MELiSSA

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ABBREVIATIONS

MELiSSA	Micro-Ecological Life Support System Alternative
HMI	Human Machine Interface
HPC	Higher Plant Compartment
PSDU	Plant Stress Detection Unit

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1 Definition of a preliminary design

For plant-level monitoring, a dedicated system is proposed to follow up on plant growth performance. Such a system will detect deviations from optimal development which would lead to suboptimal quality, insufficient quantity or delayed harvest of plant derived fresh food products. Gas phase and liquid phase (nutrient) composition monitoring coupled with non-contact growth, temperature and light use efficiency visualisation within a HPC are proposed to represent, after the needed integration, a performant system for continuous plant growth assessment.

Referring to TN 89.55 – Plant stress response: Consolidated Requirements Document, the different aspects are assessed in the following text, with reference to the available HPC1 hardware documentation.

The HPC1 (MPP – located at the Universitat Autònoma de Barcelona (UAB) system is equipped with the necessary systems for atmosphere monitoring and associated CO_2 assimilation – NCER (net carbon exchange rate) calculations [1]. On-line ethylene (and possibly other VOC) measurement capability is straightforward to add to the HPC air sampling and return loop. An extra hydrocarbon free air gas bottle for automatic calibration purposes will ensure. The detector module (30x40x5cm) could be placed in the same environment as the CO_2 and O_2 detectors already interfaced with the HPC1 prototype.

Logging of nutrient solution pH, EC and H_2O (condensate) evolution and volume additions are also established [1,2]. Such continuous monitoring has the potential of giving a first indication of changes in (root) growth response. Nutrient solution composition analysis is foreseen off-line.

On-line weight measurements using load-cells positioned under NFT gullies permits to have an average measurement of the weight of several plants, and to detect changes in the flowrate of the individual gullies. Weight measurement on gullies will most probably be difficult to achieve within the given HPC1 setup without modification to the conveyor system (perhaps a subsystem with loadcells could lift the trays slightly when they are in place. and lower them again when new tray needs to be added to the conveyor). Measurement of leaf area will however already give an approximation of biomass increase along the growth period. In addition weight measurement is evidently less likely to be considered for a system to be developed for (considerably) reduced gravity.

The gathered experience from the UGent-HSB PSDU system setup can be used to define the needs for data logging associated with techniques that can be added to the current HPC1 functionality. To obtain this goal, unit and sub-unit design of the withheld solutions need to be studied in detail to allow accommodation in the MELiSSA HPC prototype.

Such a generic plant stress detection/health monitoring unit, consisting of the online gas phase and non-contact plant monitoring plus the associated offline analytical and destructive monitoring techniques, (which complement the online observations by either enabling to corroborate or to further elucidate the cause of the seen effects) will safeguard food production of stable quality and quantity, and could after extensive testing possibly be integrated into the control strategy approach of the HPC chamber. At first some aspects are proposed to function as stand-alone systems, integration being limited to issuing of alarms and supervision by the MPP Control system interface (HMI).

1.1 Scenarios for the integration of the PSDU in to the MELiSSA HPC pilot plant.

The MELiSSA Pilot Plant located at the UAB premises
http://www.esa.int/SPECIALS/Melissa/SEMZLJ8RR1F_0.html
will in the near future integrate a Higher Plant Chamber (HPC) developed at the University of Guelph (UoG), which is designated as compartment IVb.
MELiSSA partner Sherpa Engineering was consulted regarding the control and integration aspects of the Higher Plant Compartment in the MPP, needed to assess the possibilities of interfacing of robotised systems available on the market or implemented at UGent-HSB.
Sherpa Engineering further contacted NTE SA who is involved in managing the system architecture of the MPP control network. A preliminary MPP schematic and robot/camera connection scenario was provided by NTE SA, on which Figure 9 was based.
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and further elaborated to yield Figure 9.

To accommodate a PSDU system in the MPP HPC, first of all the PSDU specifications have to be matched to the MPP hardware (dimensional) specifics, including space and functional restraints. The interface specifications are central to the possibility of incorporating the PSDU unit or particular subunits into the control or monitoring strategy of the HPC within the MPP.

The MPP is designed to drive plant growth with high efficiency. Light being one of the key factors, the allocated plant growth space height of 80cm allows to accommodate the proposed

MELiSSA crops, while keeping the plant-light distance reasonably small to obtain a light intensity that ensures efficient biomass and thus food production [2].
Therefore integrating the PSDU monitoring unit should not lead to a need for an increased plant-light distance nor structural changes that would affect light homogeneity at the plant level. A mobile system inspired of the main vertical frame of the PSDU, consisting of linear motion axis made of extruded aluminium, will likely accommodate these requirements.

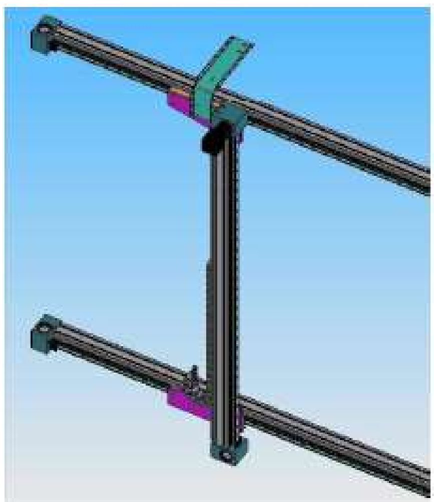

Figure 1: Basic frame of the PSDU workbench demonstrator design: double synchronized axis moving single axis with mobile carriage.

Using this concept, the basic frame of a XY mobile system has to be assembled in 1 piece (5x1m) and inserted through the air-lock.
The needed floor space for the operation needs to be assessed, as well as the needed procedures for temporary moving the chamber within the dedicated building space.
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The target area to be monitored is 5 m^2; crop height would tentatively be limited to 50cm, on the presumption that available dwarf varieties of the current MELiSSA 9 crop selection list (potato, rice, wheat, soybean as staple crops and beet, lettuce, onion, spinach and tomato as salad crops) can be successfully cultivated.

Concerning actuators and motors, high speed movements are not needed for this type of application, which alleviates the need for associated structural reinforcement constraints for the HPC.

1.2 Considerations for the accommodation of a PSDU in the HPC1

1.2.1 Optimal use of available space

At the basis of the monitoring system choice and dimensioning (strength) is the camera type, and associated optical equipment. Visual spectrum sensitive cameras (CMOS based) with good resolution (1024x1024 pixels) are available in sizes of 50x50x50mm, excluding the lens.
The choice of a miniature (approximately 30x30x50mm) low-resolution (128x128pixels) thermal camera, as used for the workbench demonstrator, proved to yield usable images from a point of view of whole plant visualisation and within-plant heterogeneity detection.

The plant growth space inside the prototype HPC chamber measures 5m x 1m x 0.8m height. The PSDU preliminary design should not interfere with the subsystems of the HPC1 prototype and more in particular with their dedicated sensors and control mechanisms [3].
Energy consumption for movement should be limited, also interference with air mixing within the plant growth volume should be avoided. Interference with manual access to the plant growth volume for cleaning and maintenance should also be minimized.

1.2.2 Non-destructive monitoring

The growth of the plants within the HPC is monitored by a fixed video camera (visual spectrum) and gives an overview of the plant growth. In addition a window in the middle module provides a direct view. Given the size and dimensions of the chamber (1m width on 5m length) a (high resolution) camera at each en could provide more detail.

Plant-level imaging using different camera systems monitoring each a key factor of plant physiology will however need a certain level of automation, with added mass and energy needs, since static arrays of camera's still have several drawbacks. Taking into account the geometry of the chamber, a classic industrial 6-axis robot will be unable to cover the whole growth area (as also mentioned in TN 89.4 conceptual design) and would need a translational stage to move it. The same holds for the typically more miniaturized SCARA robot type. A SCARA (Selective Compliant Assembly Robot Arm or Selective Compliant Articulated Robot Arm) is a 4 axis robot characterized by a single fixation point http://www.peakrobotics.com/Semi_Custom_Robots.htm.

In the conceptual design, these above approaches were not followed given the weight penalty of such a standard system. In addition and specifically for the HPC1 integration, single-point mounting of such a robot would need a special reinforced structure and would interfere with optimal light distribution or tray conveyor system.

1.2.3 Adjustment to plant growth

In order for the system to take in-focus images (with a similar field of view, depending on the allowable depth of field of the employed systems) a (possibly automatic) method to adjust distance from camera to plant needs to be established.
In the workbench demonstrator the robotic system (XYZ Cartesian system with rotary module) allowed to position the camera vertically among the different racks. In combination with a mathematical function describing plant growth in function of time (assuming sigmoidal plant growth), the software was modified to automatically increase the distance of the camera form the plant gully in order to keep the distance camera-top part of crop constant.
The workbench demonstrator was however built into an existing growth room of 2x2 m surface, and employed plant growing racks at different heights to accommodate a sufficient number of plants to validate stress detection. The tests of the conceptual design were of batch-type with all plants being transplanted at the same time, to allow for a statistical comparison of control and treatment plants.

Since the HPC is designed according to the PPU (plant production unit) strategy, with staged culture setup to provide continuous harvest, the preliminary PSDU design should be adjusted to the associated needs and constraints. The HPC1 is equipped with a conveyer system on which mobile plant trays are mounted. The air-lock access ports at each end allow the insertion of newly transplanted seedlings and the harvest of mature crops.

As a consequence of the staged culture setup, plant height increases from the seedling side of the HPC to the mature plant side. Plant growth in function of time generally displays a sigmoidal tendency. As the first phase of growth (propagation after germination) is carried out in a separated chamber in order to allow selection of seedlings with equal stature and vigour, the vegetative phase can approximate linear growth, which will then level off as the plant matures. This is especially applicable to seed and tuber producing species.

An inclinable cartesian system (using a manually or electromotor actuated pulley system) could be a solution of the structural strength of the XY system would allow such a setup. This is to be determined by FEM (finite elements) mechanical calculations. In addition a fixable joint could be added to adjust the camera field of view to be planparallel with the plants

1.2.4 Mechanical layout

To minimize mass and size of a PSDU monitoring system, its vertical positioning range can be minimised or not implemented, by adjusting the orientation of the main XY frame, if that proves feasible with regards to structure and fixing within the HPC1 structure.

Alternatively a dedicated distance measuring system can be implemented, incorporating ultrasonic or light guides (see [7] to [9]). Such systems are however, according to a preliminary assessment of available data and experience, prone to error based on the complex structure of plants, which makes it difficult to obtain a correct reading of plant height unless a very high-resolution scanning would be carried out, which does not match well with a measurement on a plant area of 5x1m with a large number of plants.

An XY translational system would in theory cover all points within the growing area, however for technical and assembly reasons this cannot be achieved (see the discussion below on the dimension of the carriages carrying the transverse axis on which the cameras are mentioned). To alleviate this problem, a rotary module could be added to the XY translation system (see Figure 2 for the rotary system used on the PSDU workbench demonstrator. With camera's or sensors mounted at predefined angular positions and with a distance to its centre corresponding to the extra reach needed to provide images of the first and last tray as well as the first and last plant in each tray.

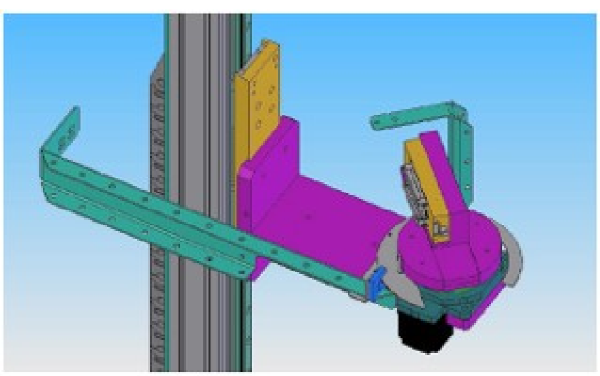

Figure 2: Rotary module with motor of the PSDU workbench demonstrator design

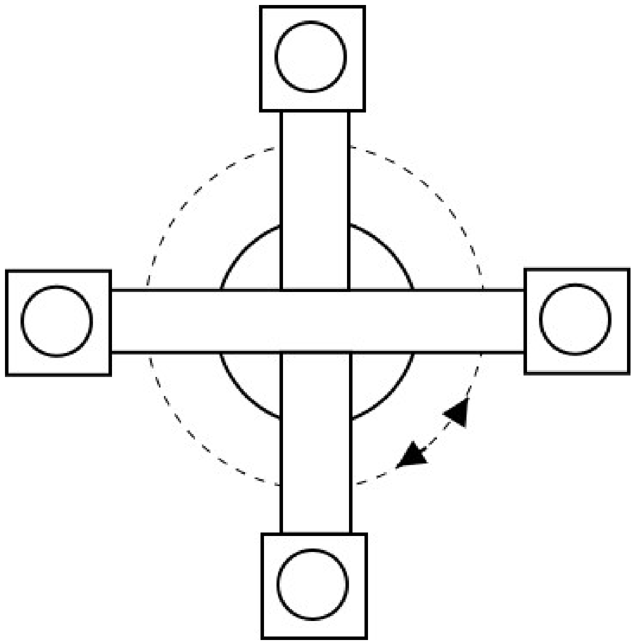

Figure 3: Possible arrangement of different sensors on a rotary module.

From the preliminary data below, a distance of 100 to 150mm would be sufficient, thus yielding a measuring head with 200 to 300 mm diameter with camera's illumination and other sensors that needs to be rotated depending on the position reached (programming issue dependent on defined grid for imaging). In Figure 3 the camera length and width are set to 50mm.

The light-shading effect and mass of the system should be minimised as much as possible, by minimising the size of components (especially rotary platform and connecting profiles), and adding white LEDS for compensating illumination on the 40mmx20mm connecting profiles and the rotary module.

For a first presentation of the preliminary design, information from one constructor is used below: Berger Lahr (Schneider-electric-motion) toothed belt driven linear motion axes made of extruded aluminium are used to assemble the PSDU preliminary design [4]. Similar hardware can be obtained from a number of other providers e.g. [5].

Figure 4: Double axes layout with shaft driven support axis

Berger Lahr (Schneider-electric-motion) MAXS2B double axis layout uses a synchronisation connection (Figure 4). This module consists of 2 PAS42BR linear axis of 5m length (Figure 7). The carriages of these 2 parallel axis will carry a single PAS41BR axis of 1m length (Figure 5).

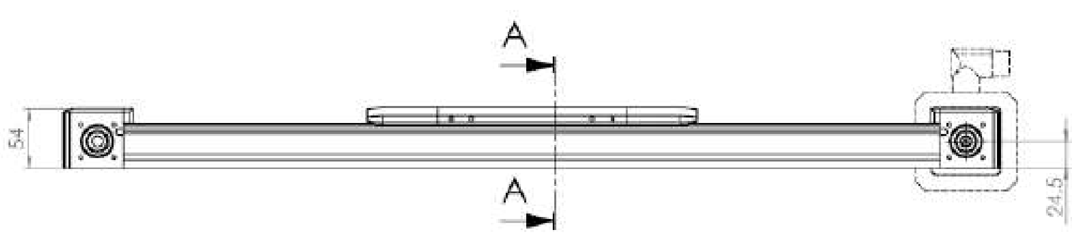

Figure 5: PAS41BR linear axis side view

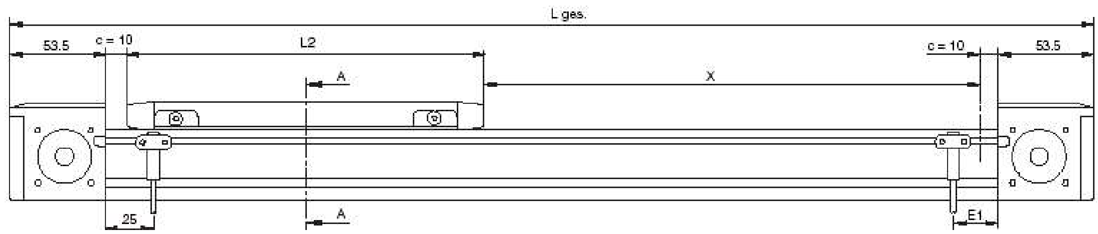

Figure 6: PAS41BR linear axis technical drawing

The PAS41BR linear axis has a 40x40mm cross section, a maximal stroke of 3000mm and a typical load of 6kg. Weight per meter of axis: 2.25 kg/m. The carriage length L2 equals 200mm (Figure 6).

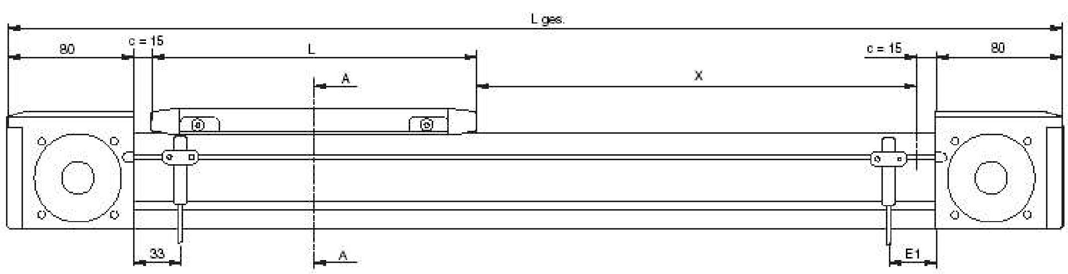

Figure 7: PAS42BR linear axis technical drawing

The PAS42BR linear axis has a 60x60mm cross section, a maximal stroke of 5500mm, a typical load of 12kg. Weight per meter of axis: 4.55 kg/m. The carriage has an effective length L2 = 206 (see figure 7).

The resulting 2 dimensional system will consist of a double X-axis of 5m length and a single Y axis of 1m..
The more simple and marginally lighter MAXH2BR double axes layout with support axis has a maximum distance between axes of 400mm and is thus unusable for this application.The MAXS2B Double axes with shaft driven support axis layout meets the requirements for buiding an XY system in the HPC1 plant growth space.
The toothed belt driven double axes system with a transmission shaft has a weight per meter of axis:specification of 9 kg/m – 2 axes (see 4.55 kg/m for 1 PAS42BR axis)
Both types of toothed belt axis have a +-0.1mm repeat accuracy which is sufficient for the needed spatial reproducibility of the image capture.
The axis ends of both types of axis represent an exclusion zone of movement: positioning is possible up to 20cm from the edge of each axis, assuming central mounting of a camera on the carriage of the Y axis.

The movement of the Linear Motion axis modules is typically ensured by stepping motors. Each motor (or a pair of motors) is associated to a motor drive which controls its power. A motion controller (PLC type controller) executes the robot positioning program by steering the motor controller(s).

Choices of the control system are dependent on the strategy to be developed:

1. all based on Ethernet + industrial Ethernet (Ethernet-IP, Profinet etc)
2. other industrial bus protocols (Profibus, CAN, Devicenet).

A Supervisory Control (Calculation) and Data Acquisition SCADA system with SCADA software consists of an HMI Supervisory system (control room supervisor PC), a middle layer with PLCs, connected by Ethernet to the supervisory system, and a Fieldbus architecture level which links the PLCs to components such as sensors, actuators, electric motors, console lights, switches, valves and contactors. Several current fieldbus protocols are compatible with Ethernet cabling network (e.g. Profinet, Ethernet/IP).
The HMI/SCADA iFIX system used at the MPP is developed by GEFanuc
http://www.gefanuc.com/as_en/products_solutions/hmi_scada/products/proficy_ifix.html
and is a solution for visualization, control and real-time information management.

The iFIX system can be coupled to the robot control interface if drivers are available from its manufacturer.

The PSDU workbench demonstrator employed drives daisy chained (VEXTA oriental motor AlfaSTEP standalone closed loop stepper motors and associated controllers) and controlled over RS232 by a dedicated computer (ideally this would be a robust industrial or embedded PC). This is a standalone system with no interface to a supervising HMI/SCADA software system. Remote control software (vnc or rdp based) allows access to the standalonedesktop over Ethernet which would allow tasks such as scheduling of imaging.

The XYZ UGent cartesian positioning system with combined thermal and chlorophyll fluorescence imaging functions with a standalone robot position controller, with the possibility of program up and download from a dedicated PC software via the serial interface 1, also excluding interfacing with a HMI/SCADA software system. The system presented extension options such as fieldbus for network integration. The serial interface2 connects to a teach in pendant FT2000 via the RS485LS protocol. The RS232 serial interface1 sends inn operational mode I/O signals to image capturing computers.

Another alternative is the NI CompactRio http://www.ni.com/compactrio/ programmable automation controller (PAC) PACs combine programmable logic controller (PLC) ruggedness with PC functionality under an open, flexible software architecture: LabVIEW graphical programming.

The most flexible solution would be interfacing a robot controlling MELiSSA (Schneider electric) PLC to the iFIX HMI/SCADA system.

A PC can then still be connected directly to the drivers controlling the robot motors. This PC's primary function would be in-situ testing after first install and after maintenence/upgrade.

Camera control interfaces and data transfer protocols include firewire IEEE 1394, cameralink and GigE. Gigabit Ethernet provides high bandwidth image transfer via the standard Ethernet network architecture.
The PSDU workbench demonstrator employed IEEE1394 for the thermal camera and USB2 for the video cameras. Non-ruggedised cables will typically fail upon repeated bending. Dedicated robotised vision system cables are the best solution.

A dedicated computer for robot and camera control can readily be added to the MEliSSA Ethernet network of the MPP, as well as an extra workstation performing the imageprocesing and signal outputs. Interfacing possibilities with the HMI system have to be further discussed at the level of alrm generation and data presentation.

Mechanical positioning of the motor of the main translational stage needs close attention since in systems studied and built within UGent-HSB this element protrudes out of the frame and would need to be accommodated with an extra access port in the HPC shell, which if possible should be avoided.

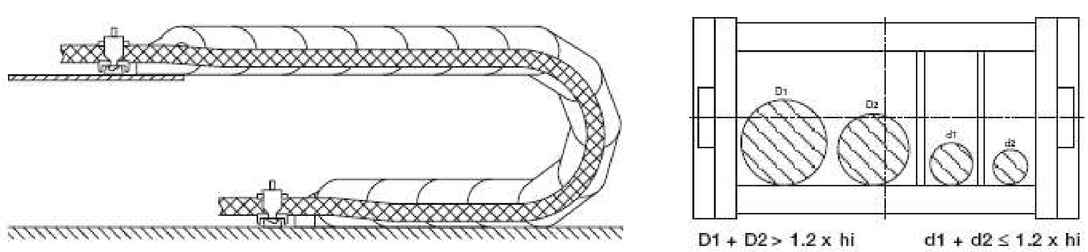

Figure 8: Cable chain layout with cables fixed by strain relief brackets, and cross-section layout with vertical separators

Guidance of motor cables and signal cables should be provided by high quality cable guides (e.g. from Igus: E-Chain [6]). In addition the camera signal and power cables should be chosen as to comply with a small bending radius and repetitive strain (e.g. Igus Chainflex cables). To avoid premature cable wear through twisting and intertwining, cables should be organised by inserting the appropriate vertical and horizontal interior separations in the cable carrier sections, and cables should be fixed at both ends of the cable carrier by tie-rapping them to strain relief brackets (see Figure 8).

1.2.5 Early monitoring and follow-up corrective action

Plant disease or transplantation-induced injury (that might have passed undetected by the operator) or most likely to be detectable when the plant is still in the first growth tray. This could still be in reach of the glove boxes.
When adhering to proper sanitation, pathogens are supposed to pose little threat given the closed air and nutrient circulation layout of the HPC1 chamber.

When in addition avoiding creating regions with excessive humidity (condensation risk) fungal growth will most likely be prevented. A **mobile humidity sensor** mounted on a robotised monitoring system can assess this parameter during crop growth trials. A **PAR sensor** could also be added to the robotised system to enable automatic mapping of the light intensity..

This is not to be seen as a replacement for the already implemented array of temperature and humidity sensors, which provide high reliability by redundancy.

Concerning mechanical installation of the PSDU preliminary design, the current PAR sensors likely have to be repositioned since they would interfere with the robotised system. Wall/shell fixation (adjustable height) at the expected canopy height would be optimal (instead of roof fixation).

A PSDU system with **plant handling capabilities** is considered a subject for future research (see also TN7). At the current level of technology, dexterity of robotic handlers is still inferior to human agility. Especially when removing plants the aspect of cross contamination will be hard to avoid by a camera-controlled robotic gripper system. Leaf or root pieces torn off during removal and even nutrient solution spread on leaves could initiate a new focus of infection.

An access door with window is available on the side of the HPC! Prototype chamber (middle compartment) to allow diseased plant removal. A human operator can better assess the need for removal based after a close inspection, triggered by the imaging expert system generated warning based on individual plant imaging by the PSDU preliminary design system..
An overview camera can be used to identify plants with slow growth, however only so at a late stage and without detailed info, hence its early warning merit is rather limited in comparison.

Further off line characterization of the threat or deficiency and further action or dedicated monitoring, and associated treatment of the harvested waste and food waste can be provided by a number of consolidated techniques.
A Q-PCR based approach in which the most important pathogenic and beneficial microorganisms in hydroponic culture are characterised can be carried out on a hydroponic solution sample without compromising the chamber closed athmosphere.
Upon sampling microbial characterisation of the rhizosphere and phyllosphere can be carried out by the same multi-microbial strain detection method.
The signatures of particular pathogens and the presence of non-microbial but sub-mm size organisms can typically be revealed by conventional or fluorescence microscopy, which will also highlight any aberrant root or shoot histology associated with suboptimal growth.

1.3 Software requirements

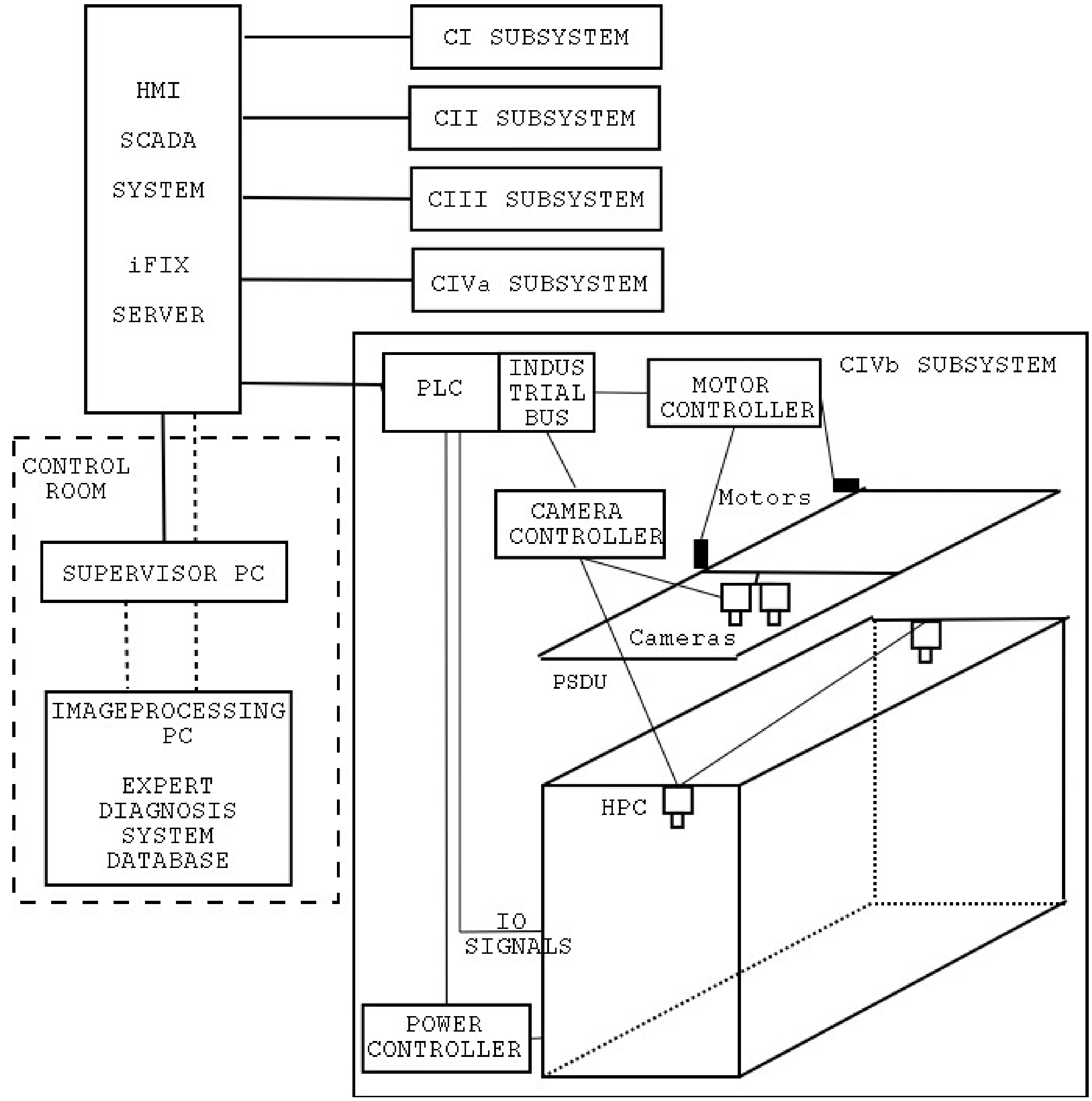

Figure 9: Possible integration of the PSDU subsystems into the MPP control and supervision strategy

This TN is a scenario for a preliminary design based on testing with the workbench demonstrator design, which was built according to the proposed conceptual design.

The conceptual design data acquisition scenario was developed in the workbench demonstrator design, by using NI Labview plus NI-IMAQ Vision.
The robot positioning and image capture software functioned as standalone on a dedicated PC system. Defining an imaging layout for time use efficiency and setting a schedule allowed for automatic hourly monitoring of 80 individual plants. The desktop with this software could be viewed from a remote location to assess its well-functioning (using VNC or RDP protocols).
More importantly the captured images are processed to an optimal resolution for combination with the lower resolution thermal images. This would typically be a processing step that could be implemented in a next generation smart-camera. Next the images are assembled into overview images (and image sequences) per unit (tray or row) for visual inspection from within dedicated web-interface. This provides a way to check that the imaging sensors function properly and that the focal distance to the plants is correct.

Robot and image capture operation can in principle be autonomous of the MPP control system, since the PSDU will, at least not in the design phase, not actively change the behaviour of the growing plants.
Integration of the robot and imaging control within the MPP control structure could eventually (after extensive testing) lead to leaf temperature or chlorophyll fluorescence being used as a short-term control parameter for plant production. Leaf area as a preliminary measure of current biomass seems a starting point for implementing a parameter to be monitored and possibly used for production control.
Some extra heat (a small amount in comparison with the continuous heat load of the lighting system) will be generated due to the motor-driven movements of the system, an amount to be calculated based on the time of functioning of the motors, and to be encompassed in the energy budget of the HPC.

To deliver trustworthy data, the thermal data have to be calibrated with respect to a temperature reference (typically one cm2) present within the field of view of the camera, taking into account the HPC1 air-loop temperature control system kinetics (see TN 89.55). Higher temperatures will typically indicate a local irrigation problem or alternatively early disease. Lower te,perature would be typically indicative of wounding or disease.
In addition, image processing will need to include noise reduction coupled to semi-automatic user-assisted shape recognition and quantification in order to provide a stress detection and warning functionality.

No special requirements were put forward for the software choice for the workbench demonstrator. A current version of NI Labview running on a recent version of the MS Windows OS complies with E40_Tailoring_baseline_for_the_HPC_UGENT.doc.

2 Conclusion

A mobile multi-camera camera avoids long-term blocking of light when operating between the main light source and plants, and permits to achieve higher resolution compared to a static camera..

After the observation step, consisting of expert assessment (human plus multi-sensor imaging coupled to a stress-classification expert-system), characterisation is needed for prompt selection of a corrective action.

The combination of non-contact PSDU preliminary design system monitoring of the plant shoots with

- atmosphere monitoring, CO_2 assimilation – NCER (net carbon exchange rate), Ethylene
- nutrient solution pH EC H_2O compensation volume input rates
- nutrient solution composition assessments

and further need-driven characterisation with

- expert system with database based on baseline and stress test runs
- Q-PCR for pathogen and stressfactors
- Microscopy for localisation or structural info

will lead to a HPC setup and protocol for growth under optimal safeguard.

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