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Low-Cost Embedded Multiview Stereo Vision System for Plant Phenotyping

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INTRODUCTION & AIM

Plant phenotyping enables the quantitative characterization of plant growth, morphology, and architecture [1]. Stereo vision techniques provide three-dimensional information for the non-destructive assessment of plant structural traits [2,3]. Reconstruction of plant architecture often relies on multi-view image acquisition, which may increase computational requirements and processing complexity [4].

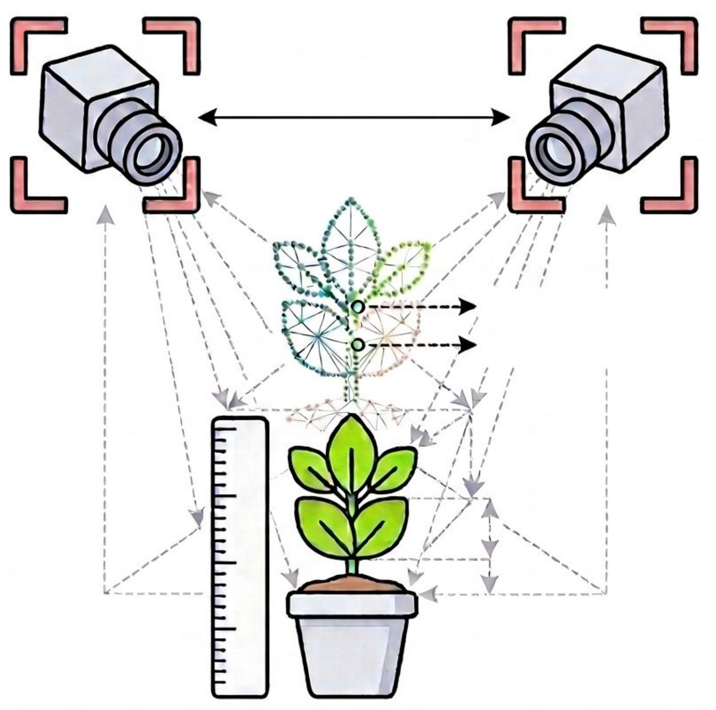

Figure 1. . Stereo vision for non-destructive three-dimensional plant phenotyping.

Aim: To evaluate a low-cost multiview stereo vision system based on ESP32-CAM modules for the estimation of plant phenotypic variables using image-based 3D information.

METHOD

Stereo image pairs were acquired using two ESP32-CAM modules configured in a hardware-synchronized master–slave architecture, with manually fixed camera parameters to ensure photogrammetric consistency. Stereo calibration was performed from 18 checkerboard image pairs, and the plant was rotated on a turntable to acquire 12 stereo views at 30° intervals. Images were rectified and processed using HSV-based segmentation and CLAHE enhancement, while depth maps were generated using Semi-Global Block Matching (SGBM) and refined with a Weighted Least Squares (WLS) filter. The resulting disparity maps were reprojected into 3D point clouds and filtered using Radius Outlier Removal (ROR) and Statistical Outlier Removal (SOR) to improve geometric consistency. Finally, local point clouds were aligned according to their acquisition angles and fused through voxel-based downsampling, generating a unified 3D model for plant height and biomass volume estimation.

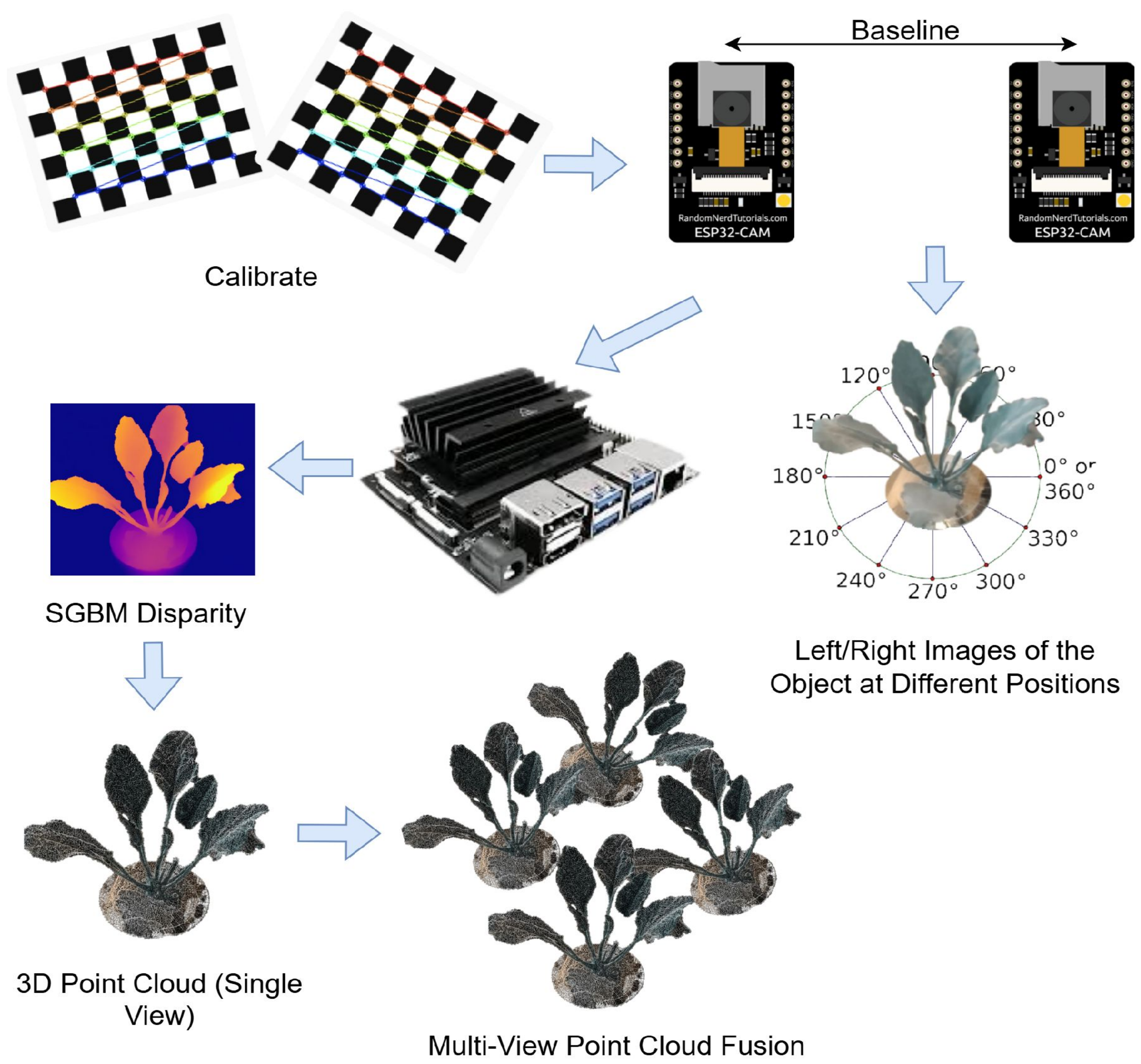

Figure 2. Multi-view stereo vision pipeline for low-cost plant phenotyping

RESULTS & DISCUSSION

Plant height was estimated from the highest point of the reconstructed 3D model, obtaining a value of 291.28 mm compared to the ground-truth measurement of 280.64 mm (3.79% relative error). Biomass volume was computed through voxelization of the fused point cloud, resulting in an estimated volume of 16,552.48 cm³ compared to 16,132.69 cm³ for the ground truth (2.60% relative error).

Table 1. Validation of phenotypic trait estimation against ground-truth measurements.

Metric	Ground Truth	ESP32-CAM	Relative Error
Height (mm)	280.64	291.28	3.79%
Biomass Volume (cm^3)	16132.69	16552.48	2.60%

These results demonstrate that the proposed low-cost multi-view stereo system provides sufficient geometric fidelity for reliable, non-destructive estimation of structural plant traits. The low relative error in plant height confirms the robustness of the reconstructed maximum vertical extent, whereas voxel-based biomass volume estimation indicates that the fused point cloud preserves the overall geometry required for accurate volumetric characterization.

CONCLUSION

The proposed methodology enables multi-view three-dimensional plant reconstruction using synchronized low-cost ESP32-CAM modules, reducing the hardware cost associated with conventional multi-view phenotyping platforms. By combining sequential stereo acquisition and point cloud fusion, the proposed system increases the geometric coverage of the reconstructed model while maintaining the accuracy required for quantitative estimation of structural plant traits

FUTURE WORK

Future work will focus on replacing sequential turntable-based acquisition with a synchronized multi-stereo network of ESP32-CAM modules. This configuration would enable simultaneous capture from multiple viewpoints, improve acquisition efficiency, and support scalable 3D plant phenotyping.

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