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For over years ten the Photon Systems Instruments (PSI) Company based in the Czech Republic has developed numerous imaging systems to investigate the growth, physiology and response to environment of plants. These imaging systems have been used in the laboratory, greenhouse, growth room and the field. Dicotyledonous plants as small as Arabidopsis seedlings, and monocotyledonous plants as large as mature corn plants, have been studied using these systems.

Qubit’s imaging systems are modular, and may include stations for:

- **RGB and Morphometric Imaging**
- **Chlorophyll fluorescence Kinetic Imaging**
- **Near InfraRed (NIR) Imaging**
- **Hyperspectral Imaging**
- **Thermal Imaging**
- **Automated Watering and Weighing**
- **Automated Nutrient Delivery and Analysis**
- **Automated Light Acclimation of Plants**

In addition, PSI have developed conveyor-based technologies for the movement of plants from their growth environment to the imaging apparatus. In situations in which it is preferred that the plants are not moved, robotic crane systems have been designed and built to bring the imaging stations to the plants. Novel systems have been designed for field-grown plants that use rails or motorized vehicles to move the imaging system from plant to plant in a growth plot or across a field transect. These field systems have been developed for plants varying from turf grass to tomatoes.

Clients include, among many others:

- The International Rice Research Institute, Los Banos Philippines
- The CSIRO Plant Phenomics Center, Canberra, Australia
- The Australian National University, Canberra. Australia
- Monsanto Corporation, St. Louis, USA.
- Pioneer-Dupont, Des Moines, Iowa
- Metanomics (BASF), Berlin, GDR
- CropDesign (BASF), Nevele, Belgium
- Synthetic Genomics, La Jolla, USA
All of PSI’s plant phenomic screening systems feature similar technology. This information document provides the background to the technologies that may be configured in numerous ways for lab, field and even aquatic screening systems.

**PlantScreen Phenotyping System for High Throughput Screening with Acclimatization Chamber and Conveyor**

PSI’s high-throughput plant screening system (PlantScreen) allows the user to monitor numerous aspects of plant growth, development and response to biotic and abiotic stresses. PlantScreen systems can be designed and configured to meet the users’ specific requirements with respect to the size and number of plants screened, as well as the environmental conditions to which they are exposed. In the standard design, the samples are placed on trays with dimensions of 293x357 mm, and the maximum height of the plant is 0.7 m. The maximum capacity of the PlantScreen in the standard configuration is 16 trays. A matrix of pots can be placed in each tray, or single larger plants in separate pots may be screened. A typical pots used in the trays (20 per tray) has a volume of 200 ml and dimension of 7x7x9 cm (W x D x H).

The PlantScreen incorporates a number of instruments for imaging plant morphometric and physiological parameters, as an acclimatization chamber that may be used to equilibrate plants under controlled conditions, or even for plant cultivation.

**Acclimatization Chamber**

The PlantScreen includes an acclimation chamber for light/dark adaptation of samples. Light levels provided by LED panels can be set with an irradiance of up to 1000μmol m⁻² s⁻¹ at the surface of the plant. Lighting can be regulated from 0 to 100% of maximum. Software protocols may be used to predefine the time and intensity of irradiance conditions.
**Chlorophyll Fluorescence Measurements**

The PlantScreen conducts chlorophyll fluorescence kinetics measurements on single plants or plant in trays. When using trays, the measured data can be sorted automatically for each single sample on the tray. The system performs automatic analysis of measured data, allows for visual display and stores both numeric and image data.

Measured parameters:  FO, FM, FV, FO', FM', FV', FT  
Calculated parameters:  FV/FM, FV'/FM', PhiPSII, NPQ, qN, qP, Rfd
Applications:

- Screening for photosynthetic performance.
- Stress resistance or susceptibility.
- Stomatal patchiness.
- Metabolic perturbations.
- Growth and yield.
- RGB digital growth analysis from 3 camera views, including thresholding and color analysis.

Software allows batch analysis of images for fluorescence quenching parameters including user-identified regions of interest and averaging of pixel values on background subtracted images. Analyzed data are stored in the database with co-registration of raw image data and analyzed data.
**RGB Structural Imaging**

RGB images are scanned with a resolution of 5 Mpx from three directions (from the sides and from the top). Samples are illuminated with consistent quantity and quality of light. Options are available for the inclusion of novel 3D scanning technology for the most in depth morphometric reconstruction of plants.

**Image Processing**

Step 1: Barrel distortion correction  
Step 2: Tray detection and cropping  
Step 3: Background subtraction  

Results: Binary and RGB images as input for analysis

---

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Barrel distortion correction" /></td>
<td><img src="image2" alt="Tray detection and cropping" /></td>
<td><img src="image3" alt="Background subtraction" /></td>
<td><img src="image4" alt="Binary and RGB Images" /></td>
</tr>
</tbody>
</table>

A: Barrel distortion correction  
B: Tray detection and cropping  
C: Background subtraction  
D: Binary and RGB Images
Parameters Computed:

- **Leaf Area**: Number of pixels covered by the plant surface converted to relevant units. Useful for monitoring growth rate.
- **Solidity/Compactness**: Ratio between the area covered by the plant’s convex hull and the area covered by the actual plant.
- **Leaf Perimeter**: Particularly useful for the basic leaf shape and width evaluation (combined with leaf area).
- **Eccentricity**: Plant shape estimation, scalar number, eccentricity of the ellipse with same second moments as the plant (0…circle, 1…line segment).
- **Roundness**: Based on evaluating the ratio between leaf area and perimeter. Gives information about leaf roundness.
- **Medium Leaf Width Index**: Leaf area proportional to the plant skeleton (i.e. reduction of the leaf to line segment).
- **Circle Diameter**: Diameter of a circle with the same area as the plant.
- **Convex Hull Area**: Useful for compactness evaluation
- **Centroid**: Center of the plant mass position (particularly useful for the eccentricity evaluation)
- **Internodal Distances**
- **Growth Height**
- **Maximum Height and Width of Plant in 3 Dimensions**
- **Leaf Angle**
- **Leaf Number at Nodes**
Parameter Validation

Parameter measurements have been successfully validated using model objects with known shape and dimensions:

<table>
<thead>
<tr>
<th>Position</th>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area [mm²]</td>
<td>1235,92</td>
<td>549,53</td>
<td>673,01</td>
<td>818,95</td>
</tr>
<tr>
<td>Perimeter [mm]</td>
<td>273,61</td>
<td>97,16</td>
<td>146,39</td>
<td>133,11</td>
</tr>
<tr>
<td>Roundness</td>
<td>0,21</td>
<td>0,72</td>
<td>0,39</td>
<td>0,58</td>
</tr>
<tr>
<td>Convex hull area [mm²]</td>
<td>1568,39</td>
<td>549,72</td>
<td>831,21</td>
<td>853,33</td>
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<tr>
<td>Eccentricity</td>
<td>0,20</td>
<td>0,87</td>
<td>0,32</td>
<td>0,96</td>
</tr>
<tr>
<td>Compactness</td>
<td>0,79</td>
<td>0,98</td>
<td>0,81</td>
<td>0,96</td>
</tr>
<tr>
<td>Circle diameter [mm]</td>
<td>39,67</td>
<td>26,23</td>
<td>29,27</td>
<td>32,29</td>
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<tr>
<td>MLWI</td>
<td>61,95</td>
<td>9,14</td>
<td>23,47</td>
<td>118,25</td>
</tr>
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</table>
Validation Data with Real Plants

<table>
<thead>
<tr>
<th>Position</th>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>A2</th>
<th>B2</th>
<th>C2</th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area [mm²]</td>
<td>301.25</td>
<td>977.39</td>
<td>787.58</td>
<td>1027.25</td>
<td>915.63</td>
<td>951.54</td>
<td>546.46</td>
<td>1078.36</td>
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<tr>
<td>Perimeter [mm]</td>
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<td>440.53</td>
<td>347.50</td>
<td>433.91</td>
<td>336.06</td>
<td>345.40</td>
<td>384.62</td>
<td>354.54</td>
</tr>
<tr>
<td>Roundness</td>
<td>0.06</td>
<td>0.06</td>
<td>0.08</td>
<td>0.07</td>
<td>0.07</td>
<td>0.10</td>
<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td>Convex hull area [mm²]</td>
<td>1407.46</td>
<td>1712.92</td>
<td>1221.46</td>
<td>1964.06</td>
<td>1560.96</td>
<td>1801.16</td>
<td>1478.33</td>
<td>2018.86</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.47</td>
<td>0.38</td>
<td>0.70</td>
<td>0.42</td>
<td>0.25</td>
<td>0.33</td>
<td>0.36</td>
<td>0.55</td>
</tr>
<tr>
<td>Compactness</td>
<td>0.57</td>
<td>0.57</td>
<td>0.52</td>
<td>0.52</td>
<td>0.59</td>
<td>0.53</td>
<td>0.57</td>
<td>0.53</td>
</tr>
<tr>
<td>Circle diameter [mm]</td>
<td>31.94</td>
<td>35.28</td>
<td>30.99</td>
<td>35.17</td>
<td>34.11</td>
<td>34.81</td>
<td>32.89</td>
<td>37.09</td>
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<tr>
<td>MLVVI</td>
<td>30.20</td>
<td>34.79</td>
<td>34.32</td>
<td>50.72</td>
<td>33.95</td>
<td>42.09</td>
<td>30.04</td>
<td>55.64</td>
</tr>
</tbody>
</table>

Other Measured Parameters

- Color segmentation for plant fitness evaluation
- Sequentially computed relative leaf growth rates
- Comparison of leaf area differences during whole experiment
- Flattening index
- Circadian leaf area differences
- Greening index
- Contribution of individual colors after color segmentation and characterization:
Healthy Green
Dark Green
Light Green
Other Color – for incidental stains

**Thermal Imaging**

To study heating of the samples during irradiation by light. Variations in mechanisms for self-cooling may allow certain plants to withstand periods of high irradiance and low water availability.

Resolution of 640x480 pixels
Temperature range from 20 to +120°C
Thermal sensitivity /NETD < 0.05°C at +30°C / 50 mK
Spectral range: Uncooled microbolometer with a range of 7.5-13 micrometers.
16 bit resolution of images.

Controlled thermal environment with LED light panel for illumination of samples with adjustable intensity of illumination from 0 to 500$\mu$mol m$^{-2}$s$^{-1}$ in increments of 1% and range from 0 to 100%.

Type of camera: FLIR SC645
The camera is fixed in the PlantScreen and cannot be moved between other devices.
Hyperspectral Imaging

Hyperspectral imaging has been used for many years to study patterns of plant growth from satellite imaging. This technology has been refined in PSI’s PlantScreen to provide hyperspectral image analysis of plants on a pixel by pixel basis.

Typical Reflectance Spectrum of a Leaf
Using a Headwall hyperspectral camera with image analysis software, plant reflective indices can be visualized across the entire surface of the imaged sample(s). These indices may be correlated with numerous physiological conditions, as well as the status of the plant or leaf with respect to content of chlorophyll, accessory pigments, nitrogen etc. Examples of published Reflective Indices, all measurable with the PlantScreen Hyperspectral station are as follows:

- **Normalized Difference Vegetation Index (NDVI)**
  Reference: Rouse et al. (1974)
  Equation: \( \text{NDVI} = (\text{RNIR} - \text{RRED}) / (\text{RNIR} + \text{RRED}) \)

- **Simple Ratio Index (SR)**
  Reference: Jordan (1969); Rouse et al. (1974)
  Equation: \( \text{SR} = \text{RNIR} / \text{RRED} \)

- **Modified Chlorophyll Absorption in Reflectance Index (MCARI1)**
  Equation: \( \text{MCARI1} = 1.2 \times [2.5 \times (\text{R790} - \text{R670}) - 1.3 \times (\text{R790} - \text{R550})] \)

- **Optimized Soil-Adjusted Vegetation Index (OSAVI)**
  Reference: Rondeaux et al. (1996)
  Equation: \( \text{OSAVI} = (1 + 0.16) \times (\text{R790} - \text{R670}) / (\text{R790} - \text{R670} + 0.16) \)

- **Greenness Index (G)**
  Equation: \( G = \text{R554} / \text{R677} \)

- **Modified Chlorophyll Absorption in Reflectance Index (MCARI)**
  Reference: Daugtry et al. (2000)
  Equation: \( \text{MCARI} = [(\text{R700} - \text{R670}) - 0.2 \times (\text{R700} - \text{R550})] \times (\text{R700} / \text{R670}) \)

- **Transformed CAR Index (TCARI)**
  Reference: Haboudane et al. (2002)
  Equation: \( \text{TSARI} = 3 \times [(\text{R700} - \text{R670}) - 0.2 \times (\text{R700} - \text{R550}) \times (\text{R700} / \text{R670})] \)

- **Triangular Vegetation Index (TVI)**
  Equation: \( \text{TVI} = 0.5 \times [120 \times (\text{R750} - \text{R550}) - 200 \times (\text{R670} - \text{R550})] \)

- **Zarco-Tejada & Miller Index (ZMI)**
  Reference: Zarco-Tejada et al. (2001)
  Equation: \( \text{ZMI} = \text{R750} / \text{R710} \)

- **Simple Ratio Pigment Index (SRPI)**
  Reference: Peñuelas et al. (1995)
  Equation: \( \text{SRPI} = \text{R430} / \text{R680} \)

- **Normalized Phaeophytinization Index (NPQI)**
  Reference: Barnes et al. (1992)
  Equation: \( \text{NPQI} = (\text{R415} - \text{R435}) / (\text{R415} + \text{R435}) \)

- **Photochemical Reflectance Index (PRI)**
  Reference: Gamon et al. (1992)
  Equation: \( \text{PRI} = (\text{R531} - \text{R570}) / (\text{R531} + \text{R570}) \)

- **Normalized Pigment Chlorophyll Index (NPCI)**
  Reference: Peñuelas et al. (1994)
  Equation: \( \text{NPCI} = (\text{R680} - \text{R430}) / (\text{R680} + \text{R430}) \)
- **Carter Indices**  
  Equation: Ctr1 = R695 / R420; Ctr2 = R695 / R760

- **Lichtenthaler Indices**  
  Reference: Lichtenthaler et al. (1996)  
  Equation: Lic1 = (R790 - R680) / (R790 + R680); Lic2 = R440 / R690

- **Structure Intensive Pigment Index (SIPI)**  
  Reference: Peñuelas et al. (1995)  
  Equation: SIPI = (R790 - R450) / (R790 + R650)

- **Gitelson and Merzlyak Indices**  
  Reference: Gitelson & Merzlyak (1997)  
  Equation: GM1 = R750 / R550; GM2 = R750 / R700
The Plant Screen hyperspectral imaging station allows the user to acquire a full spectral scan across the entire spectral range of the camera for each pixel of the image. Alternatively, the user may select specific wavelengths of interest to record reflective indices that may be correlated with, for example, leaf nitrogen status, or the production of anthocyanin to protect Photosystem II under high light stress. It is also possible, in software, to establish patterns within hyperspectral measurements that are indicative of abiotic and biotic stresses, so that novel protocols for automated stress screening may be established.

**Near Infra-Red (NIR) Imaging**

The PlantScreen system may be configured with an imaging station specific for monitoring and comparing the water status of plants, or for assessing variations of the water status within different plant tissues. In this station the camera is set to collect data in the absorbance band for water between 1450 and 1600 nm. Plants that are adequately hydrated show high absorbance of NIR light in this absorbance band (and low reflectance), whereas those subject to drying will show greater reflectance in this band.

Applying a false color palette to the images allows the researcher to quickly identify plants that are drying rapidly compared to those that are maintaining a healthier water status. In this respect, the NIR imaging station is important when studying responses to drought stress and screening for plants with enhanced water use efficiency.

Software allows individual plants to be tracked through an imposed drought cycle so that the time-course of the onset of drought stress, and response to re-watering, can be monitored. In addition, morphometric parameters, and measurements of photochemical efficiency, may be correlated with stress and recovery events.
Weighing, Irrigation and Nutrient Delivery

The PlantScreen system is able to weigh individual samples placed in trays or in individual pots. When using standard trays, 5 pots are lifted from the tray simultaneously, and the weights recorded with an accuracy of ± 2g. After weighing, each sample can be irrigated to a desired weight. Software protocols allow the user to specify a watering regime for the provision of adequate water, or for the time-dependent imposition of drought stress.

Watering and Weighing Station

Water may be supplied by gravity from a tank or the system may be configured to deliver both water and nutrients from a nutrient supply system with an option for nutrient analysis.

Identification of Samples

Individual trays are identified by a barcode that is read automatically by the system. This allows automated selection of samples from the growth chamber or greenhouse for screening. The data obtained from individual measurements are uniquely assigned to the samples on the basis of their ID and the measurement time. RFID devices may be used as an alternative, or additional, method for tracking trays, pots and individual samples.
Environmental Control in the Imaging Cabinet

The PlantScreen imaging components are housed in a cabinet that equilibrates plants to user-defined environmental conditions prior to screening. This is critically important when imaging chlorophyll fluorescence kinetics, since data are dependent on irradiance conditions e.g. dark pre-adaptation, Kautsky induction, light-adapted quantum yield etc. Controlled irradiance conditions are also critical to success thermal imaging, since variations in heat load or heterogeneity can render sensible analysis of images virtually impossible.

The entire upper surface of the interior of the PlantScreen is covered with LED panels that can deliver irradiance levels in excess of 1000 umol photons/m²/s at the plant surface. Irradiance can be controlled between 0 and 100% of maximum in 1% increments, and automated lighting protocols may be programmed in software. The LEDs are collimated to ensure that irradiance is homogeneous in a plane at any distance from the panels. Light quality may be varied by selecting LEDs of different wavelengths to create specific light environments.
Since LEDs have no warm-up period, their use allows instantaneous changes to be made in light quality and quantity. Also, unlike traditional light sources, they create virtually no heat load on the plant. The PlantScreen cabinet can, therefore, be maintained at fixed temperature without the need for cooling fans that could disturb the plants during the imaging processes.

The PlantScreen cabinet may be used for plant cultivation, and can be built to accommodate a wide variety and number of plants. Alternatively, plants may be delivered to the cabinet via a conveyor belt from a growth facility.

Environmental conditions within the PlantScreen cabinet are monitored continuously in software. Since the system only operates with the doors closed, cameras are placed strategically within the cabinet to show plant position and movement, allowing the user to intervene should any unexpected event occur.

**Graphical Control Software**

PlantScreen data acquisition and control software allows the user to define measurement protocols, and view the current status of the device. Pre-defined protocols are available that may be edited easily by the user. These protocols carry out repeated sequences of measurements under defined environmental conditions. All data are stored into a relational MySQL database, in which it is easy to search data by selected parameters. The number of measurements that may be made depends on the size of storage space. It is possible to record up to 1000 measurements on a 200 gigabytes storage device.

**Defining Protocols with PlantScan Client**

PlantScan Client software controls and monitors the entire PlantScreen device via a touch screen interface.
The touch screen is divided into several operational areas, including a schematic representation of the entire device which displays the number of trays inserted into the PlantScreen, light levels and status of individual measurement devices and their activity.
View of Online Operation of the PlantScreen using IP Cameras

Lighting in the cultivation (non-imaging) section of the chamber is divided into several sectors. In any sector, it is possible to separately switch the lighting on or off and to set the desired irradiance level.
Control allows both manual setting of all parameters and a fully automatic mode that operates in accordance with a predefined protocol. The automated mode may be over-ridden if required.

**Imaging Station Controls**

Operation of the RGB imaging station is done in a separate software tab, each camera having its own control panel. Here, the user can set the exposure time, gain, and balancing between different color components.

The *Take Snapshot* button is used for instantaneous image capture. The image is displayed in the left frame, together with details such as resolution, time of the scan, format, etc. The image can be saved.
using the Save button. For high-quality images, it is possible to turn on illumination lighting using the - On/Off button. In automatic mode, the PlantScreen software can be set so that images are automatically recorded and saved into a database for subsequent processing. The system is designed so that lighting conditions, and plant position with respect to cameras, are identical for each image. The IR camera is operated in a similar similarly to the RGB camera, under a separate tab. Chlorophyll fluorescence imaging and hyperspectral imaging have more complex control protocols.

**Automated Operation**

The PlantScreen is designed primarily for operation in automatic mode. The user may select a predefined protocol from a Wizard, or enter individual operational steps that can be saved as anew protocol:

- Switching the lighting on / off in the cultivation area
- Scanning using RGB cameras
- Scanning using IR camera
- Implementation of chlorophyll fluorescence measurements under their own measurement protocol
- Implementation of hyperspectral measurements under their own measurement protocol
- Weighing of individual samples
- On the base of weighting, supply a specified level of irrigation

The chosen procedures are implemented with defined timing and repetition.
Protocols can be started and stopped using the Start button or Stop button. Protocols may be paused using the Pause button. The user can save the developed measurement protocols onto the PlantScan computer or a portable drive.
Schematic Representation of PlantScreen

(side and overhead views)

Data Base Software

1: Introduction

Experiment settings and measured parameters obtained during experiment run are saved in database. Database supports standard SQL queries, through which the data can be accessed.

To minimize redundancy in database, there are separate tables for experiments, rounds of measurements and trays, which are created automatically as the protocol is executed. Each sensor then has its own table too, which contains among others links to these experiment, round and tray tables. That enables unambiguous data to plant assignment.
To minimize redundancy in database, there are separate tables for experiments, rounds of measurements and trays, which are created automatically as the protocol is executed. Each sensor then has its own table too, which contains among others links to these experiment, round and tray tables. That enables unambiguous data to plant assignment.

2. Basic Data Base Table Structure
Table "tab_experiment"

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp_id</td>
<td>experiment ID</td>
</tr>
<tr>
<td>exp_name</td>
<td>experiment name</td>
</tr>
<tr>
<td>exp_responsible</td>
<td>name of person responsible for experiment</td>
</tr>
<tr>
<td>exp_start_date</td>
<td>start date &amp; time</td>
</tr>
<tr>
<td>exp_stop_date</td>
<td>stop date &amp; time</td>
</tr>
<tr>
<td>exp_ending</td>
<td>experiment status flag</td>
</tr>
<tr>
<td>• OK</td>
<td>experiment finished</td>
</tr>
<tr>
<td>• UserTerminated</td>
<td>experiment aborted by user.</td>
</tr>
<tr>
<td>• Error</td>
<td>experiment aborted due to error.</td>
</tr>
<tr>
<td>exp_protocol</td>
<td>experiment protocol (JSON format)</td>
</tr>
</tbody>
</table>

Table "tab_round" - records of measuring rounds

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<th>Field</th>
<th>Description</th>
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<td>record ID</td>
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<tr>
<td>round_exp</td>
<td>experiment ID (foreign key)</td>
</tr>
<tr>
<td>round_order</td>
<td>round number within experiment</td>
</tr>
<tr>
<td>round_start_date</td>
<td>start date &amp; time of measuring round</td>
</tr>
<tr>
<td>round_stop_date</td>
<td>stop date &amp; time of measuring round</td>
</tr>
<tr>
<td>round_protocol</td>
<td>measuring protocol for round (JSON format)</td>
</tr>
</tbody>
</table>
3. Structure of Table Connection and Table Details

**IR measurement**

Table “tab_ir_measure” – records of IR measuring

- ir_id - record ID
- ir_idf_round - measuring round ID (foreign key)
- ir_idf_tray - tray record ID (foreign key)
- ir_data - measuring start data & time
- ir_light_level - light intensity [%]
- ir_idf_temp - temperature record ID

Table “tab_ir_data” – records of IR images

(Within one IR measurement could be taken more IR images)

- ir_data_id - record ID
- ir_data_idf_measure - IR measure ID (foreign key)
- ir_data_date - date of measurement
- ir_data_order - IR picture number within one IR measuring
- ir_data_width - number of pixels in one row
- ir_data_height - number of rows
- ir_data_raw - raw data
- ir_data_table - conversion table for raw data
- ir_data_fhdr - data (FHDR format)
4. FluorCam Measurement Data

Table “tab_fc_measure” – records of FluorCam measurement
- fc_id - record ID
- fc_idf_round - measuring round ID (foreign key)
- fc_idf_tray - tray record ID (foreign key) IT'S NOT IDENTIFICATION CODE OF TRAY
- fc_date - date & time of measure start
- fc_protocol - Fluorcam protocol
- fc_height - height adjustment
- fc_dataTar - tar-file containing whole FC-data from one measurement

Table “tab_fc_data” – data for particular plant
- fc_data_id - record ID
- fc_data_dfl_measure - fluorcam measuring record ID (foreign key)
- fc_data_dfl_plant - plant record ID (foreign key)
- fc_data_date - date & time of measure start

Computed parameters:
- fc_data_size - plant leaf area
- fc_data_f0 - F0
- fc_data_fm - Fm
- fc_data_cm - Cy
- fc_data_fp - Fp
5. RGB Data Base

Table “tab_rgb” – records of RGB pictures

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>rgb_id</td>
<td>record ID</td>
</tr>
<tr>
<td>rgb_off_round</td>
<td>measuring round ID (foreign key)</td>
</tr>
<tr>
<td>rgb_off_tray</td>
<td>tray record ID (foreign key) IT'S NOT IDENTIFICATION CODE OF TRAY</td>
</tr>
<tr>
<td>rgb_off_cam</td>
<td>camera number (1/3/9)</td>
</tr>
<tr>
<td>rgb_date</td>
<td>date of measurement</td>
</tr>
<tr>
<td>rgb_picture</td>
<td>RGB picture [png]</td>
</tr>
<tr>
<td>rgb_picture_size</td>
<td>size of picture [byte]</td>
</tr>
</tbody>
</table>
6. Weighing Data Base

Table “tab_wt_measure” – records of weighing
- `wt_measure_id` - record ID
- `wt_measure_idf_round` - measuring round ID (foreign key)
- `wt_measure_idf_tray` - tray record ID (foreign key) \( \Rightarrow \) IT'S NOT IDENTIFICATION CODE OF TRAY
- `wt_measure_date` - date & time of weighing

Table “tab_wt_plant_data” – data for particular plant
- `wt_data_id` - record ID
- `wt_data_idf_measure` - weighing record ID (foreign key)
- `wt_data_idf_plant` - plant record ID (foreign key)
- `wt_data_date` - date & time of weighing
- `wt_data_value` - plant weight [g]
7. Plants to Tray Registration

To assign to measurement records with corresponding plants/pots/trays, PlantScreen system needs to have all plants and trays registered before experiment starts. Registration consist of saving ID code (Barcode, QR-code, ...) of single plants along with their position in tray and trays IDs to database. For further information about registration process please refer to TrayPlant Registrar manual.

Data Base Tables Structure

Table "tab_tray_type" - tray type records
- traytype_id - record ID
- traytype_name - tray type name
- traytype_position - number of pot positions
- traytype_poscount - names of pot positions, comma separated

Table "tab_tray" - single tray records
- tray_id - record ID
- tray_textid - tray ID code - BAR-code, QR-code...
- tray_id_type - tray type record ID (foreign key)
- tray_notes - notes

Table "tab_pot_type" - pot type records
- pot_id - record ID
- pot_name - pot type name
- pot_width - pot width
- pot_height - pot height
Table "tab_plant" - single plant records

<table>
<thead>
<tr>
<th>Column Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>plant_id</td>
<td>record ID</td>
</tr>
<tr>
<td>plant_iid</td>
<td>plant ID code - #A#B-code, #C#D-code</td>
</tr>
<tr>
<td>plant_iid_pos</td>
<td>plant ID (foreign key)</td>
</tr>
<tr>
<td>plant_name</td>
<td>plant name</td>
</tr>
<tr>
<td>plant_notes</td>
<td>notes</td>
</tr>
</tbody>
</table>

Table "tab_plant_assign" - plant to tray position assignment records

<table>
<thead>
<tr>
<th>Column Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>assign_id</td>
<td>record ID</td>
</tr>
<tr>
<td>assign_iid_tray</td>
<td>tray record ID (foreign key)</td>
</tr>
<tr>
<td>assign_iid_plant</td>
<td>plant record ID (foreign key)</td>
</tr>
<tr>
<td>assign_position</td>
<td>position name in given tray</td>
</tr>
</tbody>
</table>
8. Example of SQL Queries

**Experiment info**

**Variables**
explID - experiment ID

**SQL**

```
SELECT exp_name, exp_start_date, exp_stop_date, exp_ending FROM tab_experiment WHERE exp_id = explID;
```

**Result set**

<table>
<thead>
<tr>
<th>exp_name</th>
<th>exp_start_date</th>
<th>exp_stop_date</th>
<th>exp_ending</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21/12/2012 08:58</td>
<td>21/12/2012 08:58</td>
<td>21/12/2012 10:03</td>
</tr>
</tbody>
</table>

**RGB data**

**Variables**
camID - camera number (1/2/3)
trayTextid - identification code of tray (Barcode, QR-code)

**SQL**

```
SELECT rgb_date as date, rgb_picture_size as size, rgb_picture as picture FROM tab_rgb
LEFT JOIN tab_tray ON tab_rgb.rgb_idf_tray = tab_tray.tray_id
WHERE tray_textid = trayTextid AND rgb_idf_cam = camID;
```

**Result set**

<table>
<thead>
<tr>
<th>date</th>
<th>size</th>
<th>picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>02/01/2013</td>
<td>9703823</td>
<td>blob</td>
</tr>
<tr>
<td>02/01/2013</td>
<td>9711963</td>
<td>blob</td>
</tr>
<tr>
<td>03/01/2013</td>
<td>9707206</td>
<td>blob</td>
</tr>
</tbody>
</table>
9. FluorCam Data

Variables
plantTextId - identification code of plant (Barcode, GR-code)

SQL
SELECT fc_data_date AS Date, fc_data_size AS "Leaf area", fc_data_f_m AS Fm, fc_data_qy_max AS Qy
FROM tab_fc_plant_data
LEFT JOIN tab_plant ON tab_fc_plant_data.fc_data_idf_plant = tab_plant.plant_id
WHERE plant_textid = plantTextId;

Result set

<table>
<thead>
<tr>
<th>Date</th>
<th>Leaf area</th>
<th>Fm</th>
<th>Qy</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/12/2012 16:43</td>
<td>2197</td>
<td>288.010</td>
<td>0.773</td>
</tr>
<tr>
<td>05/12/2012 16:49</td>
<td>1738</td>
<td>294.084</td>
<td>0.770</td>
</tr>
<tr>
<td>05/12/2012 16:56</td>
<td>1419</td>
<td>299.646</td>
<td>0.773</td>
</tr>
<tr>
<td>05/12/2012 17:02</td>
<td>2838</td>
<td>279.706</td>
<td>0.764</td>
</tr>
<tr>
<td>05/12/2012 17:09</td>
<td>1418</td>
<td>307.571</td>
<td>0.778</td>
</tr>
<tr>
<td>05/12/2012 17:15</td>
<td>2419</td>
<td>237.262</td>
<td>0.768</td>
</tr>
<tr>
<td>05/12/2012 17:21</td>
<td>1820</td>
<td>298.827</td>
<td>0.771</td>
</tr>
</tbody>
</table>

Weighing data

Variable
plantTextId - identification code of plant (Barcode, GR-code)

SQL
SELECT wt_data_date AS date, wt_data_value AS Weight
FROM tab_wt_plant_data
LEFT JOIN tab_plant ON tab_wt_plant_data.wt_data_idf_plant = tab_plant.plant_id
WHERE plant_textid = plantTextId;

Result set

<table>
<thead>
<tr>
<th>Date</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/12/2012 15:46</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 15:53</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 16:59</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 17:06</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 17:12</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 17:18</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 17:25</td>
<td>128</td>
</tr>
<tr>
<td>05/12/2012 17:31</td>
<td>129</td>
</tr>
</tbody>
</table>
10. Plant Registration

**Variables**

**plantTextId** - identification code of plant (Barcode, QR-code)

**SQL**

```sql
SELECT fc_data_date AS Date, fc_data_size AS "Leaf area", fc_data_fmn AS Fm, fc_data_qy_max AS Qy
FROM tab_fc_plant_data
LEFT JOIN tab_plant ON tab_fc_plant_data.fc_data_idf_plant = tab_plant.plant_id
WHERE plant_textid = plantTextId;
```

**Result set**

<table>
<thead>
<tr>
<th>Date</th>
<th>Leaf area</th>
<th>Fm</th>
<th>Qy</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/12/2012 15:43</td>
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</tr>
<tr>
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<td>2419</td>
<td>287.202</td>
<td>0.768</td>
</tr>
<tr>
<td>05/12/2012 17:21</td>
<td>1820</td>
<td>298.827</td>
<td>0.771</td>
</tr>
</tbody>
</table>

**Weighing data**

**Variable**

**plantTextId** - identification code of plant (Barcode, QR-code)

**SQL**

```sql
SELECT wt_data_date AS date, wt_data_value AS Weight
FROM tab_wt_plant_data
LEFT JOIN tab_plant ON tab_wt_plant_data.wt_data_idf_plant = tab_plant.plant_id
WHERE plant_textid = plantTextId;
```

**Result set**

<table>
<thead>
<tr>
<th>date</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/12/2012 15:46</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 15:53</td>
<td>129</td>
</tr>
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<td>05/12/2012 16:59</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 17:06</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 17:12</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 17:18</td>
<td>129</td>
</tr>
<tr>
<td>05/12/2012 17:25</td>
<td>128</td>
</tr>
<tr>
<td>05/12/2012 17:31</td>
<td>129</td>
</tr>
</tbody>
</table>
PlantScreen Detailed Technical Specifications

TRANSPORT SYSTEM

Pot holder:
The holder can accommodate a pot with diameter of 21 cm at the top and 16 cm at the bottom. Its height is 27 cm. The holder is made from non-toxic durable plastic material and is assembled from three parts:

- The bottom part is a plastic rectangular with dimension of 30 x 30 cm. It includes 4 RFID tags for identification. Tags are attached to the bottom part; each side has one tag. There is a drain hole in the center of the bottom part.
- Middle part: There are plastic legs connecting the bottom and top parts. They allow sliding on conveyor belt side bars.
- The top part is made from blue plastic (marine blue). There is one hole with diameter of 21 cm. The pot is to be positioned from the top.

The middle part contains only four legs so as to allow free air moving. Each pot has a bar code attached on its side, which is very convenient for easy barcode reading. The holder construction, which is assembled from three parts, allows cheap and flexible manufacture that can be easily adjusted according to customer’s needs. We are able to cut plastic desk on our water jet cutter and big series can be produced in cooperation with a sub-supplying company.

Only the bottom part has to have the same dimension for each pot. Length of legs can be modified to use pots with different height and the top part can have a hole with different diameter. Maximum diameter is 21 cm.

The adapter which changes the diameter of 21 cm to different sizes is inserted into holder. It is also possible to build a tray with matrix for small pots where only the ground must be of 30 x 30 cm dimension. The tray can accommodate 16 pots with volume of 200 ml each.

PSI has developed and produced its own trays for the PlantScreen high throughput system. Used materials are stable in various light and temperature conditions; they are non-toxic and resistant to abrasion. The use of 4 RFID tags allows using the holder in all positions and manipulation mistakes are thus eliminated.
Figure 1: Pot holder
Figure 2: Holder picture

Transport System:
The transport system includes conveyor belt lines. There is a loop through the measuring part and two lines for moving plants between the growing and measuring part. PSI cooperates with the following specialist for conveyor systems and aluminum profile systems:

Haberkorn Ulmer s.r.o.
Generála Vlachého 305
747 62 Mokré Lazce
Czech Republic
http://www.haberkorn.cz/en

Habekorn Company builds constructions from German aluminum profile systems:
http://www.item24.be/
Belgium Partner:

PEC products n.v.
Technologielaan 12
3001 LeuvenTel.: +32 / 16 / 398 355
Fax.: +32 / 16 / 403 445
item(at)peccorp.com
www.pec.be

Motion components are supplied by the Raveomotion Company. The company produces and distributes various components for motion, like motors, gearboxes and controllers for industrial application.

http://www.raveo.cz/en/node/4

Motors and gear box are supplied from:

![Transtecno Logo](image)

Conveyor belts use 3 phase asynchronous motors with a gearbox. Power range is 200 W – 1000 W depending on position in transport system.

Gearbox for buffer is supplied by:

**WORMGEARBOXES CM**

Gear box for accuracy positioning (transport line, image line) is supplied by:

**BEVEL HELICAL GEARBOXES CMB**

Cultivation Cabinet

<table>
<thead>
<tr>
<th>Totally</th>
<th>360 plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel lines</td>
<td>16</td>
</tr>
<tr>
<td>In one line</td>
<td>23 plants</td>
</tr>
<tr>
<td>Distance between centers of lines</td>
<td>720 mm</td>
</tr>
</tbody>
</table>
FIFO buffer (first in / first out)

A separate driver for each motor allows moving plants between lines independently on measuring protocol.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line width</td>
<td>320 mm</td>
</tr>
<tr>
<td>Line length</td>
<td>7500 mm</td>
</tr>
<tr>
<td>Free space for one plant</td>
<td>960 mm2</td>
</tr>
<tr>
<td>Load capacity for one line</td>
<td>130 kg</td>
</tr>
<tr>
<td>Motor</td>
<td>3 phase, 3x400V</td>
</tr>
<tr>
<td>Gear box</td>
<td>1:15</td>
</tr>
<tr>
<td>Speed</td>
<td>0.15 m.s⁻¹ (9 m.min⁻¹)</td>
</tr>
</tbody>
</table>

**Figure 3: Situation Scheme**

**Conveyor crossing and curves:**

Buffer and image lines are 80 cm high from ground to belt and have a simple construction: frame, conveyor belt with motor, and gearbox. Each line has two sensors at the beginning and at the end.
The transport line is built from two parallel conveyor belts; there is a space in between them for three motorized rollers and lifting equipment. The position of the belt is lower than in the buffer lines. The difference is 20 mm.

Sequence of the process during which the holder moves from buffer or image line:

- The pneumatic valves lift rollers
- The rollers rotate at the same speed and direction as the belt
- The holder is moved to the same level until the sensor is reached
- The belt and the rollers stop
- The rollers move down and the holder is positioned to the conveyor of transport line
- The holder is moved by the transport belt to a target position

Sequence of the process during which the holder moves to buffer or image line:

- The holder reaches the sensor corresponding with target line
- The transport belt stops
- Rollers with holders are lifted up
- The rollers are moved by the belt until they reach the sensor
- The rollers are moved down

Figure 4: Conveyor belt buffer line, image line
Figure 5: Lines crossing, side view

Figure 6: Line crossing top view
The orientation of plants is maintained during movement. The conveyors need minimum space.


Figure 7: Conveyor curve picture from PlantScreen

The installed controllers allow changing motors direction in buffer and transport line and so it is possible to move plants between lines without moving through image station independently on running protocol.
Control System:

Transport system and camera movement are controlled by central PLC: OMRON. Industrial components from OMRON are used in the system. Omron is a Japanese company. The European headquarters and manufacture site is located in Netherlands.

**OMRON Europe B.V. (OMCE/OEE-HQ)**

Wegalaan 67-69 2132 JD Hoofddorp The Netherlands
TEL: 31-23-568-1400  FAX: 31-23-568-1388
European regional office

**Components**

- Central processor unit: CJ2M-CPU33
- Digital I/O max: 2 560 points
- Program memory: 20 k word
- Data memory: 64 k word
- I/O units max: 40

Include USB+EtherNet/IP communication, free communication slot.

High accuracy positioning via OMRON MECHATROLINK-II max 16 axis

PLC communicates with supervisor PC via Ethernet 100Mb/s.

**Extension modules:**

- Digital Input
- Digital Output transistor/relay
- Analog Input/ Output 4-20 mA, 0-10V, -10 – 10 V
- Temperature sensors Pt1000, Pt100, PTC
- Position controller

**Sensors:**

System use optical sensors from Omron:

- E3Z - universal optical sensor, Through beam
- E3ZLS - diffuse reflectance (background suppression)

Pneumatic piston and pneumatic component made by Festo.

Sensors for pneumatic piston Festo.

Inductive and capacity sensors are used.
Measuring Station:

Measuring stations include three light-isolated measuring chambers. There are fast moving doors with open close cycle < 3s on the input, output and in between the chambers.

Free space 1,5m x 1,5m (h x w).

A plant is moved on the conveyer belt to measuring position. Optical sensors indicate its correct position.

Fluorescence/ Thermo imaging and hyperspectral box are very similar in their construction. The cabinet contains a frame which can accommodate fixed cameras or a robotic system for scanning. The system can hold different components for future enh

The RFID and barcode reader for identification of plant and light curtain are positioned at the beginning of the image line.

The identification system uses a product from http://www.automation.datalogic.com

RFID reader Cobalt HF
   Reading distance 2 – 20 cm.
   Communication via RS485.

Barcode reader: Matrix 210TM that allows reading 1D and 2D codes, QR code etc. It also includes LED light for reading in poor light conditions. Communication is via RS485.

Light curtain OMRON F3EM2
   Measuring range: 1500 mm
   Resolution: 5 mm

The curtain measures the highest point, which is used for calculation of the proper camera position. At the same time, the control program calculates the width of a plant (from the time that is taken by a plant to proceed via the light curtain).

One light curtain brings information about two plant dimensions: height and width.
WEIGHING AND WATERING STATION

The station weigh holder with a single pot. Maximum load is 7 kg pot + plant + holder. All components have at least IP 66 protection. The station has protection against splashing water, soil and dust. Weight is saved to database. If watering is used, newly reached value is saved too. The system is capable of automatic calibration of the zero point before measuring and also of recalibration by using a special holder with accuracy known mass. This process is automatic. A user must put the holder to loading space and choose calibration process in the supervising program. After the calibration process, new constants are saved and ready to be used.

Weighing accuracy: 1 g for load in the range of 0 – 7 kg

Operation programmable in protocol:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Description</th>
<th>Time for Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nothing</td>
<td>Holders move through without stop</td>
<td>0 s</td>
</tr>
<tr>
<td>Weight</td>
<td>Weight holder, information saved to Database</td>
<td>10 s</td>
</tr>
<tr>
<td>Watering</td>
<td>Add defined amount of water to each pot</td>
<td>Depend on amount, max 20 s</td>
</tr>
<tr>
<td>Weight and watering</td>
<td>Weighing before watering, save to DB. Adding to target value individual for each pot or the same for all pots from the batch. Target value can be modified in running experiment. Calculation from actual mass. Adding percentage from actual mass.</td>
<td>Depend on amount, max 25 s</td>
</tr>
</tbody>
</table>

Weighing station contains:

- Separately controlled conveyor belt with motor and position sensor
- 4 load cells
- Frame
- Communication with PLC and supervisor computer
The conveyor belt is mounted on four load cells, one in each corner. The belt can move independently up and down in range of µm. If a plant reaches center position, the belt stops and measuring can start. Each load cell is similar to UTILCELL®.


Load cell UTILCELL Model 240

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity</td>
<td>5 kg</td>
</tr>
<tr>
<td>Accuracy class</td>
<td>4000 n.OIML</td>
</tr>
<tr>
<td>Minimum dead load</td>
<td>0 % Ln</td>
</tr>
<tr>
<td>Service load</td>
<td>120 % Ln</td>
</tr>
<tr>
<td>Safe load limit</td>
<td>150 % Ln</td>
</tr>
<tr>
<td>Total error</td>
<td>≤± 0.013 % Sn</td>
</tr>
<tr>
<td>Repeatability error</td>
<td>≤± 0.01 % Sn</td>
</tr>
<tr>
<td>Temperature effect on zero</td>
<td>≤± 0.01 % Sn/5K</td>
</tr>
<tr>
<td>Temperature effect on sensitivity</td>
<td>≤± 0.006 % Sn/5K</td>
</tr>
<tr>
<td>Creep error (30 minutes)</td>
<td>≤± 0.012 % Sn</td>
</tr>
<tr>
<td>Temperature compensation</td>
<td>-10 ...+40 °C</td>
</tr>
<tr>
<td>Temperature limits</td>
<td>-20 ...+70 °C</td>
</tr>
<tr>
<td>Nominal sensitivity (Sn)</td>
<td>2 ± 10 %</td>
</tr>
<tr>
<td>Nominal input voltage</td>
<td>10 V</td>
</tr>
</tbody>
</table>
Maximum input voltage | 15 V  
Input impedance | 400 ± 20 Ω  
Output impedance | 350 ± 3 Ω  
No load output | <± 2  
Insulation resistance | >5000 MΩ  
Maximum deflection (at Ln) | 0.2 – 0.4 mm  
Protection | IP 66

The station includes a separate control box with electronic components and Digital analog convertor for load cells. D/A convertor is placed close to load cells so as to minimize cable length. Short cables reduce noises on wire and measuring is more accurate. Signals from cells are converted and send to the main PLC via RS485 Modbus RTU protocol.

Digital/Analog convertor DAT 400

The convertor is intended for industrial application and has a microprocessor with up to 6 sensors with 4 or 6 wire connections. It has two serial interfaces, analog output, 2/2 digital I/O and the ability of mathematic functions.


| Exciting supply | 5 V  
| Current load | 90 mA |
Conversion response | 50x/second
---|---
Sensibility | 0,02 µV/div
Linearity | < 0,01 %
Temperature effect | < 0,001 % from range / °C
Convertor A/D | 24 bits
Filter | 0,5 – 25 Hz
Discernment | 1x, 2x, 5x
Decimal point | 0; 0,0 ; 0,000
Calibration method | From PC or front keyboard
Power supply | 24 VDC ± 15%
Output interface | RS-232, RS-422, RS-485
Standard protocol | Modbus RTU
Transmission speed | 2400, 9600, 19200, 38400 baud
The watering station includes:
- Pipes on pneumatic arm
- Manually adjustable distance, height and angle between the pipes and steam
- Pneumatic piston
- Solenoid valves, float control unit, pipes
- Ready for automatic mixing station

All components are made from durable, non-toxic plastic material. Used valves are RainBird 100-HV-F 24V 1” (flow regulation) or similar.

The watering station cooperates with the weighing station. The pneumatic arm moves nozzle close to steam and electrically controlled solenoid valve puts accurate amount of water. The amount of water is set via a programmable protocol. If an empty holder is detected, by weight holder with mass lower than adjustable level, the information is written to database. Watering is then blocked for this actual pot and the holder is moved out.

If it is not possible to reach preset weight in standard time, error is signalized. Watering is interrupted and actual weight with error is saved to database.

If higher mass then set is weight before watering information is written to database and watering is blocked for actual pot and holder is moved out.

The position of nozzle can be set manually in two dimensions and angles. It is possible to set height in the range of -10 to +20 cm and distance from the center of the belt in the range -10 to 20 cm. Each leg can be positioned separately so it is possible to set distance and angle between nozzle and stem. Front side of the frame close to the conveyor belt is protected by a wall made of plastic material.

It is recommended to have a drain close to watering station. Emergency tank is placed under the station with connection to drain. High water level is signalized. If water reaches to emergency level, then watering is blocked.
Figure 10: Watering station

The nozzle is made of plastic material. The nozzle is formed by a pipe mounted on a pneumatic arm; the jet (dimension of 60 x 8 mm) is positioned at its end. At the opposite side, the pipe is connected to and input pipe via a fast click lock. It is possible to change pipes with nozzle; the design can be modified in cooperation with customers in future. Different nozzle can be used for different pots.

The system can be extended using a second nozzle from the opposite site. The parameters for both nozzles are then the same. This option is useful if a larger splash area is used or if the same amount of water should be applied in shorter time.
If very dry soil is manipulated and the difference between the actual and set value is too big, the watering can be applied in cycles with pauses. In this case the water amount can be extended and more time may be provided for soil to saturate water.

Variety of medium source:
- Water line; requirements 3 bar pressure, flow rate 3L/min
- Pumping from a barrel; requirements for pump: 3 bar pressure, flow rate 3L/min
- Automatic mixing station; the station includes: barrel, pump, source of water, and liquid medium.

If only water from line with pressure is used, no additional pumps are needed.

As an option, the system can use either the water line, or solution from barrel, or both possibilities. Then more solenoid valves must be installed and a user can choose if watering only with water or with added solution. The automatic mixing station includes all this components and possibilities.

**RGB IMAGE STATION**

Image station collects color picture in high resolution from three cameras from top, side and front. Data are collected in a database; if the database is not accessible then they are saved to a local disc. Image station is light isolated with its own light source. The system can measure plants with maximum dimension 1,5 x 1,5 x 1,5 m (w, h, l).

PSI has developed its own software for RGB image processing and morphology analysis. Morphological parameters:
- Leaf area
- Leaf perimeter
- Solidity / Compactness
- Eccentricity / Roundness
- Bounding box
- Equivalent circle diameter
- And many others
- Time for one scan <10 s
The system comprises of:

- Image box (light isolated)
- Conveyor belt and sensor indicating the pot in target position
- Three RGB cameras with lens
- Light sources
- Software for collecting, analyzing and representing measured data

Figure 11: RGB image station front view
Figure 12: RGB imaging station side view
Camera holders are universal, variety of cameras and lens can be mounted. Cameras have at least 10 Mpx resolution. The camera can be supplied with filters. It is possible to enhance the system and to install in future cameras and lens with improved parameters. USB and Ethernet cameras can be supplied on request. A user can opt for the camera and lens according to his preference.
We offer for example:

**Camera:** Lumenera corporation 10.7 Megapixel USB 2.0 Camera Lw 11059.


<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Sensor</td>
<td>43.3mm (diagonal), color 36.1 24.0 mm array</td>
</tr>
<tr>
<td>Effective Pixels</td>
<td>4008x2672, 9.0 µm square pixels</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>5fps</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Excellent</td>
</tr>
<tr>
<td>Exposure</td>
<td>Manual &amp; Auto</td>
</tr>
<tr>
<td>White Balance</td>
<td>Manual &amp; Auto</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>65 dB</td>
</tr>
<tr>
<td>Bits Resolution</td>
<td>12 bits</td>
</tr>
<tr>
<td>On-Board Memory</td>
<td>32 MB, 2 frames in full resolution</td>
</tr>
<tr>
<td>Dimension</td>
<td>3.25 x 2.98 x 5.59 inches</td>
</tr>
<tr>
<td>Mass</td>
<td>850 g</td>
</tr>
<tr>
<td>Communication</td>
<td>USB 2.0</td>
</tr>
<tr>
<td>Lens Mount</td>
<td>Canon-mount</td>
</tr>
</tbody>
</table>
**Figure 14**: Color response curve, source: Lw11059 datasheet, Lumenera cor.

**Lens**: Basically, depends on the type of camera and application. Different objectives with specified parameters can be used. Installing a motorized lens is possible.
We offer for example:

![Diagram of a lens with dimensions and specifications]

### SPECIFICATION

**FULL SIZE FORMAT LENS**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Length</td>
<td>268mm</td>
</tr>
<tr>
<td>Max Diameter主观</td>
<td>F 2.8</td>
</tr>
<tr>
<td>Iris Range</td>
<td>F 2.8-16</td>
</tr>
<tr>
<td>Sensor Size</td>
<td>43.2mm</td>
</tr>
<tr>
<td>Minimum Focus Distance</td>
<td>3.3m (換算約 65.5mm)</td>
</tr>
<tr>
<td>TV Distortion</td>
<td>0.7%</td>
</tr>
<tr>
<td>Flang Back</td>
<td>46.5mm in air</td>
</tr>
<tr>
<td>Filter Screw size</td>
<td>M29x1.0, 1.25</td>
</tr>
<tr>
<td>Front Aperture</td>
<td>35.0/37.4</td>
</tr>
<tr>
<td>Mount</td>
<td>Nikon F Mount</td>
</tr>
<tr>
<td>Weight</td>
<td>362g (キャップ未装)</td>
</tr>
</tbody>
</table>

NOTE: Specifications and availability are subject to change without notice.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>09.08.18</td>
<td>LM20L F</td>
</tr>
<tr>
<td>05.09.18</td>
<td></td>
</tr>
</tbody>
</table>

F2.8/26mm
Lights:

The light source is manufactured by the PSI and is mounted with white LEDs.


Light parameters: cool white

Due to the dimension of the box and distance between the cameras and object, one camera is mounted on linear guide. After a plant is in the requested position, the camera is moved down to proceed measuring. After measuring is finished, the camera is moved up and the plant can move out of the image box. The measured plant does not touch the camera objective; the objective is kept clear. Moving up and down takes less than 2 s.

The conveyor belt is built from separate parts. As an option the central part can be changed for a turning platform with a lift. The turning platform enables 3D reconstruction from images.

As an option, the image box can be supplied with an arm carrying cameras and 3D scanner, which is turned around a plant. In this option, the plant is stable while the camera is moving. As the camera can turn faster than the plant, the time required for one scan is shorter.

HYPERSPECTRAL IMAGING

The image station contains VNIR and SWIR camera with a light source. The camera with its light source moves above plant and scans line by line the whole plant.

The system includes:

- Light isolated measuring box
- Automatic doors at each side (in and out)
- Conveyor belt for plant transport into the measuring station
- Automatic lifting system for camera focus (controlled from central PLC)
- Light source
- SWIR and VNIR camera
- PC with measuring and analysis software
- Linear guide with motor mounted in the lifting frame
- VNIR camera:

<table>
<thead>
<tr>
<th>HEADWALL PHOTONIC Hyperspec® VNIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
</tr>
<tr>
<td>Aperture</td>
</tr>
<tr>
<td>Dispersion per pixel</td>
</tr>
<tr>
<td>Slit Width</td>
</tr>
<tr>
<td>Slit Length</td>
</tr>
<tr>
<td>Spectral Bands</td>
</tr>
<tr>
<td>Spatial Bands</td>
</tr>
<tr>
<td>Detector</td>
</tr>
<tr>
<td>Dynamic Range</td>
</tr>
<tr>
<td>Frame Rates (fps)</td>
</tr>
<tr>
<td>Pixel Pitch (microns)</td>
</tr>
<tr>
<td>Read A/D</td>
</tr>
<tr>
<td>Binning</td>
</tr>
<tr>
<td>Communication</td>
</tr>
<tr>
<td>Weight</td>
</tr>
</tbody>
</table>

**SWIR Camera:**

<table>
<thead>
<tr>
<th>HEADWALL PHOTONIC Hyperspec SWIR®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
</tr>
<tr>
<td>Aperture</td>
</tr>
<tr>
<td>Dispersion per pixel</td>
</tr>
<tr>
<td>Slit Width</td>
</tr>
<tr>
<td>Slit Length</td>
</tr>
<tr>
<td>Spectral Bands</td>
</tr>
</tbody>
</table>
The broadband light source is made by the PSI. The Light source is positioned in between the cameras.

When a plant reaches measuring position, the situation is indicated by a sensor. Both doors are then closed and the frame with the camera moves to proper focusing position. The plant is scanned by the VNIR camera in one direction and then by the SWIR camera in an opposite direction. The chamber contains space for calibration lane for automatic calibration.

A user can choose protocols measuring with one of SWIR, VNIR or with both cameras.

Time for measuring:

- VNIR camera use only: 15 s
- SWIR camera use only: 15 s
- Protocol in which both cameras are used: 30 s
Figure 15: Hyperspectral box front view

Figure 16: Hyperspectral box side view
FLUORESCENCE IMAGING

Fluorescence imaging is offered as an option. It uses the same box and equipment like the thermal imaging station. In one time, it is possible use only one measuring system.

Measuring process: A plant is moved on the conveyor belt to target position. Light panel with the camera can move up and down to the position calculated from the plant height and focal length.

Fluorescence measuring uses modification of the FluorCam FC-800MF manufactured by the PSI


The system includes:

- Light-isolated measuring box
- Automatic doors at each side (in and out)
- Conveyor belt for plant transportation into the measuring space
Automatic lifting system for camera focusing (connected with PLC control system)
- Light source
- 8 position filter wheel included in the camera
- PC with measuring and analysis software

Light panel dimension is 1800 x 1800 mm (w x l), the area of light homogeneity is 1500 x 1500 mm. Light intensity can reach up to 5000 µmol m⁻²s⁻¹. Lifting system allow the camera and light to move in the range of 2000 mm. The system can scan variety of plants, from a young low plants to maximum plant height of 1,5 m. The light panel with camera is mounted to linear guide. Two synchronous motors with break and feedback allow high precision positioning and fast moving to desired position.

Measured parameters: FO, FM, FV, FO', FM', FV', FT
Calculated parameters: FV/FM, FV'/FM', PhiPSII, NPQ, qN, qP, Rfd
Measured and calculated parameters depend on the used protocol.
Measuring time depends on the used protocol. The fastest protocols like Fv/Fm lasts less than 10 s.
Measuring chambers dimension: 2,5 x 2,7 x 4,0 (l x w x h) m

Figure 18: Fluorescence image cabinet front view
Figure 19: Fluorescence image cabinet side view
Figure 20: Fluorescence image cabinet top view
THERMAL IMAGING

Thermal imaging is offered as an option. It uses the same box and equipment like the fluorescence imaging station. In one time, it is possible use only one measuring system.

The frame holds a different light source and different camera. A plant is moved on the conveyor belt to target position. Light panel with camera move up and down to the position calculated from plant height and focal length.

Thermal imaging station enables the study of heating of the samples during irradiation by light.

**Camera FLIR SC645**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>640x480 pixels</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-20 to +120°C</td>
</tr>
<tr>
<td>Thermal sensitivity /NETD</td>
<td>&lt; 0.05°C at +30°C / 50 mK</td>
</tr>
<tr>
<td>Spectral range</td>
<td>uncooled microbolometer with a range of 7.5-13 micrometers</td>
</tr>
<tr>
<td>Accuracy of measurement</td>
<td>±2°C</td>
</tr>
<tr>
<td>Resolution of image</td>
<td>16 bits</td>
</tr>
</tbody>
</table>

The system includes a light panel for illumination of samples with adjustable intensity from 0 to 500 µmo m-2s-1 in increments of 1% and range from 0 to 100%. The light source is made by the Photon Systems Instruments.

ENVIRONMENTAL MEASUREMENTS

The PLC allows connecting variety of sensors. These sensors can be connected via standard industrial electric signals.

Voltage: 0–10V; -10-10V; 0–5V; 1–5V; -5–5V; 0-1,25V;
Current: 0 – 20 mA, 4 – 20 mA
Temperature sensors: Pt100, Pt1000, JPt100, Thermocouple K,J,T,L,R,S,B
Resolution: 1/4000;1/8000;1/64000;1/256000
Digital Input: 24 VDC, 240 VAC
Pulse Input, counters: 50kHz, 500 kp/s
For using smart sensors or decentralized system, it is possible to use serial communication like: RS-232, RS-485, RS-422, Ethernet 100 Base-Tx, CAN, CompoNet, CompoBus, Controller link.

Protocols: ModBus RTU, ASCII, TCP; Ethernet TCP/IP, UDP; DeviceNet; CompoNet; PROFINET-IO; FINS/UDP; CompoWay-F; Host link; User protocol.

PLC with I/O and communication units is an interface between process and supervisor PC. PLC sends process information to the server, which saves data to a database. PLC can be equipped with a Flash memory card with capacity 512MB and thus log information if server is not connected.

Minimum sampling period for sensor reading and data saving is 1 s. Sampling period can be set via Supervisor program. The system can save all data and then process their averaging, maximum / minimum value in interval...

A user can use his own sensors with standard industrial signals or the Photon Systems Instruments Company can deliver required amount and type of sensors with the system.

**SPRAYING**

Spraying is offered as an option and it serves for automatic spraying plants by water or other solution, like pesticides. The spraying system is located on the conveyor belt. Plants are moved for spraying automatically and it is possible to control the process from supervisor program.

All components have at least IP 65 protection.

The system includes:

- Conveyor belt
- Spray
- High pressure pump
- Solenoid valves
- Pipes
- Tank for solution
- Connection to water supply
- Waste reservoir
Figure 21: Spraying station

Spraying bars are separated to four parts. The information about the height of plants is used to control which parts of sprayer will be used. In this way, the amount of used solution can be economized (for a small plant only bottom part of the sprayer is used). The system is connected to clear water and its automatic cleaning in desired intervals can be set. The tank for solution is equipped with a level sensor, which indicates time for adding a new solution. All components are made from durable plastic material.
LOCAL INSTALLATION REQUIREMENTS

Power supply: 3+N+PE, AC 50Hz, 400V, 3x230V/100A
Compressed air: 10bar, 100 L/min. It is possible to deliver a separate compressor.
Water: > 3bar, 20L/min
Waste: Possibility to connect it to a drain system, only clear water, moister or solution from watering or spraying are drained

Space needed in the control room or somewhere outside the greenhouse for control cabinet installation.
Control cabinet dimension: 2000 x 2000 x 300 mm (w x h x l)mm
Ethernet connection with VPN for remote service and support.

INFORMATICS SYSTEM

Based on Central supervisor PC. Separate PCs are in the image stations and DataBase server. Computers communicated via 1Mbit Ethernet network and TCP/IP. Informatics system runs on Windows.
It is possible to integrate our informatics system into existing informatics system. The system can cooperate with existing databases.

Supervisor PC
To control process and to communicate with PLC. It is also used for changing data between technologies and information systems; it runs measuring protocols. The operator communicates with the machine via GUI, which primary runs on this computer in the control room. Remote clients can be connected. Clients can work with their protocols. Service interventions are possible only from local machine or via a special service client.

PSI cooperates on graphic design with its customers because each customer is unique requirements.

Basic level is the same. The first screen brings information about the system, its actual state, the most important control buttons, information about the image station, live picture from the technology. Next pages bring: protocol view, protocol edit, measuring data, measuring stations setting, manual control, service, alarms, logs...
Protocol:
The system uses graphic interface for protocol writing.

Figure 22: First page from the PSI’s PlantsSreen system

Figure 23: Protocol edit page
Basic functions are:

“Measuring”

A user can choose from list of measuring station, which will be used in the actual step:

- Hyperspectral SWIR
- Hyperspectral VNIR
- RGB all cameras
- Weight
- Watering
- Weight + Watering

Optionally:
- Fluorescence/Thermal imaging
- Spraying

In one cycle, a user can choose all types of measuring, or just some of them, or none of them. For each measuring different protocol can be chosen.

“Delay”

A user can choose delay between single steps.

- Absolute delay – waits for defined day time
- Relative delay – waits defined time from the last step
- Relative delay with date – waits for day and time defined, allow starting the experiment in defined day and time

These options allow scheduling experiment start at the same time of day, or starting experiments with defined delays between them.

“Repeat”

Includes two settings:

- Counter – how many times
- Step – from which step the next round will start

This function works like a loop. A user defines Starting point in an experiment and the end point is defined by Repeat. A user defines how many times will be the loop repeated. The loop can be repeated endlessly and stopped manually.
A protocol can be saved to a file or loaded from a file. It can be paused in running or cancelled. If a protocol is cancelled during its running, and if pots are not in the growing part in starting position, the system automatically moves all pots into starting position without stops. Every time, pots go in the same sequence if not changed before the protocol start.

A protocol can be written or modified in remote client and then saved to file in the Supervisor PC and then runs from this file.

**Pot and Batch Selection**

The system allows making batches from pots in growing chambers. Each batch can has own independent protocol. If two batches have planned measuring cycle at same time, an error occurs.

The system can serve for more users that will do different experiments with different plants.

---

**Buffer Control Screen**

![Buffer Control Screen](image)

**Figure 24: GUI buffer display**

On buffer screen, it is displayed the growing buffer with all positions.

- **Green** – position is occupied by plant
- **Gray** – free position
- **Red** – line error, line cannot be used
- **Yellow** – batch
Click on the position and information like: ID, barcode, notes, batch competency, date when pots was added to system is displayed.
Batch can be modified and it is possible to choose one or all batches.
Multiple selection via Ctr+clic or Drag and drop is possible.
The closest line to image station can be used for temporary plant. Temporary plants are put from loading space. One batch contains only temporary plants. This batch runs its own separate protocol with same rules like regular batch.

Option function: For temporary plants can be used transport lines, but then this plant block starting measuring action in protocol. Warning appears when line is blocked and measuring in protocol is planned.

If the closest line is empty it is possible to move plants between the lines independently on running experiment. If no experiment is running, it is possible to use image line for the same function.
Individual plant or batch can be chosen and transported to a loading space where it can be removed. Extra plants can be added to the system if there is space enough. Actual occupation is displayed on the supervisor screen.

A user can choose free line in which he plans to put new pots before starting filling process. If no line is chosen, the system automatically put pots to free lines.

**PCs in Image Station**
Some image stations, which need a lot of computing power and which calculate results in real time, like the fluorescence station, have their own PC that communicates with the supervisor PC. Measured results are saved in local discs and then sent to database.

**DATABASE COMPUTER**
Database machine is a server PC with capacity at least 10 TB. The MySQL database version 5.5.22 or higher is used. Standard TCP is used.

It is possible to integrate this system into current informatics network. The system can cooperate with central server and send data to central server.

All measured data are stored into a relational MySQL database. It is possible to search the measured data by selected parameters. The user may select the necessary data for its processing.
Number of measurements depends on the size of storage space. It is possible to record up to 1000 measurements on 200 gigabytes.

The server saves all data from the following processes:

- Measuring data, images, setting of measurement equipment
- Alarms, warnings
- Data from environment sensors
- Protocols

Users can see and work with data via programs which can analyze image data, drawing trends, plot results in time. It is possible to do the same experiment in long period and then see data in time. Measuring data are identified by unique ID.
Figure 25: Basic database structure
BASIC DATABASE STRUCTURE:

Preparing an Experiment

A user operates handheld barcode and RFID reader to put a new holder and pots into the system. Each item can have its own description. Each item includes the day when was put into the system. It is possible to edit information about plants that are included in the system.

Plants with holders are put on the belt in loading space. A user can choose which line will be used. Loading pots are moved through RFID and barcode sensor and settled in a chosen line. The system gets information about each pot location.

Data Structure

The system data, like image data, weight etc., have same structure.
“ImageStationName-HolderID-PotID-DateTime.xxx”

Example from the PlantScreen system:
Local disc content file “PlantScreenResult” with files “RGB1-Tray scan 16-12-10-2011-6-25-03-AM.png”
RGB1 – identify image station and camera
Tray scan16 – name of tray
12-10-2011-6-25-03-AM – date and time

Data name structure can be modified according to customer’s requirements.

Power Failure

The PLC has a part of permanent memory. This memory part includes information about the system before power failure. After the system is powered on again, it is able to continue from the same step.

PC and informatics system have UPS to save actual state into permanent memory. After power is on, the PC can continue from the last saved step.

If measuring protocol runs before power failure, the protocol can either continue or all pots can move to a starting position. Imaging, which is running when power fail and cannot be finished, can start again when the power is back.

Time of power failure with code of error is written into a log file.

UPS parameters: at least 1000 W in 5 minutes.
Messages

The system can send emails with errors, warnings or actual state to a predefined address. If the system includes a GSM module, it can send short messages with errors independently on main power and Ethernet connection.

FUTURE EXPANSION

The system is designed for updates in future and for adding new functionalities if there is free space in the greenhouse. One or more growing lines can be modified to measuring lines. The PLC has much free capacity. If more complex system will be required, decentralized structure with two or more PLC’s can be used. Communication capacity is much bigger then direct I/O.

It is possible to add a new PC into the basic information system. Thus the data storage capacity can be significantly increased.

Updates and software repairs are free. Adding new functionality, which is not described in this document, will depend on a separate contract.

PSI is committed to the future development of this system.

SERVICES AND SUPPORT

24 hour online support by phone or email
Remote VPN connection for remote software support
Free updates
Separate service contract

SAFETY REQUIREMENTS

System and all parts comply with laws and regulations concerning safety and health.

Include Machinery Directivity (2006/42/EG)

• Low Voltage Directivity (73/23/EEG)
SAFETY FEATURES

Emergency stops are accessible from each part of system. There are sensors on the door or light curtain; these sensors stop the system when someone enters the inside part. All moving parts are isolated from the space where users are intended to stand and/or to manipulate with pots.

Controlled Cultivation Environments for Plant Phenomic Screening

PSI designs and builds high-capacity growth chambers (Fytotrons) which allow researchers to program controlled growing conditions, with accurate measurements and regulation of temperature, irradiation cycles and relative humidity. The Fytotrons may contain either conveyor-based or robotic imaging systems, or may incorporate conveyor systems that transport the plants from the Fytotron to a Plant Screen imaging system. The chambers must allow a range of programmed day / night cycles with wavelengths and other conditions regulated for dawn / dusk transitions.

The following description relates to a Fytotron facility installed at the University of Olomouc in the Czech Republic. Numerous sizes, configurations and specifications of Fytotrons may be built to suit a client’s specific requirements. Automated intelligent greenhouses are also available from PSI, custom-designed for the client.

Dimensions

| Growth areas:                  | Cultivation facility including automated hydroponic nutrient delivery is equipped with two floors, in which each floor is divided into four parts. There eight growth areas available as a whole. LED panels provide lights to the lower shelf, and more LED panels in the ceiling of the Fytotron provide light to plants on the upper shelf. |
| Internal dimensions:           | 6.750m (w) x 5.265m (d) x 2.800 \( m \) (h). |
| External dimensions:           | 7.200 m (width of row) x 5.775m (d) x 3.900m (h) |
| Growth area:                   | 9.5 m\(^2\) |
| Growth height:                 | Minimum 2.0 m from the base of plants up to the lower edges of lights. |
| Temperature range:             | Selected by client |
| Stability: Turning the lights On / Off: | ± 1°C |
| Regularity: Turning the lights On / Off: | ± 2°C |
Lighting: Each growth area has its own control unit with independent control and regulation.
Maximum Irradiance: 1000 μmol/m2/s at 30 cm from the lights.
Regulation Range: 0% to 100% of maximum in 1% increments. Light intensity is controlled in software for each growth area individually over its entire range.
Humidity Range: 40% RH. – 80% RH.

Insulation

Interior surfaces

Covering layer of sandwich panels consisting of hot-dipped galvanized steel sheet painted with powder coating. This ensures a hygienically smooth and durable surface even on inaccessible edges, and also perfect corrosion protection.

Exterior

The Fytotron chamber is composed of modular layered panels with a thickness of 80 mm consisting of an inner layer of foam polyurethane on a substrate of galvanized steel sheet painted with a white powder coat. The connection of panels (floors, walls, ceiling) is engineered using a self-centering slot-key system. Eccentric clamping locks have plastic covers, and fastening hooks are protected against corrosion.

Door

Refrigerator double rotary door 1600x1970 mm. Metallic, layered with shell made of double-sided galvanized sheet. Surface-modified by polyester coat. Hue of door and frame RAL 9010 (white). The door is locked from the outside, but it is always possible to open it from inside - even when locked.

Insulation Material

Polyurethane foam. Coefficient of thermal conductivity = 0.025 W/mK.

Insulated Floor

Floor of the Fytotron are made from insulation panels covered with humidity resistant plywood and aluminum tread plate.
Temperature Control and Air Distribution System

The Fytotron is built as a low-energy device which, with year-round operation -will provide the user with significant savings in operating costs compared to conventional systems. Emphasis is placed on the following factors:

- Maintaining temperature in range of 10 to 40°C in increments of +1°C
- Maintaining a humidity in range of 40 and 80% in increments of +5%
- Maintaining a homogeneous field and air flow

Principles of Reducing Energy Input

- Maximize elimination of hydrothermal loads
- Use new low-energy technologies for air humidification
- Use new low-energy technologies for air dehumidification
- Appropriate design of elements to reduce pressure losses
- Appropriate placement of active elements to increase the system efficiency
- Use of sensors to capture all changes of monitored variables for most efficient control of environment.

Elimination of Thermal Loads

Thermal load is comprised of:

- Thermal load of lights
- Thermal load of fresh air delivery
- Thermal load of air-conditioning
- Opening of doors, movement of people ....
- Thermal load of active technologies within the FytoScope (e.g. conveyor)
MODEL A - POUŽITÍ U REGÁLOVÉHO SYSTÉMU

Schematic of Internal Circulation

A: RACK SYSTEM
MODEL B - POUŽITÍ U TECHNOLOGIE BEZ MOŽNOSTI PRŮCHODU VZDUCHU

LEGENDA

B: AIR TRANSIT

VALVE
MIXING VALVE
FILTER OF FILTRATION CLASS BY THE (EN779)
ELECTRIC HEATER
WATER COOLER
HIGH CAPACITY COOLER
FRESH AIR
DEVALUED AIR
REGENERATION AIR
WET AIR
DRY AIR
WATER STEAM
PRE-MODIFIED WATER
Cooling

For the production of cold water, there is a compact air-cooled chiller designed with scroll compressor and reverse valve (heating function). R410A is used as a refrigerant. Year-round efficiency of the E.S.E.E.R cooling machine is around 4 (W / W). The device is equipped with regulation for winter cooling operation at low temperatures.

Cooling medium is cold water containing 35% ethylene glycol. In order to ensure the maximum cooling effect, each Fytotron chamber has its own cooler. As opposed to the central device, this cooler allows independent control of two parameters of coolant:

a) Mass flow rate regulation by three-way valves
b) Temperature gradient of water to reduce the share of fixed cooling energy during periods of high indoor temperature and relative humidity. At low water temperature, unwanted dehumidification and loss of energy takes place, because the exhaust air from the radiator requires rehumidification.

Fresh Air Supply

Fresh air supply is necessary within the Fytoscope, but causes a hydrothermal load. By optimizing air flow rate the energy cost of supply can be reduced up to by 30%. Fresh air is drawn through the primary filters G4 (according to EN779), then its temperature is modified to the desired temperature. Its humidity is not modified by preheating and condensation. Air is filtered by the second stage of G7 filtration (according to EN779). Excess fresh air is exhausted through a HEPA filter H14 (according to EN779) with prefiltet G7 (according to EN779). It is transported by pipeline to the outside area. The entire inlet and outlet of fresh air is controlled by a central MaR system that monitors the temperature of the supply air, sedimentation of all levels of filtration and operation of fans (with warning s for unusual operation).

Elimination of Pressure Losses

The use of large cooling exchangers reduces energy losses. The construction of large aluminum groins and copper waterways results in minimum pressure loss up to 10 Pa on the air side, and thereby facilitates the use of transport ventilators for circulation of air with low pressure.

Design of fans without a spiral box and with blades curved backwards also contributes to high efficiency with low power consumption. More fans are used to ensure even distribution of air in the cooled wall. This also ensures even flow over the large-area exchangers.
Flow rate through the heat exchangers is small (up to 0.2 m / s) compared to the flow of heat exchangers for common air conditioning systems,

(up to 3 m/s). Condensate flows into an open condensate tank, so there is no risk of entrainment by air flow and use of drop eliminators, which would increases pressure losses in the system. Another benefit is the reduction of radiated heat due to fan air flow.

Required cooling capacity of 10 kW at an annual effectivity of cooling source E.S.E.E.R = 4.0 results in a consumption of 2.5 kW, equal to 21 900 kWh per year

Additional Reduction of heat load of 3.0 kW at an annual effectivity of cooling source E.S.E.E.R = 4.0 results in consumption of 0.75 kW, equal to 6 570 kWh per year

The energy consumption for ventilation (1040 m3 / h) is 0.4 kW per year equal tp 3 504 kWh

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Hydroponic Tables</th>
<th>Conveyor Belt</th>
<th>XYZ Robotic System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input of Lights</td>
<td>10</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Cooling of lights</td>
<td>10074</td>
<td>12264</td>
<td>6132</td>
</tr>
<tr>
<td>Consumption of electric motors</td>
<td>454</td>
<td>544</td>
<td>272</td>
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<tr>
<td>Cooling</td>
<td>21900</td>
<td>26280</td>
<td>13140</td>
</tr>
<tr>
<td>Saving of kWh / year</td>
<td>11372</td>
<td>13472</td>
<td>6736</td>
</tr>
</tbody>
</table>

Note: Savings refer to year-round operation of cooling at the given input of lights and E.S.E.E.R. = 4. Contribution of cooling pump to total consumption for cooling is not assumed. Additional savings of 100 kWh can be achieved by regulating of the air flow with regard to outside temperature.
Lighting Systems

Two sets of LED banks within the Fytotron allow for two levels of cultivation. One set of banks is located in the ceiling, and the other above the lower cultivation area. The LEDs produce very little irradiant heat. The thermal load from cooling the panels themselves is dissipated by the efficient heat exchange system that removes up to 70% of thermal load. This represents a significant cost savings compared to standard methods of cooling.

LED Lamps

- Intensity of irradiance min. 1000μmol m-2s-1 at a distance of 1.0 m.
- White with supplemental IR. Spectral range from 430 to 730 nm.
- Simulation of light modes (e.g. fluctuation, clouds, day, night, dawn, dusk, etc.).
- Operation modes - continuous light, harmonically modulated light, user-modulated light.
- Light dimensions 800 mm x 270 mm
- Light radiates minimum thermal energy.
- Inhomogenity of light max. ± 5%.
- Can be set in maximum increment of 0.5% or 2 μmol m-2s-1.
- Independent regulation of the intensity of white light and IR.
- Radiating angle of light max 10°.
- The light is thermally insulated from its own chamber.
- Lifetime of LED modules at least 90 000 hours at 1% tolerance of defective diodes.
The range of used LEDs

Light spectrum
Each growth area in the Fytotron is equipped with its own lighting module. Light intensity of each growth area is controllable independently from all other growth areas. Lighting is adjustable with small increments from 0 – 100%.

All lighting units in the Fytotron are controlled so that all the lamps comply with the same day and night cycles of exposure, and start-up periods corresponding with dawn and dusk.

Lighting units are made out of stainless steel to resist corrosion and to have a long service life. Surfaces illuminated by light modules are painted white, to ensure maximum utilization of the light output and to ensure regularity of illumination.

Notice: When working in a Fytotron with lights on, use protective goggles.

Grain Growth Under LED Lighting

The following photos show the gradual evolution of grain grown under LED lighting (WHITE + IR) in the Fytoscope. Pictures were taken at the same time each day.
Humidification System and Humidity Regulation

Low-Energy Humidification System
An ultrasonic humidification system is used in the Fytotron. By comparison, conventional team humidification requires nine times more energy-intensive or the same result. Another advantage of water vapour produced by ultrasound is its low temperature, which eliminates excessive condensation. As a result there is no formation of mineral deposits from minerals contained in the water. The ultrasonic humidifier operates on the principle of high frequency vibration of metal membranes that create an ultra-fine mist during contact with the water surface. The water must be sterilized in advance, using UV filtration, to prevent the release of microorganisms into the air. Water vapor moves through distributors into the stream of circulating air, after heat treatment to ensure the required humidity of supply air.

The total costs of humidification depends on the RH conditions chosen by the user. However, it is possible to compare the total cost of operation with other systems.

<table>
<thead>
<tr>
<th></th>
<th>Steam Humidification</th>
<th>Water Jets</th>
<th>Air Pressure Jets</th>
<th>Ultrasound</th>
</tr>
</thead>
<tbody>
<tr>
<td>For 18 kg of water</td>
<td>input (W)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13 500</td>
<td>2 700</td>
<td>2 250</td>
<td>1 440</td>
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<tr>
<td>Estimated cost per year</td>
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<td>$3154 US</td>
<td>$2628 US</td>
<td>$1665 US</td>
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<tr>
<td>Estimated cost for 5 years</td>
<td>$78840 US</td>
<td>$15768 US</td>
<td>$13140 US</td>
<td>$8326 US</td>
</tr>
</tbody>
</table>
Adsorption Dehumidification System

An important element in the reduction of energy costs is the use of an adsorption method of dehumidification. A Dehuter-rotor technology is used in which water vapour from chamber air is absorbed into rotary heat exchanger plates formed from high absorption materials. After the plates are saturated by moist air, regeneration takes place through dehydration by dry regenerative air that dehumidifies the rotor blades. Regeneration rate (6-10 x / h) is determined individually and controlled by an automatic measuring and regulation system. This system operates at low temperatures and high efficiency compared to conventional dehumidification based on condensation saving up to 50% of energy costs.

Air Filtration

HEPA Filtration for Exhaust Air

- Each zone of the Fytotron is delivered with a connection for exhaust air duct.
- Piping system is designed so that it is possible to perform volumetric tests of all filters used to filter the exhaust air from the Fytotron.
- The air leaving the Fytotron is filtered according to the requirements of the GMO2.
- The outlet pipe of the ventilation system includes a HEPA filter.
- The device is designed to measure pressure losses on the filter. If the pressure value indicates that the filter has reached its maximum of recommended pressure drop, it activates a warning signal and the filter must be replaced.
- The filter is installed in a special box equipped with gel seal and appropriate pre-filter.
- The filter is exchanged securely from the inside of the chamber. The technician is protected from contact with pollutants that may be found on the surface of filter.
- Fan on the output system has controllable speed to allow the chamber to maintain specific constant pressure with respect to exterior pressure.

HEPA Filtration of Supply Air

- Each zone of the Fytotron has a connection for air supply with a mounted special box for an inlet filter equipped with gel seal.
- Piping system is designed to allow volumetric tests on all filters used.
- The air coming into the Fytotron is filtered according to user requirements to prevent contact of samples with outdoor contaminantst (insects, dust, pollen). Filtering occurs in accordance with GMO2.
The inlet duct ventilation system includes a HEPA filter.

The device is designed to measure pressure losses on the filter. If the pressure value indicates that the filter has reached its maximum of recommended pressure drop, it activates a warning signal and the filter must be replaced.

The filter is installed in a special box equipped with gel seal and an appropriate prefilter.

The filter is exchanged securely from outside of the chamber. The area above the chamber is designed to allow easy service during which the internal environment of the Fytotron is protected from contact with outdoor concentrations of pollutants that may be found on the surface of the filter.

Fan of the input system: If the pressure value indicates that the filter has reached its maximum of recommended pressure drop, it activates a warning signal and the filter must be replaced.

Management Software, Data Acquisition and Storage

Control software

Software is installed on a PC, which is installed with the Fytotron.

- Compatible with Microsoft Windows© operating system including Windows 95/98/NT/2000/ME/XP.
- Communicates with control panels of Fytotrons via Ethernet / LAN system.
- Password configured for permitted-user access only.
- Allows users to change protocols remotely.
- Generates reports with current conditions and error messages.
- Generates email notification about Fytotron status and error messages.
- Graphical display of temperature, humidity and light intensity and analysis.

Main Screen

Shows actual and preset values of temperature, relative humidity and individual lights. Graph shows curves of all measured functions.
Graph Screen

Screen depicts curves of all the quantities from the last 30 minutes to 12 hours (depending on setup). Actual set temperature is plotted on the main Y axis. The secondary axis displays relative humidity (actual and set) and light. Quantum yield ($Q_Y$) is presented at a detached axis on the left next to the temperature.
Individual parameters display can be turned on/off by ticking the check boxes. A Reset graph button deletes all recorded curves in the graph and a new curve projection starts. This does not affect saved data. A Full screen button switches the graph into a Full-Screen mode.

Full-screen mode enables a more detailed graphical presentation of data. Data are divided into two graphs for greater clarity. The upper graph presents temperature (set and actual) and relative humidity (set and actual). The bottom graph shows all light data and the time-course of fluorescence (QY), if measured.

Protocol Screen
A Protocol tab enables the user to set the cultivation conditions. The protocol can be very simple, such as unchanging parameters during the whole experiment, or it can involve diurnal changes in light, temperature and humidity that simulate complex changes in the natural environment. Each protocol can be saved to a file and opened again later.

The FluorPen
The FluorPen is an optional device to take spot measurements (not images) of chlorophyll fluorescence kinetics. Readings from the FluorPen can be viewed and stored in the FytoScope software. If the FluorPen is connected to the FytoScope and switched on during the program, it is recognized by the program and a tab Pen appears in the main menu. The FluorPen measures only steady state fluorescence (Ft) and quantum yield (QY) when in on-line mode.
The Pen tab has control features for the FluorPen use:

**Get QY** – starts fluorescence kinetics measurements. The measurement of QY takes several seconds. Afterwards measured values and measure time appear in the cells Last measured QY, Last measured Ft, and Last measure Time.

**Start Auto and Stop Auto** – Allows measurements to be carried out continuously, regularly, and within a particular period. The period of an automatic measurement is set in the Measure period cell. The period is entered in minutes. By touching Start auto and Stop auto buttons, an automated sequence of readings is started or stopped. The current state of the protocol is displayed in the State cell.

Read values of QY and Ft are added to a list on the left in the Pen tab, both during automatic and manual measurement. Values are display in the graph in the Main tab.

**Clear List** – erases the chart with measured values in the Pen tab (it does not affect stored data).