Digital Twin of a plant factory : simulation of RGB-D data with the CPlantBox FSPM

Bouvry A.[1], Leemans V.[1], Lobet G.[2], Tocquin P.[3], Lebeau F.[1]

[1] Gembloux Agro-Bio Tech, University of Liège, [2] IBG3 Agrosphäre, Juelich Forschungzentrum, [3] InBios/Phytosystems, University of Liège

Solving occlusion issues in nadir view through data assimilation

Our phenotyping facility was designed with data robustness in mind, especially regarding image data acquisition. To adhere to this philosophy, the Kinect Azure camera was fitted **above** the growing plants, capturing RGB-D data in a **nadir point of view**.
This poses the major challenge of optical **occlusions** of lower leaves as they are cover by new leaves during plant growth (**Figure 1**).
We hypothesize that the occlusion issue can be resolved through data assimilation coupled with simulations in a FSPM, namely CPlantBox [1]. Given sufficient calibration data to fit the FSPM parameters to observations, data assimilation will fill data gaps due to occlusions. This goal requires the generation of simulated data similar to sensor data, implemented here by the means of a ray casting based approach to mimic a time-of-flight camera [2]. This enables us to generate synthetic point clouds presenting occlusions similar to those in real data.

Figure 1 - Lettuce plant in nadir view. Some leaves are already occulted by the upper leaves.

Digital Twin

To manage the vast amount of data generated by phenotyping experiments and integrate them in a coherent manner with modeling tools, we leveraged the Digital Twin (DT) conceptual framework [3]. Through its different components (**Figure 2**), it allows us to structure the research in two main parts : the **physical** and **virtual** entities. Each of those branch out in several components:
- Monitoring DT: monitoring of plants and environmental data
- Autonomous DT: regulations that make operation of the facility autonomous
- Recollection DT: integration of data over long periods of time
- Imaginary DT: modeling tools for design purposes
- Predictive DT: modeling tools to predict short and long term outcomes of growth based on environmental conditions
- Prescriptive DT: recommending actions to undertake to achieve specific goals (e.g. specific phenotype)

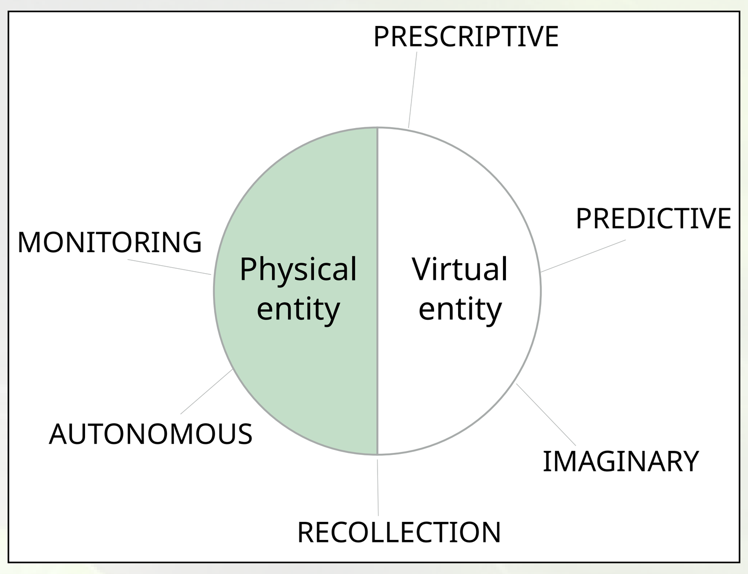


Figure 2 - Digital twin conceptual framework spread into 6 components (adapted from Verdouw et al., 2021)

PHYSICAL ENTITY

The physical entity in our Digital Twin comprises the facility itself, as well as the actuators and sensors inside it. The plants grow in a hydroponic facility with **controlled environment** (T°, RH, [CO_2], nutrient solution concentration and pH) and **customisable lighting** (PPFD, spectrum wavelength, pulse frequency, day/night cycle). All variables are measured and logged into a database, with actuators to regulate the environmental parameters.

Observations on plants include general direct observations, image data as well as continuous weight monitoring (**Figure 2**).

The integration of data and metadata is meant to occur over long time spans and several experiments, so as to massify data.

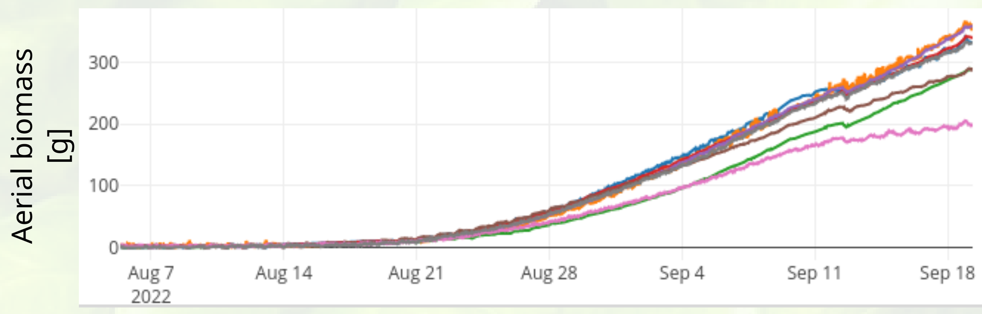
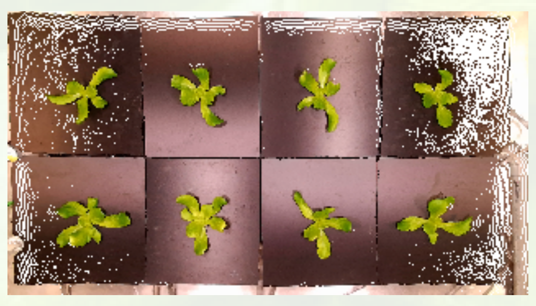


Figure 3 - Aerial biomass timeseries (*Lactuca sativa* L.).

The point clouds are in x,y,z + r,g,b format (i.e. colorized point clouds). The raw point clouds contain several plants in their field of view, thus some pre-processing (**Figure 2**) is required to extract single plants and remove the background (**Figure 3**).



Raw point clouds → Remove irrelevant data (NaN, etc.) → Convert depth to elevation → Clip single plants → Excess green index segmentation (remove background)

Figure 4 - Raw point cloud and processing workflow to extract single plant architectures.

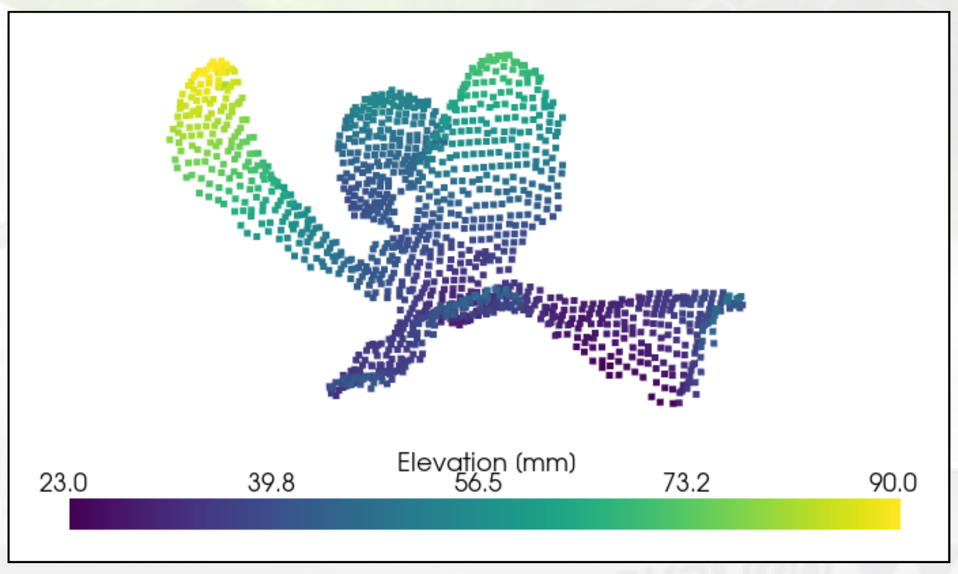


Figure 5 - Processed point cloud captured with the Kinect Azure camera in nadir view.

VIRTUAL ENTITY

Simulating plant architecture with CPlantBox

The CPlantBox FSPM stems from CRootBox, a root system modeling framework. While its focus is on simulating water and element transport in plants, we use it to simulate aerial plant architecture. The choice fell on CPlantBox because of its active development and flexibility, as well as its modeling capabilities.
The current simulation parameters represent typical young lettuce plants architecture (**Figure 6**).

Figure 6 - Example of plant architecture generated with CPlantBox.

Ray casting to simulate a time-of-flight camera

To simulate data from the Kinect time-of-flight sensor, we used a ray casting method : shooting rays from the virtual camera's pinhole to a uniform grid on the ground of the simulated scene, the algorithm detects intersections between rays and an object's surface, i.e. leaf or stem (**Figure 7**). All intersections are saved in a point cloud data structure, providing synthetic data matching the real-world 3D point clouds.
To provide point clouds similar to the real-world ones, the properties of the virtual camera are identical to those of the Kinect Azure (e.g. the number of rays cast to provide point clouds containing roughly the same number of points).

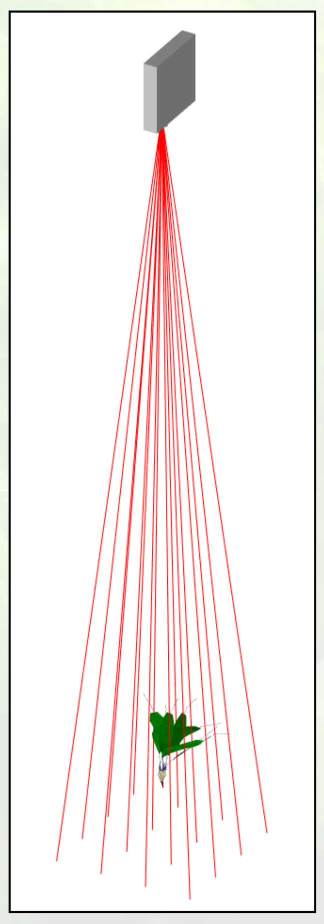


Figure 7 - Ray casting.

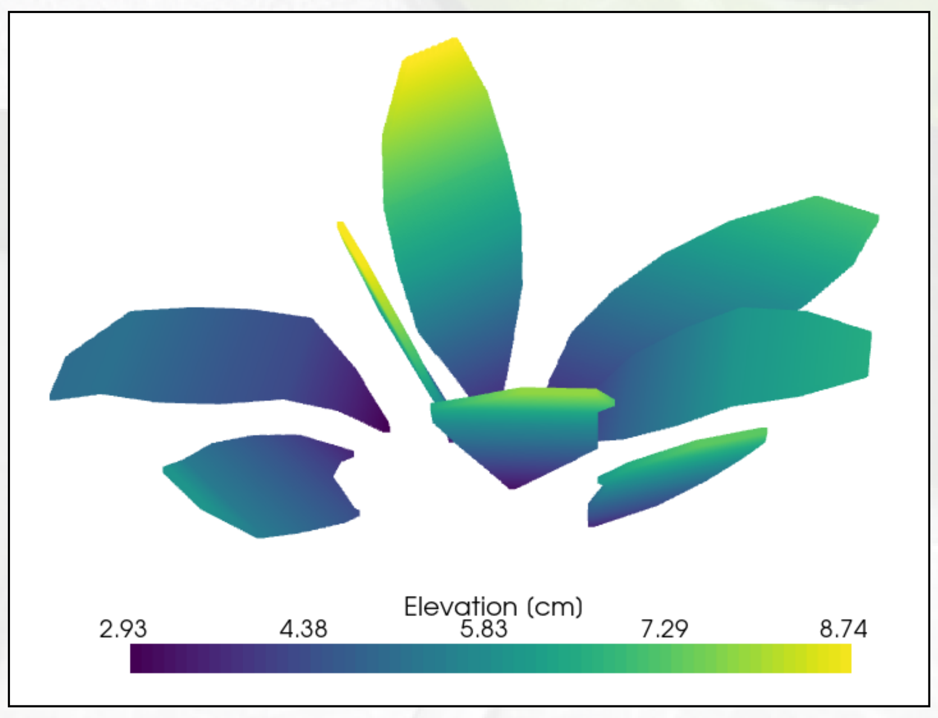


Figure 8 - Synthetic 3D point cloud generated with CPlantBox.

The workflow generates **synthetic data in accordance with real-world data** requirements and characteristics (**Figure 8**), ready to be challenged in the next phases of the project to really resolve occlusion issues. Another milestone will be to estimate biomass based on imaging data alone, thanks to a model built on both images time series and weight data.

LIÈGE université Gembloux Agro-Bio Tech

Corresponding author

Arnaud Bouvry
abouvry@uliege.be
+32 81 62 26 92
Passage de Déportés 2, B5030 Gembloux

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