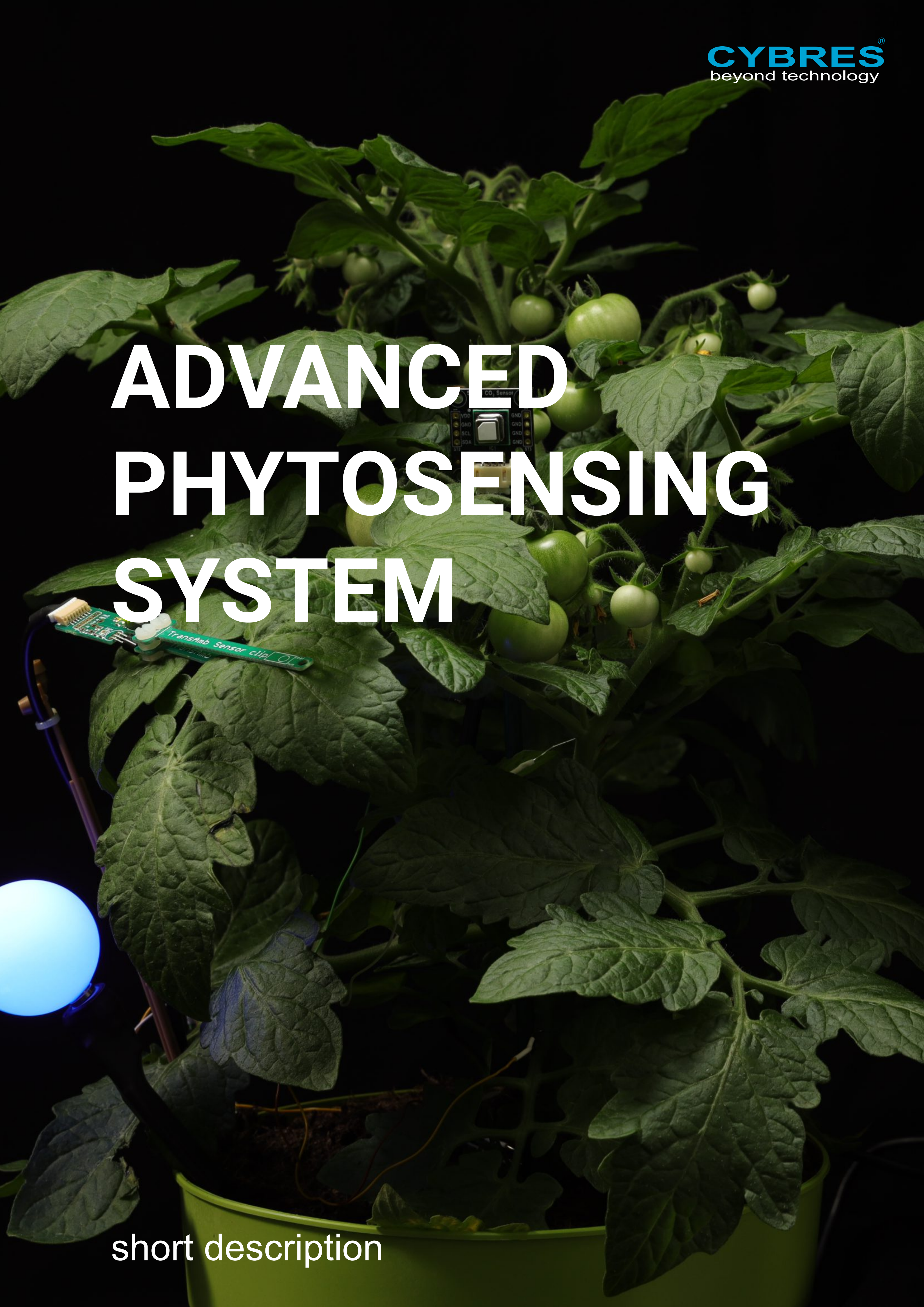
CYBRES®
beyond technology

ADVANCED PHYTOSENSING SYSTEM



short description

1 Foreword

ATTENTION. Read carefully these instructions. Follow closely the recommendations for measuring weak changes of electrochemical and physiological parameters.

ATTENTION. Make sure that the 5-/16-/26- pin connector on the EIS devices is used properly: the connector should be first fully inserted and then screwed.

ATTENTION. The spectrometer contains the CR2032 lithium battery.

ATTENTION. The device has one USB port for data exchange and power supply. It is necessary to use the USB 3.0 active hub for powering the device. Connect the USB 3.0 hub to the low-noise power source. This USB power supply should not be used by any other device.

ATTENTION. The USB ground loops can distort functionality of the device. To avoid ground loops it is strongly recommended to use commercially available USB-to-USB isolators.

ATTENTION. No calibration is required for differential measurements. For absolute measurements (e.g. conductivity, temperature, etc.) the device should be calibrated regularly. It is recommended to contact the manufacturer for a calibration.

The device is made in accordance with the following European Directives: 2006/95 / EG (Low Voltage), 2004/108/EG (EMC), 2011/65/EU (Directive on the use of hazardous substances in electrical and electronic equipment, 2009/125/EG (eco-design/energy-using products). The device is manufactured in accordance with the latest technological developments. However, there are residual risks. To avoid danger observe the safety instructions. The manufacturer is not liable for damages caused by non-compliance with safety instructions. Children should not play with the device. When leaving the device for a long time, disconnect it from the power supply.

The device does NOT fail under the Directive 2014/32/EU on measuring instruments as MI-001 'WATER METERS' (An instrument designed to measure, memorise and display the volume at metering conditions of water passing through the measurement transducer); MI-005 'MEASURING SYSTEMS FOR THE CONTINUOUS AND DYNAMIC MEASUREMENT OF QUANTITIES OF LIQUIDS OTHER THAN WATER' (An instrument designed to measure continuously, memorise and display the quantity at metering conditions of liquid flowing through the measurement transducer in a closed, fully charged conduit); MI-003 'ACTIVE ELECTRICAL ENERGY METERS'

VERSIONS. This manual v.2.5.2 is based on the firmware v.1190.x and the client program v.1.4.x.

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2 Terminology and used notations

EIS – Electrochemical Impedance Spectroscopy.

MU – Measurement Unit. Series of precision measurement systems developed by CYBRES GmbH (Cybertronica Research). The notations MU EIS, CYBRES EIS or CYBRES MU EIS mean the same notion.

FRA – Frequency Response Analysis, the method of signal analysis.

DFT – Discrete Fourier Transformation, the method of signal anaysis.

ADC – Analog to Digital Convertor, the hardware component used to convert analog signals into digital form.

DAC – Digital to Analog Convertor, the hardware component used to convert digital signals into analog form.

DDS – Direct Digital Synthesis, the hardware approach used to generate excitation signals.

RMS – Root Mean Square, also known as the quadratic mean, is defined as the square root of the arithmetic mean of the squares of a set of numbers.

PCB – Printed Circuit Board, it contains electronic components on a non-conductive substrate.

USB – Universal Serial Bus, the interface between computers and electronic devices.

PID – Proportional-Integral-Derivative controller, a hardware - software control system used to keep a predetermined temperature in thermostats.

DA – Detectors-Actuators module, see Section 10.

DI – Deficit Irrigation.

V_V – the excitation signal that drives electrochemical test system.

V_I – the response signal based on the flowing current I thought the test system.

f – the frequency on which the analysis is performed.

$Z(f)$ – impedance of the test system for a harmonic signal of frequency f.

$Re^{FRA}(V_I)$ – real part of the response signal obtained by the FRA analysis.

$Im^{FRA}(V_I)$ – imaginary part of the response signal obtained by the FRA analysis.

t – temperature.

Contents

3 General description

3.1 The device

The CYBRES MU (Measurement Unit) is a bio-hybrid interface device for real-time interactions with various biological, microbiological and fluid systems. It includes:

- differential Electrochemical Impedance Spectrometer (EIS);
- differential analyzer of bio-potentials;
- interface for analog and digital phyto-, bio- and environmental electrodes/sensors.

The MU performs high-resolution differential measurements of ionic properties in liquid or organic samples, enabling electrochemical and physiological analysis of plants, microorganisms, tissues and solutions. This device is designed for precision agriculture (including hydroponics and indoor farms), phytosensing, biosensing, and non-chemical water treatment. Its high sensitivity allows the detection of weak electrochemical and physiological changes caused by environmental and technological factors. The MU conducts real-time data processing and controls actuators like lights, pumps, valves, or relays. It supports instrumentation tasks with autonomous bio-/phyto-/fluid-sensing for complex feedback-driven adaptive scenarios.

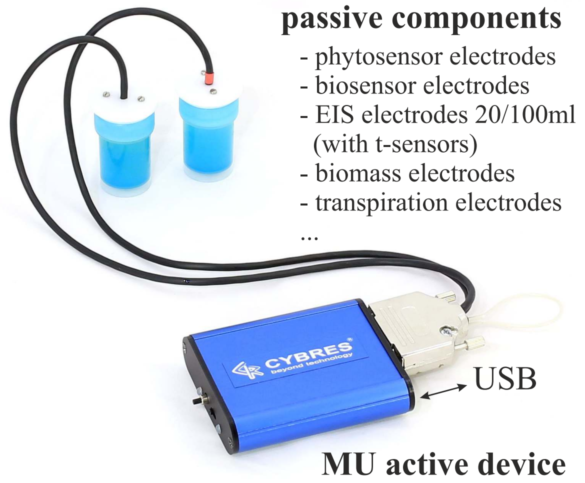


Figure 1: MU system with active and passive components, example with EIS electrodes for electrochemical analysis of fluids.

The structure of MU system is shown in Figure 1. It consists of an active electronic module and replaceable passive components for phytosensing, biosensing and EIS applications. The system features:

- real-time operating system;

- internal embedded sensors;
- interfaces to external analog and digital sensors;
- the thermostatic system with two channel digital PID controller for fluid samples and electronics;
- analytic tools for real-time data analysis.

USB 2.0 is used for data transfer to the host computer and for powering the device. All data are recorded in real time with time stamps and are stored on PC or in the on-board flash memory.

The system measures up to 45 physical parameters (45 physical data channels), and calculates in real time up to 35 numerical/statistical parameters (35 synthetic data channels), which are programmable by users.

ATTENTION. The MU operates in three main modes: 1) **phytosensor** with specific electrodes; 2) **electrochemical impedance spectrometer** for analysis of aqueous solutions; 3) **biosensor** with specific electrodes. Additional sensors in each mode can be turned on/off.

3.2 Applications

3.2.1 Phytosensing and indoor farming

Three main phytosensing applications[1] are shown in Figure 2.

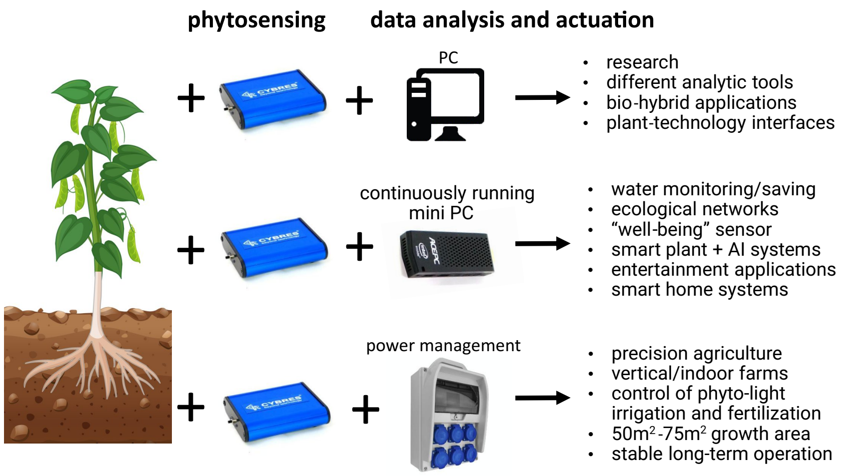


Figure 2: Three main phytosensing applications.

They depends on connected computational and power management systems and allow *in-vivo*, *in-situ* or *in-vitro* electrophysiological measurements of plants or organic tissue, e.g. monitoring

[1] see Kernbach, Biofeedback-Based Closed-Loop Phytoactuation in Vertical Farming and Controlled-Environment Agriculture. Biomimetics 2024, 9, 640, doi: https://doi.org/10.3390/biomimetics9100640

Figure 3: Overview of different phytosensors and phytoactuators supported by the MU system for soil-based and soil-free cultivation.

plant physiology and electrophysiology, analysis of bio-potentials and tissue impedances, sap flow, transpiration, soil moisture and other parameters. Several supported phytosensors and phytoactuators for soil-based and soil-free cultivation are shown in Figure 3. The MU can be used as a standalone device for control of hydroponic systems, vertical and indoor farms.

3.2.2 Biofeedback systems and AI phenotyping

The MU represents a tool for design and implementation of biohybrid or AI (Artificial Intelligence)-based systems with plants. Such systems can be used to control different agricultural actu-

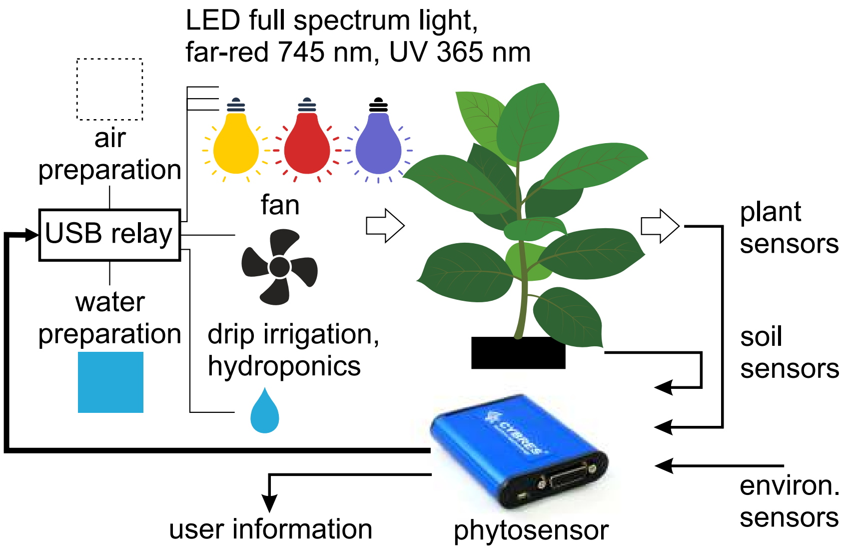


Figure 4: Using the phytosensor in a biofeedback-based system.

ators with biofeedback-based (based on sensor data) protocols, see Figure 4. Water-/air-preparation, fertilization, ozonation/AOP (advanced oxidation process), aeration/OMB (O_2 microbubbles), magnetic treatment and other approaches, can also use this scheme with a biofeedback from plants. Access to physiological and environmental parameters enables using this system in machine learning techniques; phytoactuation provides a possibility to integrate a bio-exploration in AI schemes, e.g. for fast AI phenotyping[2].

3.2.3 Using plants as biosensors

Environmental pollutants, various stressors and stimuli trigger physiological reactions in plant organisms. Biological detection of such factors can be conducted by measuring electrochemical, bio-electric, hydrodynamic and other responses of plants in-situ. Biosensing ap-

[2] see Buss et al, Stimulus classification with electrical potential and impedance of living plants, Bioinspir. Biomim. 18 025003, 2023, doi: https://doi.org/10.1088/1748-3190/acbad2

plications, e.g. for environmental monitoring[3] have great practical relevance due to high sensitivity, simplicity and reliability of sensors, enabling outdoor and field applications. Tomato, tobacco, dracaena or any other plant can be used for biosensing purposes, motivated by a sensitivity of these plants for a particular stressor, see Figure 5.

Figure 5: Examples of biosensors (phytosensor + plant sensitive to a particular stressor or pollutant), here – tomatoes are measuring environmental ozone.

3.2.4 Water monitoring/saving technologies

According to the United Nations World Water Report, agriculture accounts for almost 70% of global water consumption, and 40% of this is wasted due to inadequate irrigation systems, evaporation, and poor water management. In 2011, the global water footprint of agricultural production was 8,362 km^3/year. To meet the growing demand for food and biofuels, agricultural production will need to

[3] see Kernbach, In-situ biological ozone detection by measuring electrochemical impedances of plant tissues, doi: https://doi.org/10.48550/arXiv.2411.16321,2025

increase by almost 50% by 2050 compared to 2012. This is expected to require even more water. Global water demand is expected to increase by 20–30% between 2010 and 2050.

In addition to improving overall water management systems, water saving technologies can also be implemented at the phytosensing level through various deficit irrigation (DI) strategies. DI is a practice where a crop is irrigated with water below the full requirement for optimal plant growth. For example, irrigating crops with -50% water increased water productivity by +24% over full irrigation with yield reduction by -38% (compromise strategy: water vs yield). DI has emerged as a viable approach to increasing agricultural water productivity and to save a significant amounts of water. However this cultivation method deliberately induces drought stress at plant development. By using sensors that measure the physiological state of plants in real time and in vivo, DI strategies can be implemented without damaging plants with better water vs yield ratio. Beside DI, specific sensors, such as biomass

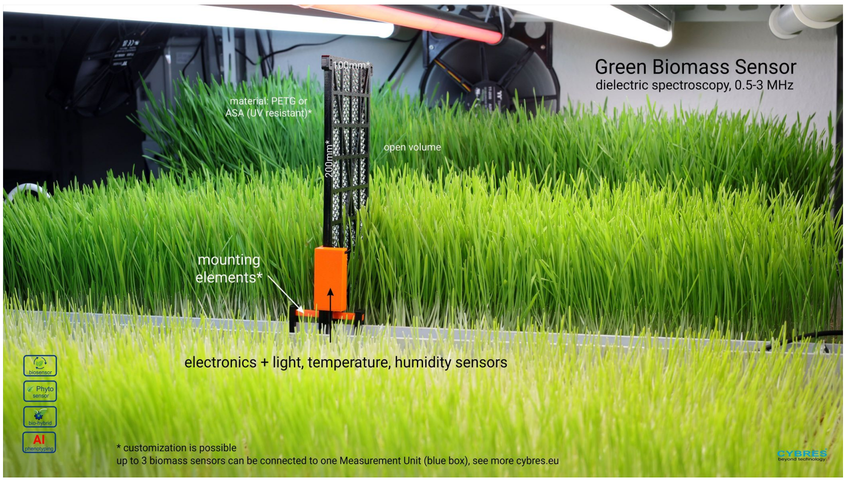


Figure 6: Green biomass sensor (open volume measurement) in indoor farming environment for monitoring of water distribution by root and green biomass, and optimization of water flow.

and irrigation sensors, enable monitoring of water distribution and consumption by root and green biomass, and optimization of energy and water flow in the cultivation facility, see Figure 6.

3.2.5 Microbiology: fermentation and sedimentation

Microbiological applications[4] include bio-sensors that measure fermentation, sedimentation, gas production (or degassing), metabolic production or any other processes that change concentration and mobility of ions in the solution (e.g. control of fermentation

[4] see Kernbach et al, The biosensor based on electrochemical dynamics of fermentation in yeast Saccharomyces cerevisiae, Environmental Research, 213, 2022, 113535, doi: https://doi.org/10.1016/j.envres.2022.113535

activity of yeast), see Figure 7. The MU system is designed for

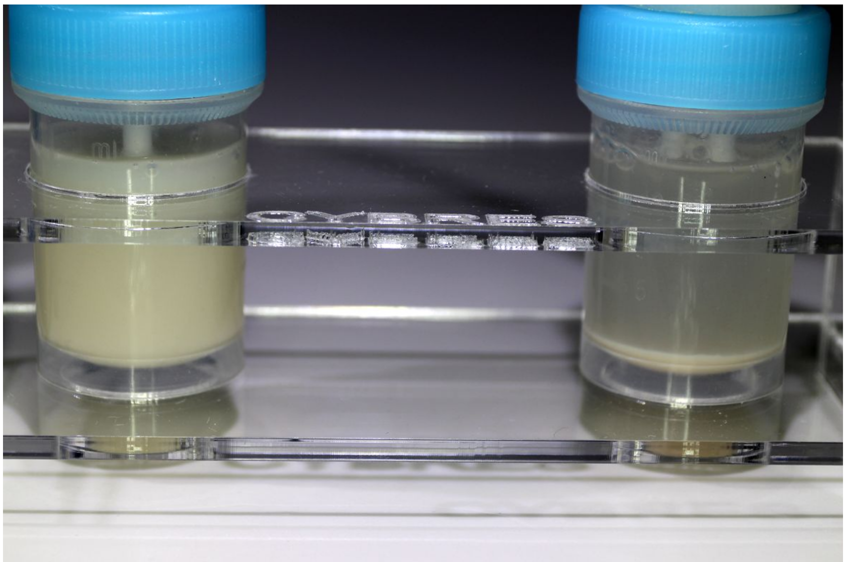


Figure 7: Example of fermentation and sedimentation processed analysed with electrochemical impedance spectroscopy.

long-term monitoring of biological samples, e.g. for quality control purposes or for the analysis of biochemical reactions.

3.2.6 Non-chemical treatments of aqueous solutions

Electrochemical applications[5] are precise industrial fluid measurements and differential fluid meters in research and laboratory usage, detectors of non-chemical treatments by analysing electrochemical changes in fluids (e.g. water filtering, decalcination, removing of organic contaminants), optical or magnetic excitation of

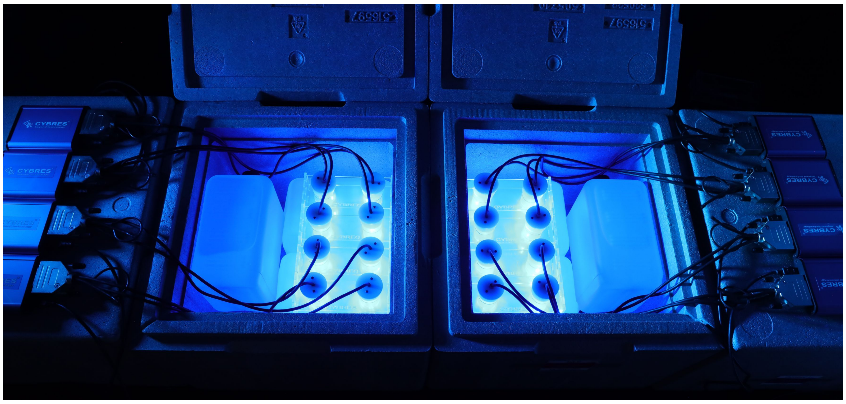


Figure 8: MU systems (MU3 units + open EIS electrodes) used for electrochemical analysis of fluid samples.

[5] see Kernbach, Electrochemical Characterization of Ionic Dynamics Resulting from Spin Conversion of Water Isomers, 2022 J. Electrochem. Soc. 169 067504, doi: https://doi.org/10.1149/1945-7111/ac6f8a

fluids, see Figure 8. These measurements can also be used for analysis of weak interactions in aqueous systems, in particular caused by quantum phenomena in macroscopic systems (e.g. the proton tunneling effect or change of electrochemical reactivity by para- and ortho- isomers of water. The device allows statistically significant measurements of these effects with the standard EIS method.

3.3 Main measurement modes

Depending on the electrodes used, the MU device can perform the measurements shown in Table 1.

Table 1: Main measurements (depending on electrodes/sensors).

N	Measurements	Applications
1	Electrochemical Impedance Spectroscopy (EIS)	ionic analysis, frequency-response analysis, detection of photosynthates vs minerals or ionic contaminates
2	Dielectric Spectroscopy (DS)	green/root biomass growth (fixed frequency DS)
3	Excitation Spectroscopy (ES)	excitation-response analysis, distortion analysis, measuring chlorophyll
4	Dynamics of Impedances	water content, sap flow, metabolic products, analysis of temporal ionic dynamics
5	Dynamics of Biopotentials	plant signalling system (action potential, systemic potential), 4x-electrode EIS, analysis of temporal dynamics
6	Physiological parameters	measuring plant physiology
7	Environmental parameters	environmental measurements

For these purposes, the system has embedded analysis tools, which are shown in Table 2. Considering these tables, the device can operate in 11 different measurement modes, see Table 3, their selection is controlled by settings of the 'DDS mode', 'configuration', checkboxes 'regression analysis', 'excitation' and DA/Python scripts.

ATTENTION. Measurement modes of MU devices depends on samples (plants, biological tissues, fluids, microorganisms), used sensors/electrodes and analytic tools. The measurement methodology is different for pre-processed samples (i.e. experiments before measurements), processing-during-measurements and post-processing of measured data, see corresponding application notes.

3.4 MU-family of devices

The MU device is produced in three main versions:

1. The **modular/reconfigurable version** that includes
    - the main measurement unit MU3 or MU3T, see Figure 9(c) and 9(d);
    - electrodes for measuring plant (electro-)physiology and phytosensing, see Figure 20;

Table 2: Embedded analytic tools.

N	Analytic tools	Applications in real time
1	Regression analysis	analysis of weak signals
2	Statistical analysis	computing statistical parameters
3	Correlation analysis	conducting correlation analysis
4	DA-processors	embedded script for data processing
5	Python scripts	Python script for data processing
6	External tools	analysis by e.g. MS Excel, SPSS and others

Table 3: Main measurement modes of MU devices.

N	Application	DDS mode	Configuration
1	signal distortion analysis, fast statistical analysis	signal scope	EIS
2	analysis of temporal EIS/temperature dynamics, 'experiment during measurement' mode, biosensor applications, 3D time-frequency analysis	continuous modes	EIS, biosensor
3	**regression enabled**, the highest resolution of temporal dynamics	continuous modes	EIS
4	**excitation enabled**, analysis of pre-treated fluidic samples, characterization of non-chemical treatment	continuous modes	EIS
5	**EIS statistics enabled**, statistical analysis of EIS noise, see App.Note 24, pre-treated or on-line treated fluidic samples, characterization of non-chemical treatment	continuous modes	EIS
6	**timed regression/MIND enabled**, specific statistical/regression analysis, see App.Note 26, on-line treatment of fluidic samples, characterization and weak impact factors	continuous modes	EIS
7	frequency analysis, impedance spectroscopy, differential analysis of samples, FRA profiles	frequency modes	EIS
8	environmental measurements	off	EIS
9	electrophysiological measurements of tissues, physiological measurements (with corresponding sensors), differential potential analysis	off	phytosensor
10	electrochemical interface to bio-samples, biological tissues and plants	continuous modes	phytosensor, biosensor
11	correlation analysis	continuous modes	EIS, phyto-bio-sensor

- EIS electrodes with integrated temperature sensors for fluid measurements, see Figure 18(a);
- electrodes for biosensing purposes with additional sensors;
- additional modules, actuators, power management systems;

2. The **embedded system for differential EIS analysis** with thermostabilization of fluidic samples and optical excitation, see Figure 9(a);
3. The **embedded biosensor system** for measuring microbiological samples based on fermentation, sedimentation or ionic processes (with thermostabilization of samples and op-

tical excitation), see Figure 9(b).

Additionally, the MU-family includes the MU actuation board and power management system (that connect different high power real-world actuators, see Figure 9(f)), and EHM-C board (for generating electric and magnetic fields). All devices in the MU family are compatible with each other.

Table 4: Device versions with hardware and software options.

N	Device versions	Hardware	Software
1	(**reconfigurable**) phytosensor basic	1 channel biopotentials & impedance	enabled
2	(**reconfigurable**) phytosensor advanced	+ TransAmb sensor (leaf transpiration) + 2 channels biopotentials & impedance	enabled
3	(**reconfigurable**) phytosensor full	+ sup flow sensor	enabled
4	(**reconfigurable**) EIS	+ 2x EIS open electrodes, + fluidic/environ. t sensors, + excitation spectroscopy	activation code*
5	(**embedded**) EIS	different device with thermostat, + RGB/IR excitation spectroscopy	enabled
6	(**embedded** & **reconfigurable**) biosensor	+ fermentation module, + RGB/IR excitation spectroscopy	enabled

*transition from phytosensor to EIS/Biosensor requires software activation

The measuring unit (MU) – MU20, MU31, MU32, MU33, MU34, MU34T (with enhanced termostabilization, see Figure 9(c,d)) and MU40 – is based on the 32-bit ARM processor with a real-time operating system (the MU RTOS). It has accurate analog-to-digital and digital-to-analog converters, an internal non-volatile memory, real time clock, low-pass filters and additional sensors. The measuring unit is characterized by a low noise level. Note that the embedded EIS spectrometer uses round 5-pin micro connectors, MU33 uses D-Sub 16-pin connectors and MU34, MU34T – D-Sub 26-pin connectors.

3.5 Features

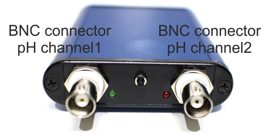
- main processor: ARM cortex M3 MPU, 80 MHz
- hardware support of analysis: PSoC system
- non-volatile (flash) memory: 512 Mb
- level of noise[1]: $< 1\mu$ V
- sampling frequency: (12-24 bits) up to 1 Msps
- accuracy of temperature stabilization[2]: 0.02C
- temperature resolution[3]: up to 0.001C
- F_{min}, min. frequency: 8 Hz

(a)

(b)

(c)

(d)



(e)

(f)

Figure 9: **(a)** the embedded version of MU EIS differential impedance spectrometer; (1) – measurement cell with two channels (closed by lids on the image), (2) – connector for two electrodes; (3) – hull with RGB LEDs, electronics and additional sensors; (4) – electrode, the channel 1 (with red mark); (5) – electrode, the channel 2; **(b)** the embedded version of biosensor (for comparison – 15ml and 100ml containers); **(c,d)** the measuring unit (MU) MU3 and MU3T (with enhanced termostabilization); **(e)** the MU for differential pH measurements; **(f)** the power management module with 6 switchable outputs.

- F_{max}, max. recommended frequency for EIS-tissue sensing-manual[4]: 0.1MHz-0.3MHz-0.65MHz
- EIS: number of frequency bands: 3 (8-450Hz, 100-10.000Hz, 450Hz-F_{max})
- EIS: ranges of excitation voltage: 0.001-0.01V AC, 0.01-0.1V AC, 0.1-1V AC (max. amplitude $\pm$1V)
- EIS: amplification factors: 50, 500, 5000, 50000
- EIS measurement modes: 1) impedance spectrometer; 2) signal scope; 3) continuous measurements at a constant f; 4) continuous measurements at variable f; 5) Frequency Response Profile (FRP) at a fixed set of frequencies; 6) continuous FRP
- EIS analysis: Amplitudes, FRA Phase, RMS Magnitude, Correlation, Electrochemical stability in time/frequency/time-frequency domains, Statistical analysis, Excitation analysis
- EIS: self-calibration with integrated calibration resistors: 4.99 kOm, 499 Om, 0.1% 25 ppm
- external analytic tool: regression/correlation/statistical analysis
- high-impedance differential potential input: -0.5:+0.5V, 200pA (2x instrumental OA INA333)
- analog input: 0-1V (max. resolution 64 nV); 0-2V (max. resolution 128nV)
- electrode system: two (standard configuration) and four electrode measurements
- conductivity measurement range[5]/conductivity of used water: 0.6μS/cm–200 mS/cm
- support external Gnuplot and Python scripts (Python server is implemented)
- duration of long-term measurements: on the level of weeks
- embedded sensors: 3D accelerometer/magnetometer (optional), two internal temp. sensors, air pressure sensor, RF power meter (450Mhz-2.5Ghz)
- external sensors: analog or digital phyto-, bio- and environmental sensors
- basic accuracy class[6]: 0.5%, 0.1%
- output: 5 MOSFETs (linear and PWM modes) e.g. to control external SSRs or RGB LEDs
- supported buses: UART (front connector, MU34), I2C (back connector)

- typical current consumption[6] at 5V: ≈0.3A
- powering[7]: external active USB3.0 hub
- data interface: USB 2.0

[1] Test conditions: battery power supply, no galvanic isolation on power, all interfaces off, MCU clock 6Mhz, low level of environmental EM noise.

[2] This varies inside a volume of thermo-insulating containers.

[3] This resolution is primarily defined by electronic noise, data are shown for the LM35 precision sensor (10mV/C with 64 nV ADC resolution).

[4] The maximal and minimal frequency depends on the selected analytical tool, the frequency resolution and the requirement on a minimal number of samples in the sweep. The firmware provides different options based on other selected values.

[5] Conductivity measurements (and conductivity calibration) should be performed at one fixed frequency.

[6] This depends on requirements, in-situ calibration capabilities and reconfiguration options, ask info@cybertronica.de.com for more information.

[7] It depends on the MCU clock frequency, number of connected sensors and the thermostat's operating mode, see the Section 5.3.

3.6 Sensors

MU has analog (ADC-DAC) and digital (I2C and UART) interfaces for embedded and external sensors. Depending on applications, all external sensors are grouped into phyto-electrodes, bio-electrodes and EIS electrodes. Different versions of electrodes contain different combinations of sensors. For instance, in the phytosensor mode, the system measures physiological and environmental parameters, shown in Table 5. The following sections provide brief descriptions for separate sensors as well as their combinations in electrodes.

3.6.1 Embedded sensors

The device is equipped with several internal sensors, see Table 5:

- temperature of the thermostat, CPU and electronic module;
- the control of 4.2V power supply (used to monitor interferences on the power line);
- control of the thermostat (used to control the energy level supplied to the measuring part of the device)
- 3D magnetometer (used to control the static magnetic field during experiments) and 3D accelerometer (used to control mechanical impacts, optional)
- 450Mhz-2.5Ghz RF power meter;
- air pressure sensor.

Data from these sensors are available any time in the section 'plot', several sensors (e.g. 4.2V power supply) are available only with specific electrodes.

Table 5: Overview of measured phyto-parameters and phyto-actuation (depending on used electrodes/sensors).

parameters	description
	phytosensing
tissue impedance	differential, 4x Ag99 electrodes, 0.01-1V excitation
electrochemical spectroscopy	time-frequency EIS, fast EIS for *in-situ* sap analysis
biopotentials	differential, 4x Ag99 electrodes, input impedance 10^{-15}Ohm, input bias current ±70pA
leaf traspiration	differential air-humidity-based method, CYBRES
leaf temperature	precision LM35 sensor
thermal sap flow	heat-balance and heat-pulse methods, 3x *t*-sensing, PID stabilized, CYBRES
electrochemical sap flow	4x electrode method, CYBRES
wet green biomass	dielectric spectroscopy, 0.5-1 MHz, CYBRES
root biomass and irrigation	dielectric spectroscopy, 0.5-1 MHz, CYBRES
chlorophyll content	excitation spectroscopy, fluorometry 430nm
	environmental sensing
light, humidity, temperature	APDS-9008-020, HIH-5031-001, LM35CA
EM emission	450Mhz-2.5Ghz RF power meter, MAX2204
magnetometer	3-axis, LIS3MDL
air pressure	internal sensor, BMP280
soil moisture, temperature	capacitive-based sensor, CYBRES
CO_2, PM1-2.5-10, O_3	SCD4x, accuracy ±(40ppm+5%); SPS30, accuracy 10%, CENSIRION
I2C sensors	different digital external sensors, e.g. PAR sensor
water sensors	e.g. conductivity, pH, dissolved oxygen, etc.
	(phyto-)actuation
220V/110V	ON-OFF, 4 channels, up to 3kW (limited by power network), light/spectral light/irrigation
12V	ON-OFF, PWM, 2 channels, up to 10A, irrigation/aeration/fertilization/disinfection O_3, H_2O_2

3.6.2 External temperature sensor

Measuring module supports an external high resolution temperature sensor (Texas Instruments LM35CA), connected to the 26/16/5-pin connector. It has a typical absolute accuracy of ±0.2°C, typical nonlinearity of ±0.15°C and the conversion factor V/°C of +10mV/°C (see more the Datasheet 'LM35 Precision Centigrade Temperature Sensors'). With the ADC resolution of 22 bit, this sensor provides a resolution of relative temperature measurements < 0.001°C. The sensor is useful for monitoring environmental temperature and is included into different sensor sets. If using this sensor in outdoor conditions, protect it from direct sun light!

3.6.3 Phyto: transpiration, environment

Leaf transpiration sensor with several environmental sensors are combined in one sensor (the transAmb stick), shown in Figure 10. Environmental sensors measure the air humidity (the sensor Honeywell HIH-5031-001), light intensity (the sensor Broadcom/Avago APDS-9008-020) and air temperature (with different temperature

Figure 10: The transAbm stick – Leaf transpiration sensor with environmental sensors (air humidity, light intensity, air temperature).

sensors: Texas Instruments LMT70AYFQR or LM35CA). Overview of main parameters is shown in Table 6.

With 22 bit ADC conversion these sensors provide a theoretical resolution of measured parameters as $< 0.001°C$, $< 0.001\%$, < 0.001 Lux. Data from these sensors are available in the section 'plot', 'plot 1x: external sensors'. The transAmb stick can be used as a high-resolution environmental data logger without transpiration sensor and the leaf clip.

Table 6: Parameters of the transAmb sensor stick.

sampling resolution	20-24 bit
min. resolution of analog input	$\pm$64nV
conversion factor V/t of LM35CA sensor	10mV/°C
conversion factor V/t of LMT70AYFQR sensor	5.19mV/°C
conversion factor V/% of HIH-5031-001	$\approx$23.5mV/%
measurement range of light sensor	0-1000 Lux
size of data logger sensor panel	100x10x5 mm

3.6.4 Phyto: EIS and biopotentials

For EIS and tissue impedance measurements, the system provides needle electrodes, see Figure 11(a), and clip electrodes, see Figure 11(b). Biopotentials can be measured only with the needle electrodes. Ag-99 needle electrodes are primarily used for penetration of soft tissues, while clip electrodes are used for hard and woody

(a)

(b)

Figure 11: Differential EIS with **(a)** needle electrodes and **(b)** clip electrodes.

tissues. The distance between EIS electrodes is selected experimentally so that the RMS impedance is below 100 kOhm, typically at the distance of 10 mm. The penetration depth is about 2-3mm to have a stable mechanical contact and reach phloem and xylem tissue. Electrodes can be inserted directly into the leaf or completely penetrate the stem. Parameters of these electrodes are shown in Table 7. After insertion, electrodes can trigger a tissue reaction (lignification of the puncture hole) and an increase in impedance. The electrodes remain functional under such conditions and do not require replacement (tested for up to several months of continuous measurement). Note that EIS electrodes are used for measuring different parameters such as water content, sap flow or photosynthate vs minerals ratio.

Table 7: Parameters of EIS/biopotentials electrodes.

material of needle electrodes	Ag99 (silver)
material of clip electrodes	Cu3Zn2 (brass) or X6CrNiMoTi17-12-2 (stainless steel V4A)
channel 1 wires	white, yellow (labelled)
channel 2 wires	brown, green (labelled)
distance between EIS electrodes	typically 10 mm
distance between biopotential electrodes	maximal distance allowed by wires

ATTENTION. EIS electrodes should be placed approximately at 10 mm from each other, and biopotential electrodes should be placed at a maximum distance from each other. Impedance of both channels should demonstrate similar values (typically $\pm$5kOhm), large differences between the channels lead to a suboptimal measurement range and greater noise.

3.6.5 Phyto: sap flow, water content

The heat-based sap flow sensor is shown in Figure 12. It has two upflow and downflow temperature sensors and a thermo-stabilized heater between them. The sensor supports both the heat-balance and heat-impulse measurements as state-of-the-art approaches for sap flow measurements. The heater temperature is measured by an independent sensor, the PID controller monitors the heating dynamics with high accuracy. Embedded electronics forms all necessary signals. The heat-based sensor represents an invasive mea-

Figure 12: Heat-based sap flow sensor with two upflow and downflow temperature sensors and a heater between them.

surement technique that causes tissue damage if used over a long period of time. This damage is not related to overheating but represents a systemic response upon long-term energy influx to the vascular tissue. Therefore, the heat-based sensor is not recommended to use for phytomonitoring purposes (however it can be produced on request) and is replaced by two-point electrochemical sensor for measuring water content and sap flow, see Figure 13.

Electrodes in two-point EIS are inserted in the upper and lower parts of stem tissues and use the following hydrodynamic model. Effective measurement range with two needles (in one sensor position) is limited by applied excitation potential, electric field and dielectric properties of tissues, and can be represented as a volume V containing fluids, see Figure 13. EIS needles penetrate all tissues including the phloem and xylem layers and can be considered as sensors that measure the enrichment of tissues with ionic fluids in the volume V. The more fluid the tissue contains, the lower its impedance.

Upper and lower EIS sensors in stem have two such volumes V_U and V_L. Water with nutrients is pumped from roots through transverse osmotic pressure and evaporated through leaves via stomata by following vapor pressure deficit (VPD). In the simplest term, the amount of fluids evaporated by leaf transpiration goes through the volume V_U and the amount of fluids obtaining from roots goes through the volume V_L. Due to low transport velocity and structure of phloem and xylem tissues, the stem can be considered as a sponge-like vertical media with a slow refilling between V_U and V_L. The slow refilling means that changes in the upper part (variations of VPD, environmental influences such as ozone-induced stomatal sluggishness, changes of photosynthetic activities) will be first reflected in V_U, changes in the lower part (irrigation, soil moisture, nutrients, water contaminates) will be first reflected in V_L.

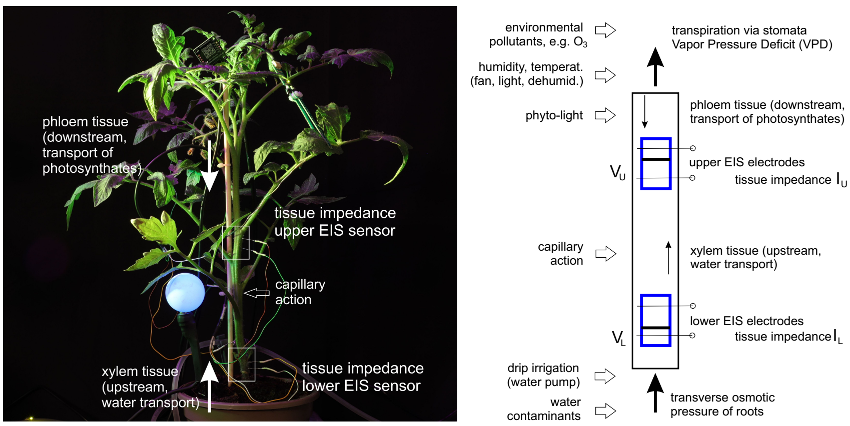


Figure 13: Hydrodynamic model of two-point electrochemical measurements in the upper V_U and lower V_L stem areas for measuring the water content.

Dynamics of upper and lower EIS sensors can be understood in the following way. Turning on the light starts transpiration and photosynthesis, this decreases amount of fluids in the upper part of the stem (in V_U area due to evaporation via stomata and the photosynthetic reaction). This, in turn, is reflected as increasing the impedance of I_U. Production of photosynthates introduces the first transient period until the downflow is stabilized along the whole stem. Any intrinsic or extrinsic variations of VDP, photosynthesis or air pollutants are reflected in the dynamics of the upper EIS sensor – it follows closely the transpiration data. Turning off the light stops transpiration and photosynthesis, the V_U volume is slowly refilling and its impedance is decreasing. This introduces the second transient period until the downflow is stabilized again. Any intrinsic or extrinsic variations of irrigation, osmotic pressure or water contaminants are reflected in the dynamics of V_L volume and data from I_L.

Differential dynamics of V_U and V_L is of especial interest. First of all, plant-common events, such as irrigation, first provide more fluids to V_L then with some delay to V_U. Similarly, turning off the light is first reflected in V_U then with some delay in V_L. In all such cases we observe a delayed reaction between I_U and I_L. Parameters that influence the chemical reactivity and capillary force are measurable in the differential dynamics of I_U and I_L.

Following a physical nature $\Delta T_{upper} - \Delta T_{lower}$ of thermal sap flow measurements, electrochemical $I_U - I_L$ data represent a similar meaning for the region $U - L$ of the stem. However, the difference is that thermal sap flow measurements are conducted in a small region of stem, whereas electrochemical data are applied to much larger U, L region. Based on the discussion about sap flow rate and sap flux density, the temporal dynamics $I_U^{\Delta t}$ and $I_L^{\Delta t}$ correspond to the sap flow at U and L, their differential value $I_U - I_L$ corresponds to the sap flux in the region $U - L$. However, results of thermal and electrochemical measurements do not completely coincide due to their different physical principles.

3.6.6 Phyto: detection of ionic vs organic fluids

EIS sensor in spectral mode can measure ionic content and differentiate between low-/high-ionic fluids such as nutrients and photosynthates. This opens additional possibilities for physiological analysis. The difference between the upflow and downflow, see Figure 13, lies in their content of nutrients and photosynthates, which generate different ionic dynamics. Considering the classic chemical reaction of photosynthesis

$$6CO_2 + 12H_2O \xrightarrow{hv} C_6H_{12}O_6 + 6O_2 + 6H_2O, \tag{1}$$

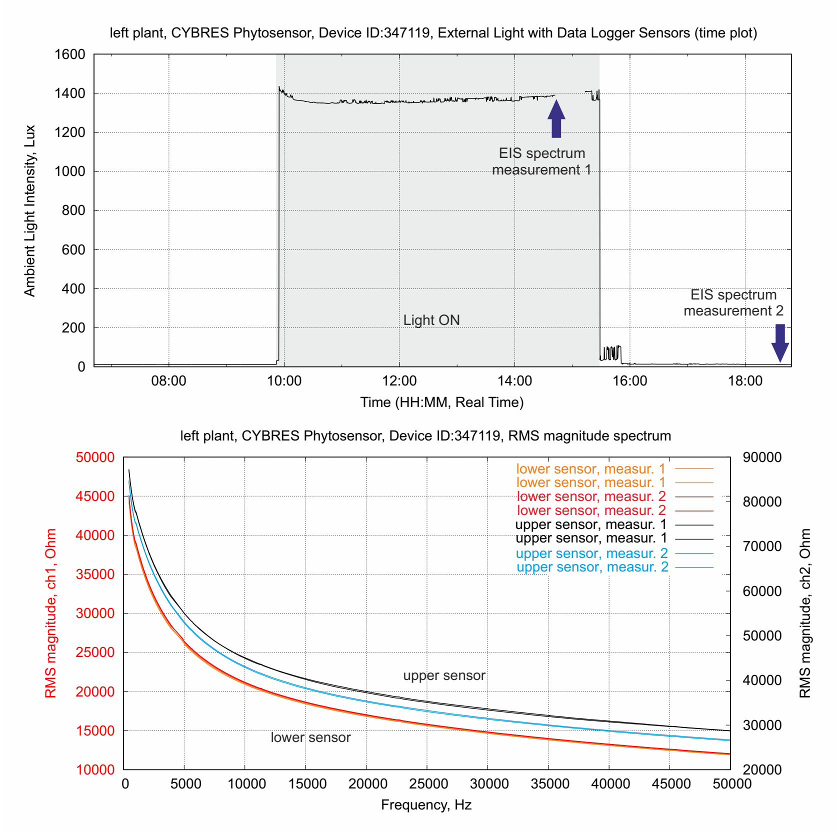


Figure 14: EIS in frequency domain applied to lower and upper sensors. Electrochemical spectrogram of the upper sensor demonstrates clear differences before and after a light excitation (presence of photosynthates in the upper area of stem), whereas the lower sensor has the same ionic content before and after the light excitation (water and nutrients from soil).

we see that the upflow in xylem tissue is represented by the LHS of (1), with H_2O containing different dissolved ions. Among them, potassium (K) and magnesium (Mg) play an important role in ionic dynamics since plants take up both minerals only in their ionic form (as ${Mg_2}^+$ and K^+). Upflow also transports ${NO_3}^-$, ${PO_4}^{3-}$ and ${SO_4}^{2-}$ ions and different ionic solutions of copper Cu and phosphorus P, such as Cu^{2+}, $H_2{PO_4}^-$ and others. The RHS of (1) represents a downflow in phloem tissue, which contains fewer dissolved ionic molecules due to the decrease in H_2O and presence of non-ionic sucrose $C_6H_{12}O_6$.

Since EIS electrodes penetrate all xylem and phloem tissues, electrochemical measurements always contain a combination of upflow and downflow. Different ionic dynamics are detectable by EIS and shown in Figure 14. Spectral EIS is performed twice in the light-on (with photosynthesis) and in the light-off conditions (without photosynthesis) for the lower and upper electrodes. The electrochemical spectrogram of the upper sensor demonstrates clear differences before and after a light excitation (via the presence of photosynthates in the upper area of stem). It is important that the second measurement in the light-off phase demonstrates a lower impedance, as this points to a higher ionic content according to (1). The lower sensor also measures differences between the light-on and light-off phases; however, these differences are much smaller than those in the upper sensor. This reflects a different combination of ionic components and photosynthates in the plant's sap in the leaf and root areas of the stem. Thus, in vivo impedance spectroscopy allows for the discrimination between aqueous solutions containing high levels of ionic nutrients and low levels of ionic photosynthetic products in a hydrodynamic system.

3.6.7 Phyto: soil moisture sensor

Soil sensors use the capacitive principle and measure soil moisture in relative units as % of containing moisture. The phytosensor has two different soil sticks – digital I2C sensor with RGB light ball (it measures the temperature and soil moisture with low resolution) and analog sensor with plastic mounting part (it measures only soil moisture with high sensitivity and resolution), see Figure 15. Since analog and digital sensors use the same data structures, only one of them can be connected to MU at the same time. The soil sensor uses internal values to determine moisture, it must be calibrated to the soil type and its moisture-holding capacity. Parameters of these sensors are shown in Table 8.

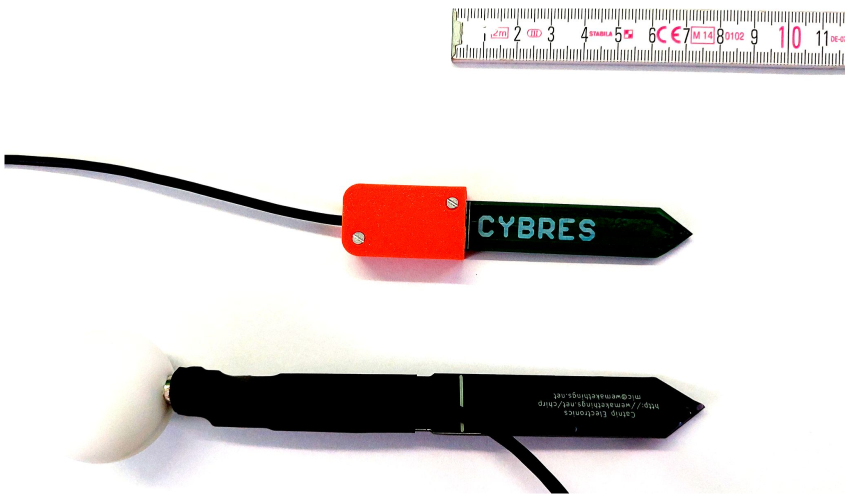


Figure 15: Analog (upper) and digital (lower) soil moisture sensors with 67 mm lower part (in soil).

Calibration. Connect the sensor to the MU module and start the measurement. First, insert the lower part of the sensor into dry soil. The recorded values correspond to the first point, '0% moisture' on the scale. Add water to dry soil until it is completely saturated. The recorded values correspond to the second point,

Table 8: Parameters of the soil moisture sensor.

principle of operation	capacitive sensing, digital and analog interface
frequency	1MHz
duration of single measurement (AC field on, periodical mode)	180ms (all sensors off) – 500ms (all sensors on)
recommended sampling rate	once per 30-60 sec.
power supply	4.2±0.1V, 5mA
output voltage range	0.1-1.1V proportional to soil moisture (pre-calibrated in analog sensor)
dimension (lower part, analog sensor)	15x67x1.5 mm or 15x100x1.5 mm
dimension (upper part, analog sensor)	21.3x36x14 mm
material	PETG or ASA (upper part), coated PCB FR4 (lower part)

'100% moisture' on the scale. All other measurements will represents the moisture in % between 0 and 100 on this scale. The analog soil sensor is pre-calibrate to air (values around 10) – water (values around 100) conditions and possesses better sensitivity and resolution than the digital sensor.

ATTENTION. To avoid root damage, place the soil sensor sideways between the pot and the soil (the sensor side with the CYBRES label should face the soil).

3.6.8 Phyto: green biomass sensor

Green biomass sensor measures the wet biomass of growing plants in a fixed volume, see Figure 16 or in open volume, see Figure 6. The sensing radius of open volume version is about 20 cm from

Figure 16: Green biomass sensor, the version for a fixed volume measurement.

each side of the sensor; it is less complex, however possesses a nonlinear sensitivity: objects close to the plate generate a higher response and objects with high water content limit the sensing range (due to high damping factor of water). The green biomass sensors use dielectric spectroscopy at 0.5-3MHz based on different relative dielectric permittivity (dielectric constant) of material (e.g. water – 78.4 at 25C, 60% of sucrose solution – 60.19 at 25C, glycerol – 42.5 at 25C, air – 1.0006). Considering a high air-water dielectric contrast, the sensor primarily measures a water content of organic tissues, its dynamics follows the wet biomass dynamics. Main applications of this sensor are non-disruptive biomass monitoring in young plants, AI phenotyping, control of mass production in indoor farms and other similar cases. If the sensor is placed close to the ground (less than the distance between plates), it can also measure irrigation dynamics in soil-based and soil-free cultivation. Note, the sensor is off between short measurements (typical duration of measurement – 180-500ms) and does not generate the electric field at this time, see more details in Application Note 28.

Table 9: Parameters of the green biomass sensor.

material of electrodes	PETG or ASA, anodized aluminium
operation frequency	0.5-3MHz (dielectric spectroscopy)
duration of single measurement (AC field on, periodical mode)	180ms (all sensors off) – 500ms (all sensors on)
AC field generation (non-periodical mode)	continuously
recommended sampling rate	once per 30-60 sec.
output voltage range	0-2V proportional to wet biomass
sensing range	about 20cm left and right (open volume version, limited by objects with high water content), between the plates left and right (the fixed volume version)
zero point	variable to adapt to different geometries of electrodes
environmental sensors	air humidity – Honeywell HIH-5031-001, light intensity – EVERLIGHT ALS-PDIC15-21C, air temperature – Texas Instruments LM35
power supply	4.2±0.1V, 5mA
dimension of a single plate	100x200 mm, it can be customized by production on demand

The biomass sensor includes environmental sensors (air temperature, air humidity and light intensity – similar to the transAmb stick), one MU can sample data from three biomass sensors (only the biomass sensor 2 can have environmental sensors and thus cannot operate in parallel with transAmb stick). Parameters of this sensor are shown in Table 9. The sensor can be manufactured with customizable geometry on request; the zero point of the measuring scale can be changed (trim potentiometer on the sensor) to adapt the measuring range to different geometries of the sensor.

ATTENTION. All biomass sensors can work in autonomous mode; if powered but not connected to MU, they are operational and continuously generate AC electric field. Only if the sensor is connected to MU and configured (enabled), the sensor enters into the periodical measurement mode and does not emit AC electric field between measurements. The AC electric field is generated only for 180-500ms during measurements. If the sensors is disabled (removed from MU configuration), it enters again into non-periodical measurement mode.

3.6.9 Phyto: root biomass/irrigation (RBI) sensor

The root biomass and irrigation (RBI) sensor is similar to the green biomass sensor and uses the same approach with dielectric spectroscopy. The main difference is the placement and geometry of electrodes – they are placed below the growth containers (electrodes for green biomass sensor are placed above the growth containers), see Figure 17. The RBI sensor is optimized for soil-free

Figure 17: Root biomass and irrigation sensor placed below the growth containers.

cultivation but also works with soil-based systems. Its sensing range extends approximately 20 cm above the tray, but due to the high damping factor of water and moist root biomass, it is limited to the root layer on the tray. Thus, in addition to root biomass, it also measures the ability of the root layer to store water, including in capillary form. Note that the root biomass sensor cannot distinguish between water used for irrigation and water stored in organic tissues. The variable part of dynamics in root biomass sensors can be used to monitor irrigation. Typically, the RBI sensor replaces the soil moisture sensor, allowing three biomass sensors to be connected to one MU (see Application Note 28). Parameters of this sensor are shown in Table 9.

3.6.10 Phyto: chlorophyll sensor

The chlorophyll sensor uses the excitation spectroscopy and measures the fluorescence emitted by chlorophyll molecules after excitation at 430nm. The measured emission is at 680nm (peak) wavelength. Fluorometry is generally more sensitive than spectrophotometry and enables the *in vivo*, *in situ* and real-time measurements. The chlorophyll sensor can also be used for measuring fluorescent phytoplankton in water, however need recalibration due to light backscattering from particles in the water. LED emitter consumes one of actuating channels of MU and thus limits applications for real-time actuation (3 or 4 free actuating channels instead of 6). Note, that chlorophyll stick on the leaf requires periodical displacement in long-term measurements due to local leaf degradation, see more details in Application Note 28.

3.6.11 EIS-fluids: low ionic solutions

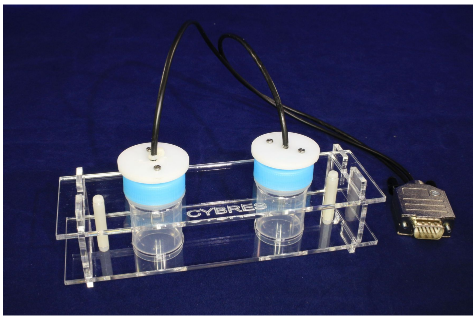
Several applications require open containers without thermostabilization, where fluids are exposed to experimental conditions during measurements. To monitor the fluid temperature in such containers, differential EIS electrodes with integrated temperature sensors have been developed, see Figures 18(a), 18(b). These electrodes are equipped with D-Sub 16/26 connectors compatible with MU34/T measurement units and feature built-in 470/940 nm LEDs for optical excitation, see Table 10. Additionally, they include an antenna for RF sensors, external temperature sensors, and monitor the supply voltage.

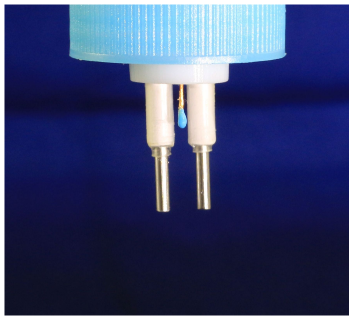
Table 10: Parameters of the EIS electrodes EIS-D15EIVL-16/26.

electrodes	stainless steel V4A (1.4571/ASTM AISI 316Ti), d=2mm, X6CrNiMoTi17-12-2
distance between electrodes	12mm
differential measurements	2x channels EIS
optical excitation	470/940nm LEDs inside containers
containers	polypropylene, 2x, 15 ml
additional sensors	2x internal fluid temperature sensors, external RF antenna, supply voltage sensor (4.2V)
minimal fluid measurement temperature	16C
external temperature sensor	LM35
cable length	500 mm

3.6.12 EIS-bio: fermentation and metabolic reactions

Biosensing applications typically require larger volume than fluid applications to provide better homogeneity of dispersions and suspensions. The electrodes EIS-D100EIVL-16 are equal to EIS-D15EIVL-26 but are mounted on 100 ml containers and used primarily for bio-applications with fermentation and sedimentation processes, see Figure 18(c).





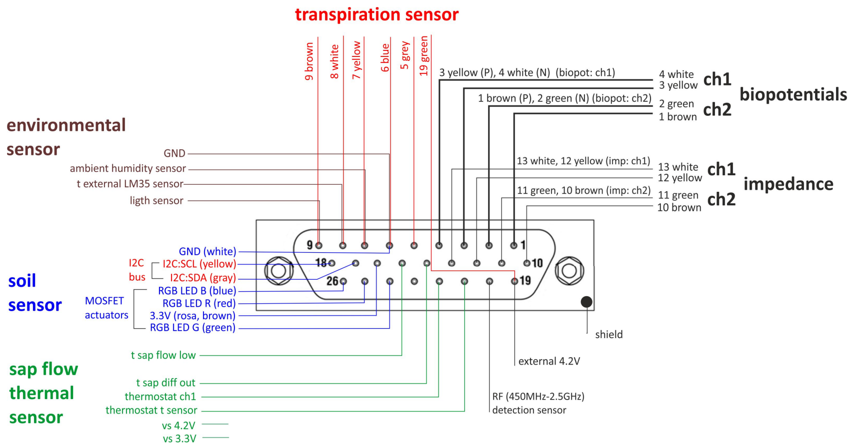
(a) (b)

(c)

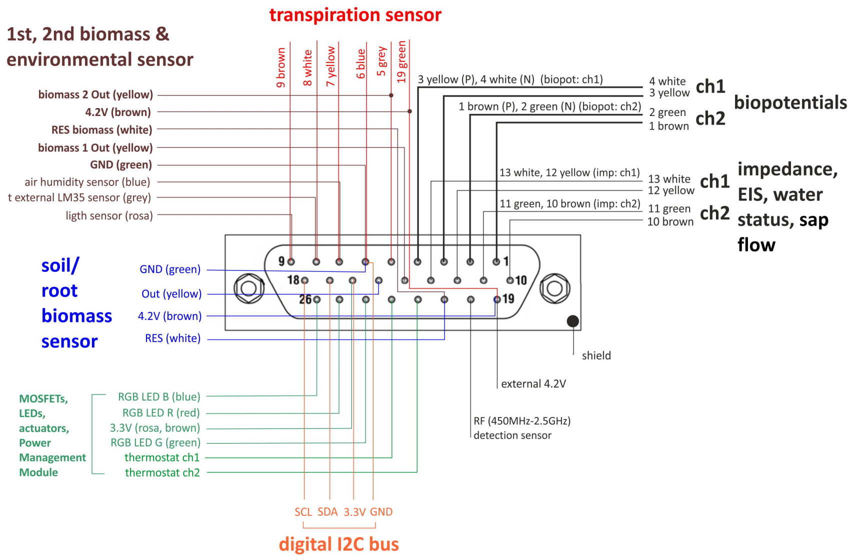
Figure 18: **(a, b)** Differential EIS electrodes EIS-D15EIVL-16/26 with 15 ml containers, integrated temperature sensors, IR/blue LEDs and D-Sub 16/26 connectors; **(c)** Differential EIS electrodes EIS-D100EIVL-16 with 100 ml containers (compared to 15 ml containers) for bio-applications with fermentation and sedimentation processes.

3.6.13 Phytosensing and phytoactuating sets

Since the MU has only one 16- or 26-pin-connector, different bio- and phyto-electrodes/sensors as well as actuators (LEDs, MOSFETS, relay or the high-power management module) are combined to sets and soldered to this connector. Such sets are customizable and depends of requirements of a particular application, however the pinout of the 26-pin-connector defines possible combinations of sensors supported by one measurement unit, see Figure 19.
If more sensors are required, it needs to take two or more MUs. All sets are labelled as Phy- (for phytosensing) or EIS- (for fluid EIS applications) sets, their notation is shown Table 11. Figure 20 shows an example of Phy-IBTSF-26 and Phy-IsBsL-26 sets of electrodes. Antenna for RF power sensors is soldered in all sets.



(a)



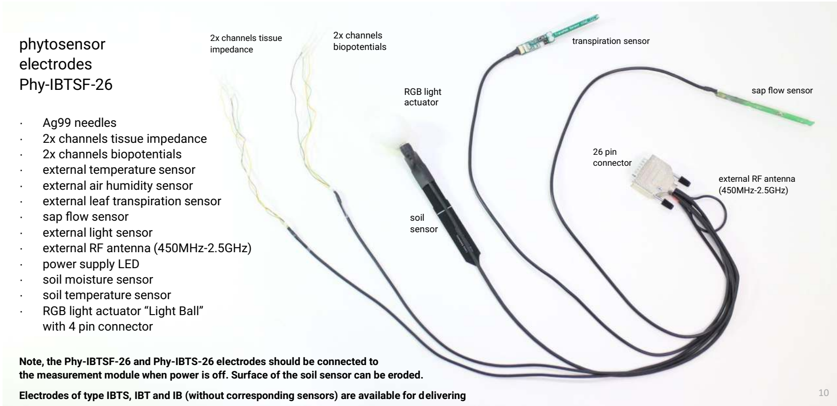
(b)

Figure 19: Pinout of the MU for connecting different phytoelectrodes/sensors; **(a)** v.1; **(b)** v.2.

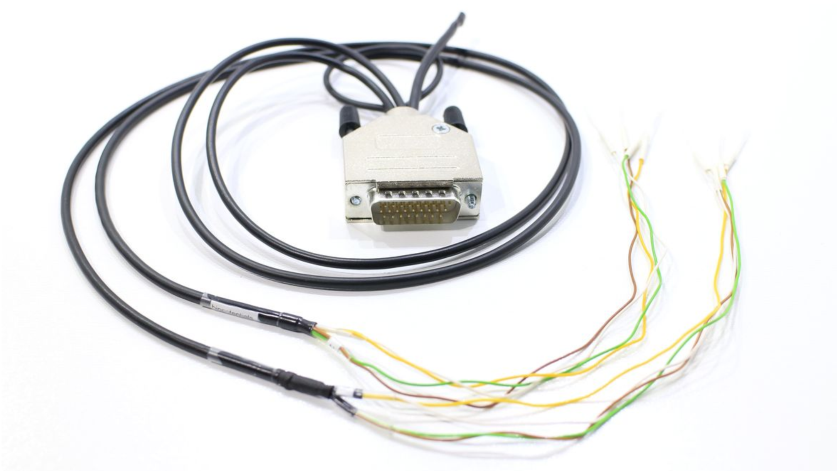
For customization of electrodes, contact info@cybres.eu.

There are several pre-configured ready-to-order sets with short delivery time (all Phyto- versions, beside chlorophyll stick, can be additionally equipped with P-part – 6-pin connector for the high-power management module, see Figure 9(f)):

- **Phy-IBTS-26**, phytoelectrodes (differential impedance/EIS and biopotentials with needles, tranAmb stick, soil sensor)
- **Phy-IsBsL-26** phytoelectrodes (single-channel impedance/EIS and biopotentials with needles, external temperature sensor)
- **Phy-IcTS-26** phytoelectrodes (differential impedance/EIS with clips, tranAmb stick, soil sensor)



(a)



(b)

Figure 20: Example of phytoelectrodes **(a)** Phy-IBTSF-26; **(b)** Phy-IsBsL-26.

- **EIS-D15EIVL-26**, EIS electrodes with 15 ml containers, 470/940 nm excitation, t sensor in fluid (available also in S version with ion-cleaning procedure)
- **Phy-Me-26**, phytoelectrodes (green biomass sensor with 100x200 mm places, with environmental measurements, available in open- or fixed-volume versions)
- **Phy-MeMr-26**, phytoelectrodes (green biomass sensor with 100x200 mm places, with environmental measurements, available in open- or fixed-volume versions, root biomass/irrigation sensor for soil-free cultivation with 50x100 mm plate)

3.6.14 Outdoor applications for phytosensor

The phytosensor is suitable for outdoor use, all plastic parts made of ASA are UV-resistant, and parts made of PETG are partially

Table 11: Notations of electrodes for Phy- (Phytosensing) or EIS- (electrochemical fluid applications) sets.

I	differential impedance electrodes, needle Ag99
B	differential biopotentials electrodes, needle Ag99
Is	single impedance electrodes, needle Ag99
Bs	single biopotentials electrodes, needle Ag99
Ic	differential impedance electrodes, clip Cu_3Zn_2
Ip	single impedance electrodes, clip Cu_3Zn_2
T	transAmb stick (transpiration + environmental sensors)
Te	transAmb environmental stick (without transpiration)
S	soil sensor, digital
Sa	soil sensor, analog
M	green biomass sensor
Me	green biomass sensor + environmental sensors
Mr	root biomass/irrigation sensor
F	thermal sap flow sensor
O	optical chlorophyll sensor
P	6-pin connector from internal MOSFETS for the high-power management module, see Figure 9(f) (it can be used also for low-power LEDs or Solid State Relays)
L	external temperature sensor LM35
V	4.2V supply voltage sensor
D15	EIS fluid cells 15 ml with optical excitation 470nm, 940nm and fluid t sensors
D100	EIS fluid cells 100 ml and fluid t sensors
E	optical excitation 470nm, 940nm
I	immersed in liquid t sensors (thermistors)
26	26-pin-connector
16	16-pin-connector
5	5-pin-connector

UV-resistant. However, the MU electronic module and electrodes should be protected from rain and direct sunlight. Examples of outdoor protection packages IP66/IP67 are shown in Figures 5 and 21(a). There are multiple options for communication and powering, e.g. PoE (Power over Ethernet) solutions, see Figure 21(b), USB-WiFi bridge or embedded systems developed for MU, see Application Note 28. Example of outdoor applications for the phytosensor from the watchPlant project[6] with the 'Orange Box' system for powering and communication[7] is shown in Figure 21(c).

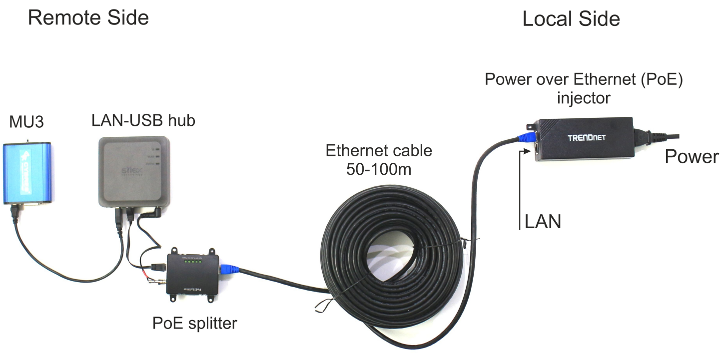
3.6.15 Configuring sensors and processing data

Embedded and external sensors need to be configured in section 'System', the field 'additional sensors', see Figure 22(a). All sensors are divided into three groups:

- environmental sensors: blue group, only one of these options can be selected;
- analog interface sensors: black group, all sensors can be switched on or off, multiple sensors are possible;
- digital interface sensors: green group, all sensors can be switched

[6] https://watchplantproject.eu/
[7] https://github.com/WatchPlant/OrangeBox/wiki

(a)



(b)

(c)

Figure 21: **(a)** Examples of outdoor protection packages for the phytosensor with **(b)** PoE powering and communication; **(c)** Examples of outdoor application from the watchPlant project with the 'Orange Box', developed by the University of Zagreb, Faculty of Electrical Engineering and Computing for powering and communication, image by CYBRES.

on or off, multiple sensors are possible;

The sampling time of an analog or digital sensor is approximately 100 ms. Turning off all sensors shortens the total sampling time in one measurement cycle. Turning on all sensors slows down the overall sampling time in one measurement cycle. If some parameter need to be sampled faster (e.g. EIS data), turn off additional sensors.

Data from corresponding sensors are available in the section 'plot', 'plot 1x: external sensors', see Figure 22(b). Note, if the sensor is configured but not connected, the corresponding sensor data will have arbitrary numbers. If the sensors is switched off, the corresponding sensor data will have '0' values.

Data processing can be conducted in several different ways as real-time or post-processing:

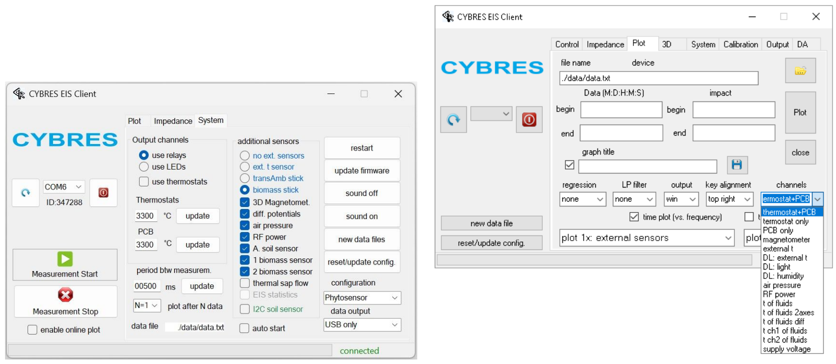
- **with embedded gnupolt scripts**, they are located in the folder '/scripts' and can be can easily adapted for particular requirements;
- **with embedded data processing engine** (e.g. statistical processors) in DA module, they can be configured and executed in real time as synthetic data channels;
- **with real-time python scripts**, the python server is implemented and provide real-time data to any external python program running in parallel to the client program;
- **post-processing of recorded data** by any analytic software.

ATTENTION. The parameter 'period between measurements' introduces a delay between measurement cycles, specified in this field. It does not specify the duration of a single measurement cycle (due to the user-defined variable sampling time of the on/off sensors).

3.7 Documentation

Documentation includes the Extended User Manual, the short Device Description, the short User Manual (translated in different languages), Technical Presentation, publications, application notes and videos:

- EIS spectrometer, all materials
- Phytosensor, all materials
- Extended User Manual
- short Device Description



(a) (b)

Figure 22: **(a)** Configuration of additional onboard and external sensors; **(b)** Selection of additional sensors data for plotting.

- short User Manual
- Technical Presentation
- Application Note 18. Online system for automatic detection of remote interactions based on the CYBRES MU EIS impedance spectrometer;
- Application Note 20. Increasing accuracy of repeated EIS measurements for detecting weak emissions;
- Application Note 24. Analysis of electrochemical noise for detection of non-chemical treatment of fluids;
- Application Note 26. Methodology and protocols of feedback-based EIS experiments in real time;
- Application Note 27. Using regression scan for electrochemical 'treatment-during-measurement' experiments;
- Application Note 28. Using phytosensor in precision agriculture, vertical farms, hydroponics and agricultural AI applications