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Digital Twins and Low-Cost Sensors to Improve Pistachio Management

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INTRODUCTION

Three-dimensional (3D) reconstruction technologies are becoming essential in precision agriculture, offering more accurate and intelligent management tools compared to traditional observation methods. While high-end systems such as LiDAR or UAV-based surveys provide detailed data, they remain expensive and require technical expertise, limiting their accessibility for farmers. In contrast, low-cost solutions like smartphone-based photogrammetry are gaining interest for their practicality and affordability. However, challenges remain regarding the influence of acquisition parameters on model quality. For example, differences between nadir and oblique image acquisition impact the quality of 3D reconstructions in woody crops.

This study evaluates how frame sampling rate and lens type affect the 3D reconstructions of pistachio trees captured with smartphones, proposing a simple and field-validated protocol for digital twin generation in orchards.

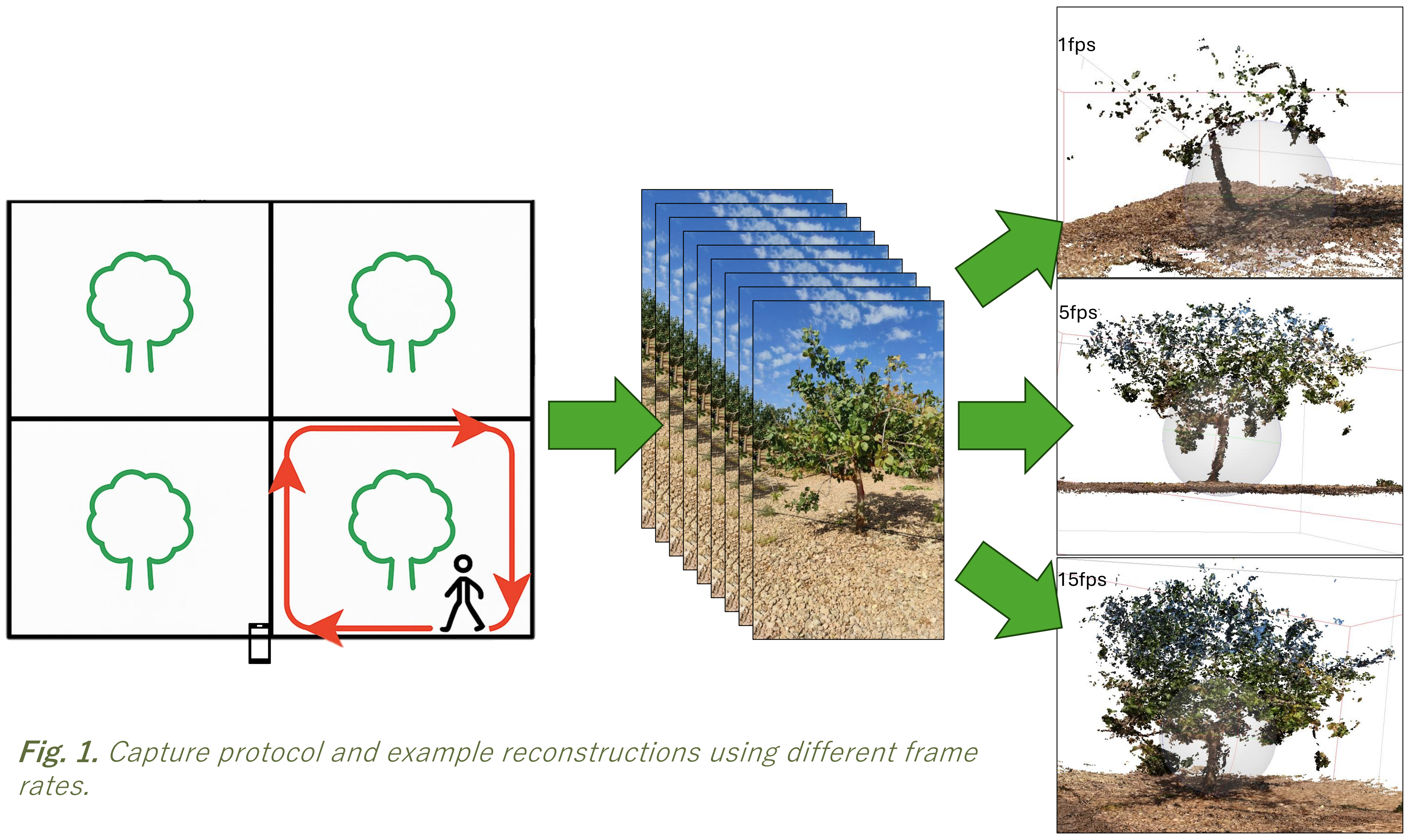

Fig. 1. *Capture protocol and example reconstructions using different frame rates.*

MATERIALS AND METHODS

The study was conducted in a commercial pistachio orchard in Castilla-La Mancha (Spain), using trees planted in a real spacing layout of 7 × 6 m. Ten representative trees were selected, and videos were recorded at 30 fps using a Xiaomi Note 9 Pro smartphone, employing both the standard 1x lens and the ultra-wide 0.6x lens. A custom capture protocol was designed and followed, walking around each tree along the perimeter of its influence area (3.5 × 3 m from the trunk) defined by half the planting distances (**Fig. 1**). The operator maintained a constant pace of approximately 1 m/s, with the camera aimed at the trunk and including the base of the canopy. Ground visibility was preserved to enhance photogrammetric accuracy using stable reference points. Videos were then processed using FFmpeg to extract image frames at multiple frame sampling rates (1, 2, 3, 5, 10, 15, and 30). Initial tests using RealityCapture produced incomplete models, especially for tree canopies. Consequently, Agisoft Metashape was used, following a standard workflow: photo alignment (high accuracy, 400k key points, 40k tie points), optimization, and dense cloud generation (high quality, mild filtering).

FPS	Trunk		Canopy		Connectivity		Visual Realism		Ground Plane		Artefacts	
	1x	0.6x	1x	0.6x	1x	0.6x	1x	0.6x	1x	0.6x	1x	0.6x
1	3	2	2	1	3	2	3	2	4	3	4	3
2	3	2	3	2	3	2	4	3	4	3	4	3
3	4	3	4	3	4	3	4	3	4	3	5	4
5	4	3	4	3	4	3	4	3	4	3	5	4
10	5	4	5	4	5	4	5	4	5	4	5	4
15	4	3	4	3	4	3	4	3	5	4	4	3
30	3	2	3	1	3	2	3	2	4	3	3	2

Table 1. *Qualitative evaluation (average values) of 3D tree reconstructions across frame rates and lens types. Higher scores (1 to 5) indicate better quality for each evaluated metric.*

RESULTS

Image sets captured with the smartphone's standard 1x lens produced more visually accurate and complete reconstructions than those obtained with the ultra-wide 0.6x lens, which frequently introduced distortions and reduced canopy definition. The frame sampling rate had a clear impact on reconstruction quality. Very low rates led to incomplete models, while excessively high rates (e.g., 30 fps) increased redundancy, processing time, artefacts, and noise without improving output. Intermediate values achieved the best balance, generating detailed, consistent reconstructions while remaining computationally efficient. The combination of 1x lens and 10 fps yielded the highest qualitative scores across all evaluated criteria (**Table 1**), including trunk and canopy definition, connectivity, realism, ground clarity, and minimal artefacts. The most pronounced differences across configurations were observed in canopy completeness and the presence of reconstruction artefacts. Finally, the models obtained under optimal settings (1x lens, 10 fps) were used to estimate canopy volume and LAI, and compared with manual field measurements using a measuring tape. A strong correlation ($r = 0.86$) confirmed the potential of this low-cost methodology for generating agronomically relevant 3D data. In addition, preliminary analysis showed a positive correlation between canopy volume and yield, reinforcing the usefulness of 3D models for predicting tree productivity.

DISCUSSION AND CONCLUSIONS

This study confirms the feasibility of using standard smartphone video and photogrammetry to generate digital twins of pistachio trees in real field conditions. Unlike more complex systems, this method uses tools already available to most farmers, making it accessible and scalable. The 1x lens with a 10 fps frame rate yielded the most complete reconstructions, while the 0.6x lens underperformed due to optical distortion. A major contribution of this work is the structured capture protocol, based on the planting layout (7 × 6 m), which ensured consistent geometry. Applied in a commercial orchard, the method produced realistic models strongly correlated with field measurements. As a low-cost tool for digitizing woody crops, this approach enables tree-level monitoring on each field visit and supports informed irrigation and management decisions. Preliminary comparisons between estimated canopy volume and yield suggest a strong correlation, supporting its use as a proxy for productivity and potential quality traits. Future work should focus on refining the workflow, automated trait extraction and temporal analysis.

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