Supplementary data

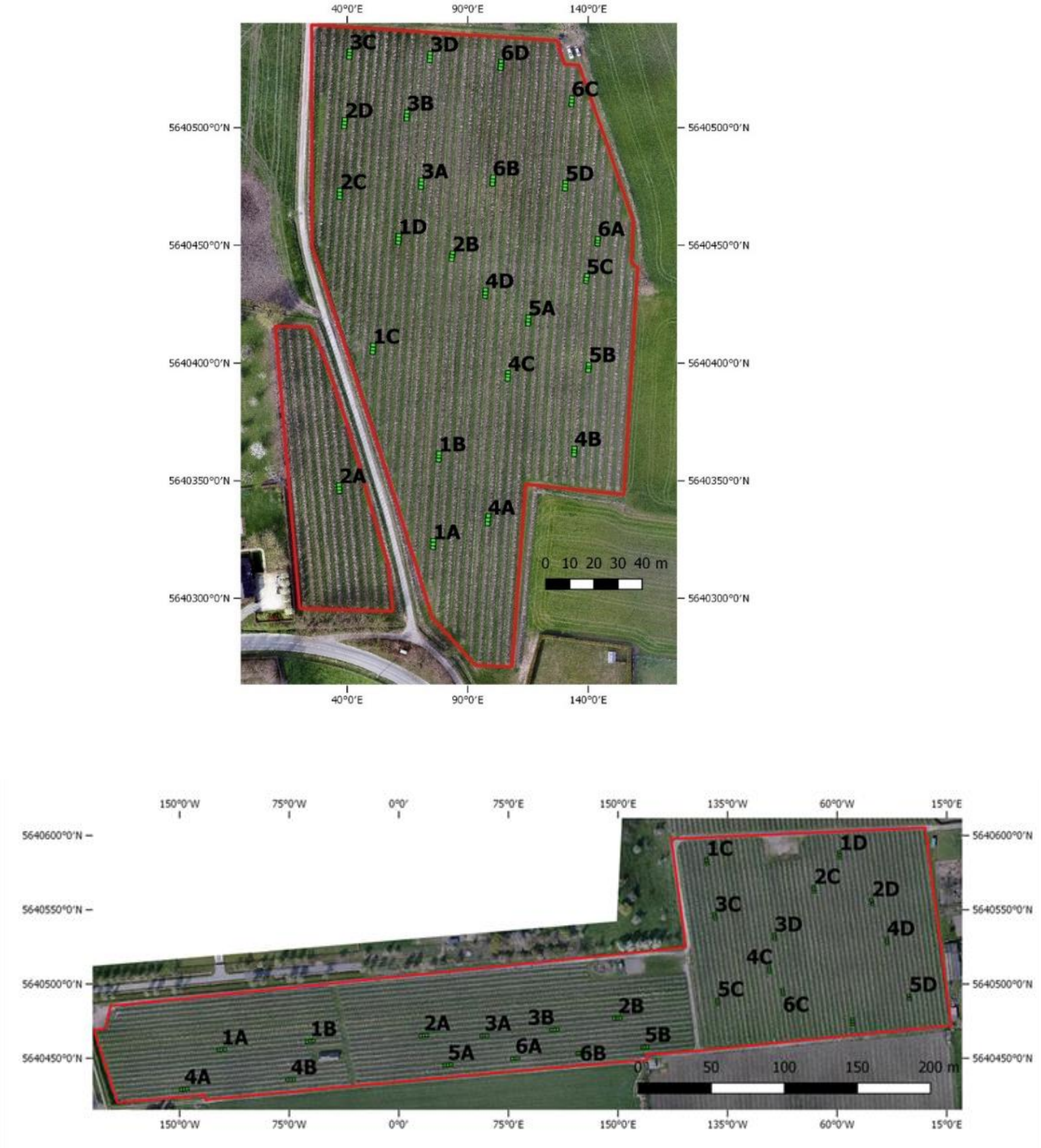

Figure S1. Conference pear orchards in Wimmertingen (top) and Rummen (bottom) and the labels of the 24 plots (1A-6D).

RGB imagery

Platform and sensor characteristics

In 2018, RGB imagery was obtained with a DJI Phantom 4 Pro, a commercial off-the-shelf quadrotor unmanned aircraft system (UAS) equipped with a 1” 20 MP (2.4 µm pixel pitch) camera with a fixed 8.8 mm focal length (24 mm expressed in 35 mm format equivalent) autofocusing and variable aperture lens, providing 1 cm GSD from a flight height of 38m AGL. Images are geotagged by the system’s autopilot GPS, which writes coordinates in WGS84 decimal degrees with vertical reference to the EGM96 geoid model to the image EXIF tags, with an accuracy of about 2 – 5 m. The system is operated at a flight speed of 5 m/s and 80% forward and sideward overlap, with the camera exposure set to fully automatic (variable shutter speed, aperture and ISO). While the main system is controlled trough the DJI Go 4 app, the mapping flight planning and monitoring was executed in the DJI Ground Station Pro app running on an Apple iOS tablet connected to the controller.

In 2019, The RGB imagery was acquired with a commercial off-the-shelf Sony ILCE-7R, a 36 MP full-frame (4.88 µm pixel pitch) mirrorless interchangeable lens camera. The lens used was a 35mm Color Skopar Pancake to obtain 1 cm GSD from a flight height of 75 m above ground level (AGL) or 1.2 cm GSD from the maximum legally allowed flight ceiling of 90 m AGL. The camera and lens came integrated with the commercially available Trimble UX5HP, a 1 m wide fixed wing UAS capable of flying for 35 minutes at 23.5 m/s in winds up to 15 m/s. The system is designed specifically for surveying tasks based on photogrammetric image processing. Therefore, the optical axis and geometry of the mechanically focusing lens are stabilized through a modified screw mount and focus and aperture locking screws. Additionally, the UX5HP is equipped with an active dual frequency patch antenna embedded in the starboard wing, connected to a dual frequency Global Navigation Satellite Systems (GNSS) receiver, logging raw observables at 20 Hz as input to Post-Processing Kinematics (PPK) analysis of the flight trajectory. A feedback cable from the camera to the GNSS receiver provides an event marker for every image in the observables file, for which interpolated positions can be calculated with 2 – 5 cm accuracy in PPK. Inertial measurement unit (IMU) data are also recorded for every image, albeit with an accuracy of around 2° in pitch and roll and around 5° in yaw. While the lens aperture is mechanically locked at f/5.6, the camera is also operated with a fixed shutter speed depending on the flight plan characteristic (typically 1/2000), to prevent forward motion blur while allowing as much light to be captured as possible. The ISO values is set to variable with a maximum of 6400, evening out brightness fluctuations in the imagery while keeping noise to a minimum. The flight plan ensured 80 – 90% sideward and around 70% forward image overlap, depending on the flight conditions. Flight planning and monitoring is done in the Trimble Aerial Imaging software running on Windows on a ruggedized tablet connected to a modem, acting as the system’s controller.

Ground measurements

For the DJI Phantom 4 Pro flights in 2018, at least five artificial ground control point (GCP) markers were installed per field, while for the Trimble UX5HP flights in 2019, the number was reduced to at least two GCP markers per field for geometric camera calibration and accurate georeferencing. The position of the ground control points was measured in the field using real-time kinematics (RTK) GNSS, taking corrections from a virtual reference station (VRS) in the Flemish positioning service (FLEPOS) network, with an average horizontal accuracy of around 2 cm and an average vertical accuracy of around 3 cm.

Image processing

For the Trimble UX5HP flights in 2019, image identifiers are linked to the event markers in the GNSS log and images are corrected for vignetting in the Aerial Imaging software on a desktop computer after the flight. The flight trajectory and precise image positions were then calculated in Trimble Business Center 5.0 using PPK of the raw observables file, with forward and backward processing and linear interpolation of event marker positions based on two GNSS log positions on either side of the event marker, accounting for antenna lever arms and signal delay from the mid exposure time to the event marker. The processing was done against base data from the nearest continuously operating reference station (CORS) in the FLEPOS network, downloaded at 1 Hz for a period starting 30 min before and ending 30 min after the flights from the online archive after the beach survey. The corrected positions reduced to the center of the imaging plane (sensor) along with the respective image identifiers, IMU values and an accuracy indicator were exported to an exterior orientation csv file in the WGS84 UTM zone 31N coordinate system with vertical reference to the EGM96 geoid model (the expected output coordinate reference system, in which ground control points were also made available).

For both Trimble UX5HP and DJI Phantom 4 Pro flights in 2018 and 2019, images were processed through a structure from motion (SfM) photogrammetry workflow in the commercial software Agisoft Metashape Pro 1.5.x. After importing images, image GPS positions are either automatically read from the EXIF tags (in the case of DJI Phantom 4 Pro imagery) or the associated exterior orientation file resulting from the flight trajectory PPK processing was loaded (in the case of Trimble UX5HP imagery) and coordinate reference system and initial camera parameters were set. The workflow consists of tie-point extraction and matching (alignment), geometric camera self-calibration and refinement of the georeferencing (optimization), dense point cloud generation, dense point cloud classification (into ground, above-ground and noise classes using a topographic filter with threshold values relating to maximum angle, maximum distance and search grid cell size), raster digital surface model (DSM) generation based on the ground and above-ground point classes, raster digital terrain model (DTM) generation based on the ground points only, and orthomosaic generation based on the DTM. Alignment was done at image pyramid level 2, and the camera self-calibration optimized for focal length (f), principal point (cx, cy), skew and aspect ratio (b1, b2), three radial distortion coefficients (k1-k3) and two tangential coefficients (p1, p2). In the case of DJI Phantom 4 Pro imagery, estimation of the camera interior orientation (camera self-calibration) and absolute georeferencing of the project was done based on at least 5 GCPs, using any remaining points as independent check points. In the case of Trimble UX5HP imagery, camera self-calibration was done entirely relying on the precise image position measurements, while absolute georeferencing (elimination of any potential global shifts) was done using 1 GCP marker, using the remaining points as independent check points. Each GCP was indicated in at least 9 overlapping images, with care taken to maximize the observation angles of the GCP markers. Check points were used for independent accuracy assessment, to ensure the output products were characterized by an absolute accuracy in the range of the image GNSS measurements (2 – 5 cm, which is the limiting factor with this methodology). Dense point cloud generation was done at image pyramid level 1 with depth filtering disabled, resulting in DSM/DTM generation at a GSD twice that of the original image and orthomosaic GSD.

Known issues

Due to the limited flight endurance and the slower speed of the DJI Phantom 4 Pro quadrotor, it is often necessary to perform multiple flights to cover the same area at the same GSD and overlap compared to the fixed wing Trimble UX5HP. In combination with the autofocus and auto aperture settings, this reduces the stability of the photogrammetric block and can result in a reduced accuracy by about 2-3 pixels. The DJI Phantom 4 Pro GPS-based geotags often suffer from incorrect height initialization. In these cases, the GPS-based height values were removed upon import and replaced by a fixed height value corresponding to the planned flight height (with reference to the EGM96 geoid). This is not expected to have an impact on the accuracy of the results, but using the incorrect height values resulted in a difficult or incomplete bundle block adjustment.

Due to the high cruise speed of the Trimble UX5HP, and the limited sustained triggering rate of its camera, the forward overlap can be locally reduced depending on flight plan and wind characteristics. This can be mitigated by increasing the lateral overlap. Since a reduced overlap is known to play a role in the incorrect estimation of the focal length when performing PPK GNSS self-calibration without the use of ground control points, thereby causing a global vertical shift, the use of at least 1 GCP is necessary to maintain absolute accuracy. Due to the lens lacking an electronic connection to the camera, images show optical lens effects such as vignetting straight out-of-camera. The vignetting correction module implemented in the Trimble Aerial Imaging software reduces this effect, but does not eliminate it because it is based on a general vignetting model valid for the type of camera and lens, rather than each specific unit. Therefore, an under- or overcorrection may occur, mainly in the corners of the images. This is not expected to affect the orthomosaics because of the high image overlap.