

SEEmear: a system for large scale geo-referenced stereo imaging of orchards

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Abstract

Precision agriculture applications at the plant level require high-resolution, detailed imaging that cannot be adequately provided by satellite-based remote sensing due to insufficient resolution and suboptimal viewing angles. While Unmanned Aerial Vehicles (UAVs) offer improved capabilities, their downward-facing perspective and navigation challenges in orchards limit their effectiveness for fruit monitoring and anomalies detection. To address these limitations, we present SEEmear, a novel ground-based proximal sensing system for large-scale geo-referenced stereo imaging of orchard environments. The system integrates high-performance embedded computing, wide-angle global shutter RGB-D cameras, and precision RTK GNSS positioning, enabling simultaneous imaging of both sides of orchard rows from close proximity. SEEmear's 110° field-of-view cameras capture entire tree structures even at distances of 1 meter, while global shutter sensors eliminate motion artifacts essential for moving platforms. We tested the system in apple orchards, collecting comprehensive geo-referenced RGB-D imagery across 1.50 ha in approximately 40 minutes per session. The resulting dataset supports advanced applications including depth estimation, 3D reconstruction, background filtering, and object segmentation. The adaptable platform integrates with various ground vehicles and provides substantial data storage and processing capabilities needed for hardware-accelerated AI algorithms. SEEmear addresses the critical need for high-quality proximal sensing data in precision agriculture research, supporting applications in fruit detection, tracking, yield mapping, autonomous navigation, and field robotics.

Keywords: Formatting; Abstract; Academic-scientific Production.

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1. Introduction

Long-term monitoring of agricultural fields has traditionally relied on satellite data time series, offering consistent coverage over extended periods. However, satellite-based remote sensing lacks sufficient spatial resolution and optimal viewing angles for critical plant-level applications such as fruit detection, disease identification, and anomaly detection. These specialized tasks require proximal sensing methodologies with field-deployed instrumentation to capture detailed information unavailable from space-based platforms.

While Unmanned Aerial Vehicles (UAVs) have emerged as accessible platforms for proximal sensing with multispectral capabilities and specialized agricultural software, they face significant limitations in orchard environments. Their conventional downward-facing imaging often fails to capture optimal perspectives for fruit monitoring or pathogen detection in linear tree arrangements. Additionally, close-proximity inter-row flights may be impossible due to collision risks or physical obstructions like anti-frost protective screens commonly used by apple producers in regions such as Vacaria DAT.

Field-acquired public image datasets using proximal sensing significantly accelerate precision agriculture research by eliminating redundant data collection efforts, but their limited availability constrains innovation in crop monitoring and field automation (Lu; Young, 2020). Ground-based sensing platforms present a viable alternative, with pioneering systems like the "Shrimp" mobile ground vehicle (Underwood et al., 2016) and more recent advanced multimodal systems incorporating cameras, LiDAR, IMUs, and GNSS receivers (Cheng et al., 2024; Lei et al., 2024) . To address substantial data requirements for proximal sensing research, we present *SEEmear*, a prototype system engineered for large-scale geo-referenced stereo imaging of orchards, featuring extended-duration operation, high-resolution imaging, substantial storage capacity, and adaptability for integration with various vehicles. Unlike previous systems, *SEEmear* employs wide-angle global shutter cameras capable of capturing entire tree structures at close proximity, complemented by high-performance embedded computing for processing substantial data streams and executing hardware-accelerated AI algorithms.

2. Methods

SEEmear is built around a Jetson AGX Orin Dev Kit computing device (NVIDIA, Inc.), enhanced with a Non-Volatile Memory Express (NVMe) solid-state drive connected via PCI

Express interface. This storage configuration enables the recording of large data streams at high transfer rates.

The system incorporates two ZED X RGB-D cameras (Stereolabs, Inc.) connected to the computing device using Gigabit Multimedia Serial Link version 2 (GMSL2), a high-speed serial connection developed for automotive applications with bandwidth capabilities up to 6 Gbit/s. The cameras are mounted in opposing directions, facilitating simultaneous imaging of both tree lines in an orchard row (Figure 1). These wide-angle cameras feature a 110° horizontal field of view (FOV), capable of capturing objects up to 3.0 meters in height even at close proximity of just 1 meter—a capability particularly valuable for proximal sensing in narrow orchard rows. The cameras' global-shutter sensors eliminate motion artifacts such as skew, wobble (commonly known as the *jello effect*), and partial exposure issues that typically distort images, making them essential for deployment on moving platforms. The ZED X devices also include inertial units (IMUs) providing accelerometer and gyroscope reading at 400 MHz.

SEEmear also incorporates a Reach M2 (Emlid Inc.), a multi-band RTK GNSS module that supports multiple navigation systems including GPS, GLONASS, BeiDou, and Galileo. This module connects to the Jetson computer via USB interface, with GNSS data collected through the `gpsd` daemon (Raymond, 2012). The system synchronizes the computer clock with the GNSS clock, ensuring precise temporal alignment between camera streams and navigation data. A Reach RS3 device (Emlid, Inc.) is used as a base station, sending RTK corrections to Reach M2 using a LoRa radio link.

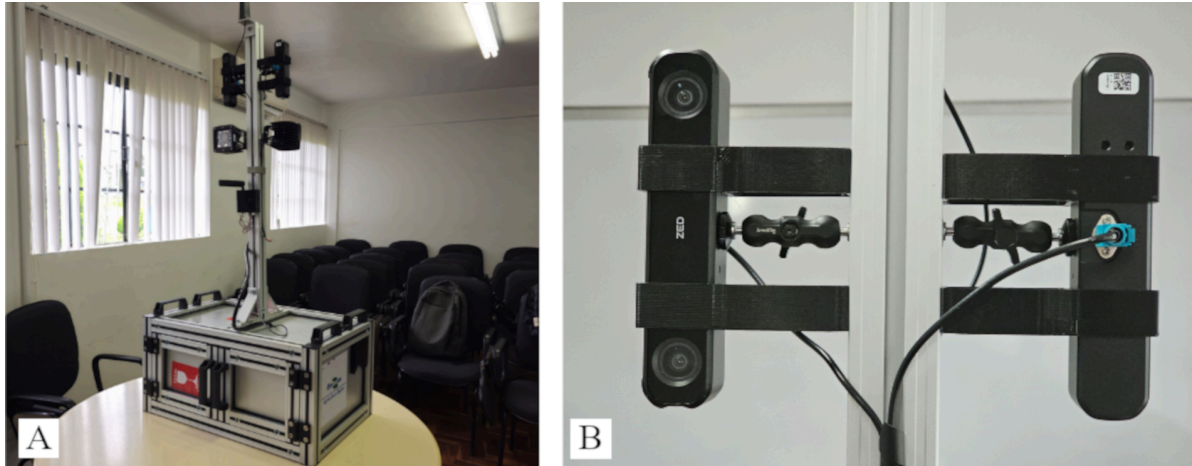


Figure 1. The SEEmear system. (A) The integrated system, including the sensors tower and the aluminum case that hosts the Jetson computer and the batteries. (B) Detail of the ZED X RGB-D cameras.

Photos: Lilian Nogueira de Faria.

Tests were performed at Embrapa’s Temperate Climate Fruit Growing Experimental Station (EEFCT) located in Vacaria (one of the ten Agrotechnological Districts of the Semear Digital Project Embrapa, 2024), Rio Grande do Sul, Brazil ($28^{\circ}30'58.2''S$, $50^{\circ}52'52.2''W$), on January 29 and 30 and March 11 and 13, 2025. In each test, approximately 1.50 ha of apple orchards were imaged. The SEEmear system was adapted to a tractor that performed the trajectory shown in Figure 2, as registered by the GNSS RTK module. A total of six successful tests were performed, each one taking around 40 minutes to complete. The full RGB-D camera footage, at 30 frames per second, including the IMU readings, are recorded and stored, plus the GNSS RTK positions (raw data, base corrections and RTK corrected locations).

3. Results and Discussion

Figure 3A shows an example of the image data captured by the RGB-D sensing system. The stereo pair can be used to estimate the depth of surfaces in the scene. Figure 3B shows the results of depth estimation using Selective-Stereo, a state-of-the-art deep neural network-based method for depth estimation proposed by Wang et al. (2024). Depth information has several applications: 3D reconstruction, volume measurement and,

object segmentation, to cite a few. Figure 3C shows how the depth information can be used to filter background elements out, isolating the foreground tree row.



Figure 2. The positions registered by the GNSS RTK module in the mission performed on March 11, 2025, at Embrapa's Temperate Climate Fruit Growing Experimental Station, Vacaria, RS.

Photo: Thiago Teixeira Santos

By the time, the data generated by the SEEmear in the tests at Vacaria are being employed in research on fruit detection, fruit tracking, yield mapping, autonomous navigation, and field robotics.

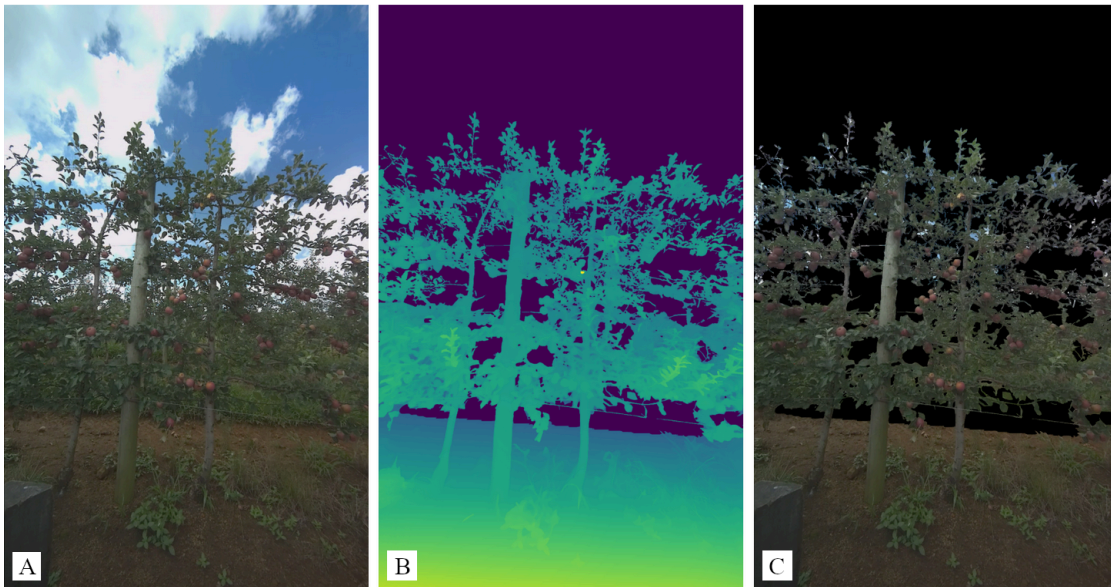


Figure 3. Example of RGB-D data. (A) Left frame from one of the ZED X cameras. (B) Depth estimation. (C) Filtering the frame content, removing pixels corresponding to far objects.

4. Conclusion

This paper presented SEEmear, a novel proximal sensing system designed for large-scale geo-referenced stereo imaging of orchard environments. The prototype integrates high-performance embedded computing, wide-angle global shutter RGB-D cameras, and precision RTK GNSS positioning to overcome limitations in conventional agricultural sensing platforms. Field tests conducted in apple orchards demonstrated the system's capability to collect comprehensive datasets with precise spatial and temporal alignment. SEEmear's adaptable design for integration with various ground vehicles, combined with substantial data storage capacity and processing power, makes it a useful tool for addressing the growing requirements for data collection of high-quality proximal sensing data in the field.

Acknowledgements

The authors would like to thank Fapesp (Proc. 2022/09319-9) for the funding.

References

CHENG, D.; CIADERA, F.; PRABHU, A.; LIU, X.; ZHU, A.; GREEN, P. C. Treescope: an agricultural robotics dataset for lidar-based mapping of trees in forests and orchards. In: INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION, 2024, Yokohama.

Proceedings [...]. [Piscataway]: IEEE, 2024. p. 14860-14866. DOI: <https://doi.org/10.1109/ICRA57147.2024.10611103>.

LEI, J.; PRABHU, A.; LIU, X.; CLADERA, F.; MORTAZAVI, M.; EHSANI, R.; CHAUDHARI, P.; KUMAR, V. **4D Metric-semantic mapping for persistent orchard monitoring**: method and dataset. Available at: <https://arxiv.org/abs/2409.19786>. Accessed on: 5 Jun. 2025.

LU, Y.; YOUNG, S. A survey of public datasets for computer vision tasks in precision agriculture. **Computers and Electronics in Agriculture**, v. 178, 105760, Nov. 2020. DOI: <https://doi.org/10.1016/j.compag.2020.105760>.

RAYMOND, E. GPSD. In: BROWN, A.; WILSON, G. (ed.). **The architecture of open source applications**. Morrisville: Lulu. Com., 2012. v. II, chap. 7, p. 101-112.

UNDERWOOD, J. P.; HUNG, C.; WHELAN, B.; SUKKARIEH, S. Mapping almond orchard canopy volume, flowers, fruit and yield using lidar and vision sensors. **Computers and electronics in agriculture**, v. 130, p. 83-96, Nov. 2016. DOI: <https://doi.org/10.1016/j.compag.2016.09.014>.

WANG, X.; XU, G.; JIA, H.; YANG, X. Selective-stereo: adaptive frequency information selection for stereo matching. In: IEEE/CVF CONFERENCE ON COMPUTER VISION AND PATTERN RECOGNITION, 2024. **Proceedings** [...]. 2024. p. 19701-19710.