THE USE OF A MULTIROTOR AND HIGH-RESOLUTION IMAGING FOR PRECISION HORTICULTURE IN CHILE: AN INDUSTRY PERSPECTIVE

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ABSTRACT

As part of the prototype development of a yield forecasting and precision agriculture service for Chilean horticulture, we evaluated the use of an eight-rotor Mikrokopter for high-resolution aerial imaging to support ground-based surveys. Specific considerations for UAV and communications performance under Chilean conditions are windy conditions, limited space for take-off and landing in orchards, tree height and plantation density, and the presence of high metal contents in soils. We discuss our experiences with this hobby-grade UAV after two seasons of flights.

We also compared several free and commercial image stitching and orthomosaicing programs, including in-house software for pre- and post-processing. Criteria for comparisons were based on our requirements for application in the field, in particular, ease of use by non-specialists and rapid processing times on a laptop. Other considerations included value (features vs cost), technical support and hardware requirements. Mosaics were evaluated for their suitability for decision making in terms of accuracy of global and local features. Results for the different software are presented in terms of number of images, GPS accuracy, and processing times.

Keywords: Hobby-grade UAV, Multispectral imaging, Orthomosaic, Software, Yield Forecasting

INTRODUCTION

Chile is the largest exporter of off-season fruit to the northern hemisphere, with more than 300,000 ha of fruit trees under production (National Institute of Statistics, Chile), and 7,800 growers and 580 exporters serving the export market (www.fruitsfromchile.com). The ability to obtain early, accurate yield forecasts provides an opportunity for producers and exporters to plan labour, storage and transport, order materials, negotiate down-payments, contract insurance and bank loans, as well as make offers on the market for volume sales of their products. Traditional methods used by the industry are based on unrepresentative fruit counts and ad-hoc projections and produce absolute errors of 20% or more, depending on the species and climatic conditions. Following a survey of several large fruit, wine and olive oil exporters, our goal is to consistently provide yield forecasts with absolute errors not exceeding 10% with 90% probability. For the last four growing seasons we further developed objective sampling-based methodologies for yield estimation in fruit (Wulfsohn et al., 2010) and row-crop production with promising results from orchard and field-scale trials in hybrid cucumber (seed), onion, kiwifruit, grapes, sweet cherries, apples, and olives. In the period 2012-2014, we developed hardware and software support systems and evaluated the prototype system in orchard-scale trials in Chile and Argentina.

In this paper, we describe our approach to yield estimation, the supporting hardware and software systems, our experiences using a high-end hobby-grade unmanned aerial vehicle (UAV) equipped with an adapted NIR-G-B digital camera for orchard imaging, and an evaluation, from the perspective of a commercial user, of several third-party stitching and orthomosaicing software solutions.

MATERIALS AND METHODS

Yield forecasting procedure

The steps of the proposed yield forecasting service is shown in Fig. 1. A UAV equipped with a high-resolution camera is used to reconnoitre the orchard, vineyard or field with the goal of mapping the variability and optimizing the selection of trees or groups of plants for sampling. Depending on the objective of the survey, multispectral, RGB or thermal digital cameras may be used. The UAV permits us to obtain in less than one day a quantitative description of variability of a field for which we may have no prior experience. Knowing the location and extent of the orchard and the camera configuration all flight planning was done in the office.

Images are synchronized with flight telemetry data using in-house software to geotag images and save image latitude, longitude, altitude, (optionally roll, pitch, yaw data) to a textfile for input to a third-party orthomosaicing software. Vegetation index maps are created from the orthomosaic using an in-house ImageJ macro. All maps are interpreted by the agronomist or field technician and verified on the ground as necessary.

In-house software is used to identify individual trees in the mosaic with their locations and calculate between-tree variability, and the number and locations of trees to sample. The selected tree locations and associated sampling parameters are output to a text file, which serves as input to handheld software used by the ground-survey team.

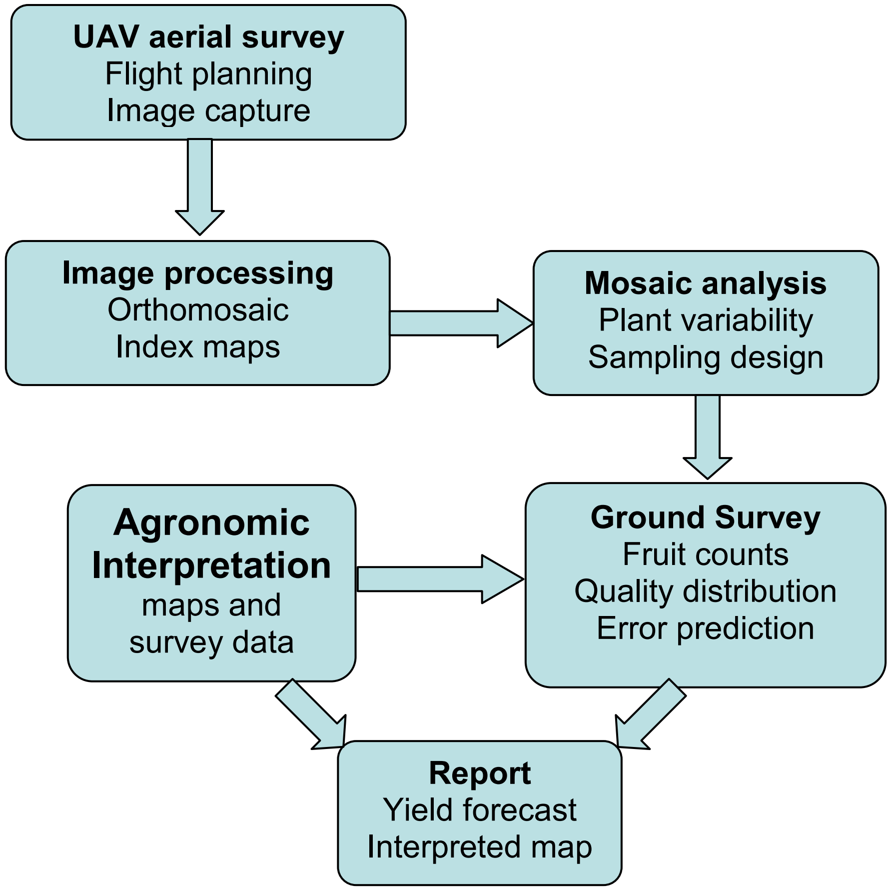

Fig. 1. Schematic of Pronofrut yield forecasting service.

Fruit counts, measurements (e.g. color, calibre, ºbrix) and other observations (e.g. defects, insect infections, disease) are done manually, on small portions of the selected trees by a two-person team. One person is responsible for sampling, while the second person operates the handheld software and provides some quality control. The survey software, adapted from Gardi et al. (1997), is used to select the next tree, segment and fruit to sample based on objective sampling mechanisms, to input data and observations, and compute estimates and predict estimation error using semi-empirical models.

Data from the handheld software are processed using software developed in R (R Core Team, 2013) to provide a summary report of estimates, sample statistics and graphics of size and quality distributions. A short, easily interpretable report is prepared for delivery to the grower providing the survey date, species and variety and block/orchard location, estimates of total fruit number and size, quality and defect distributions on the survey date, projections of the yield in kg and kg/ha at the expected date of harvest, any problems identified in the orchard, and, if ordered by the client, an NDVI map with interpretation. Because the sampling methodology is mathematically unbiased and relies on small sample sizes, it is feasible to return to do rapid follow up surveys for updating quality and size predictions as many times as desired up to the harvesting period.

UAS and flight campaign

We used a hobby-grade vertical take-off and landing (VTOL) Mikrokopter (Octocopter-XL, 1.5 kg payload) from HiSystems GmbH (Moormerland, Germany) powered by a 6600 mAh 20C 14.7 V LiPo (Fig. 2). Under the typically windy conditions experienced daily in the spring and summer months, this provided us with 10 mins flight time (to 20% battery capacity). The GPS has about ±5 m accuracy and for software imposed limitations; flight distances were limited to within 250 m of home base. Flight waypoint maps and plans were created using MikrokopterTool (HiSystems GmbH). The camera gimbal was a mkTR Professional (PhotoShip One, Mesa, AZ, USA). Wireless data communications between PC and UAV were using the MK-Bluetooth-Set v.2 in 2012 and 2013, replaced in early 2014 with a RangeExtender 903 MHz wi232 system. The system software controls the UAV automatically between waypoints but because the ground was often uneven and stony and there usually was limited space for manoeuvring between adjacent blocks or rows in an orchard, all take-offs and landings were done under manual control. The co-pilot monitors flight development, and system status, especially GPS satellite number, UAV battery and magnetic field levels. For practical reasons, manually registered ground control points (GCP) were not used.

All results presented in this report are using images taken with a 12.1 MP Canon Powershot SX230 HS, 6.17 x 4.55 mm chip size, 28 mm focal length (35 mm equivalent), adapted for NIR-G-B image capture (www.maxmax.com). Stills were captured with Fine JPEG quality giving an image size about 2.3 MB. The camera weighs 215 g and has an inbuilt GPS with about ±20 m accuracy. Images were captured with fixed ISO value and 1/2000 s shutter speed. Images were stored on a micro-SD card for later download and processing. An intervalmeter script and CHDK software (firmware vers. 1.01c, chdk.wikia.com) were used to trigger the camera at fixed time intervals (depending on the altitude) for a minimum 60% lateral and 75% along-flight-line overlap between adjacent images. A 1.3 m × 1.3 m 60% reference target was used for purposes of reflectance calibration for index calculations. Multiple flight programs were carried out within the period solar noon ± 3.5 hours.

Over 100 flight campaigns were carried out during the 2012-2013 and 2013-2014 growing seasons (November to April) for imaging of horticultural fields and fruit orchards in the central region O'Higgins of Chile. In January 2014, additional flights were carried out in Argentina. The majority of campaigns were of fruit tree orchards including table grapes (50), cherries (10), winegrapes (6), apples (8), nectarines (2), pears (1), and avocados (1) and field or block sizes ranging from 2 ha to 50 ha and altitudes between 75-200 m.

Yield forecasts

Validation of the yield estimation methodology were made using fruit counts shortly after fruit thinning in commercial sweet cherry, apple, and wine grape orchards. Projections of yield were provided to the grower and exporter within three days of the ground survey. In the case of cherries, which have a very short growing season, estimates were made about one month before harvest, whereas for wine grapes, apples and pears, estimates were made 3-4 months before harvest. Field, bodega or packing house reports were provided by the companies after harvest and packing. These data were used to determine actual estimation errors and compare them with our estimates.

Comparison of mosaicing software

An important step in the procedures shown in Fig. 1 is the creation of a geo-referenced mosaic from images captured using the UAV. In-house software (Pronofrut Mosaik) was developed using Visual C++ and opencv libraries to use the UAV telemetry data and waypoint plan files to geotag the captured images, determine the images corresponding to the flight plan (excluding take-off and landing), and call a third-party mosaicing software. Orthomosaicing software produce georeferenced mosaics, whereas mosaics created using image stitching software have unknown scale, orientation and position with respect to ground coordinates. In the latter case, Pronofrut Mosaik searches for feature matches between photographs from the flight plan and the mosaic, and creates a KMZ file for the mosaic. Some transformation corrections to the georeferencing may then be made in Google Earth (rotation, translation, scaling), which Pronofrut Mosaik uses to update the georeferenced mosaic.

We considered several free photo stitching software including Hugin (hugin.sourceforge.net) and Microsoft Research Image Composite Editor (ICE) (vers. 1.4.4, research.microsoft.com/en-us/um/redmond/groups/ivm/ICE) which can also create mosaics from videos. Such photo stitching algorithms combine images based on matching of keypoints (features) visible in several overlapping images (Szeliski, 2006) without use of image elevation data or position.

Fig. 2. Octocopter-XL carrying a modified Canon Powershot SX230 HS camera for multispectral imaging.

Orthomosaicing combines orthorectification (correcting images for distortion using elevation data and a camera model and producing images that are planimetric and ground registered) and image stitching. There are two general approaches to orthorectification: using “rigorous sensor models” and “replacement sensor models” (Dial and Grodecki, 2005). A number of software solutions based on the Structure-From-Motion (SFM) and Dense Multi-View 3D Reconstruction (DMVR) algorithms to construct high-resolution mosaics are available for processing of aerial images. The SFM method uses corresponding features present in different images depicting overlapping areas to calculate intrinsic and extrinsic camera parameters and a sparse point cloud that represents the 3D geometry of the scene. The bundle adjustment method (and GCPs) may be used to improve the accuracy of the 3D reconstruction (Atkinson, 1996; Engels et al., 2006). The 3D point cloud that can be converted to a triangulated 3D mesh and to 3D digital elevation models (DEM) and 2D orthomosaics.

We investigated several orthomosaicing software solutions. Our requirements were ease of use by non-experts (agronomists and technicians) and the ability to generate sufficiently accurate mosaics for ultimately mapping tree variability in rapid processing times on a field computer (laptop). Other considerations included cost, technical support and hardware requirements. Several systems were ruled out for reasons related to technical support or because they did not meet our requirement for ease of use by non-specialists.

Two programs were tested further: Pix4Dmapper (vers. 0.9.11 - 1.0.11 64-bit, Pix4D SA, Lausanne, Switzerland) and Photoscan Pro (vers. 1.0.0 - 1.0.2 64-bit, Agisoft LLC, St. Petersburg, Russia). Processing was carried on a Toshiba Portege 930 laptop, Intel core i5-3320M 2.6 GHz, 1 CPU with 4 threads, 16 GB RAM, Intel® HD graphics 4000 graphics card running Windows 7 64-bit.

The goal of these tests was not to rigorously compare processing times and results under the same conditions – each program uses different algorithms and different configurable settings and options – but to use settings that would allow us to rapidly generate good quality mosaics so that it could be feasible to carry out remote sensing and all image processing in the field on the same day or one day before ground sampling (depending on the area and number of blocks or varieties under study). A mosaic was considered of good quality if it produced correct global features (e.g. number of rows and trees, curvature of rows and roads), correct georeferencing and intact tree canopies with minimal artefacts. Errors of several meters in georeferencing was considered acceptable given that we did not use GCPs.

The processing times presented in this paper are for images of table grape orchards at two physiological stages: flowering in November 2013 and harvest time in March-April 2014 (Fig. 3). Photoscan Pro and Pix4Dmapper were used to create orthomosaics with 60 mm spatial resolution (depending on flight altitude, the original pixel resolutions were between 28 mm and 47 mm). Furthermore, the merging of two or more flights covering larger areas was carried out for several projects for table grapes, nectarine and apple orchards. Comparisons were made for analysis using the camera GPS Exif data (low accuracy GPS) and the GPS coordinates obtained from the UAV telemetry data (medium accuracy GPS). Both software were used to generate KML files to be able to inspect global accuracy of the mosaic in Google Earth. After some experimentation, the options used were those summarized in Table 1.

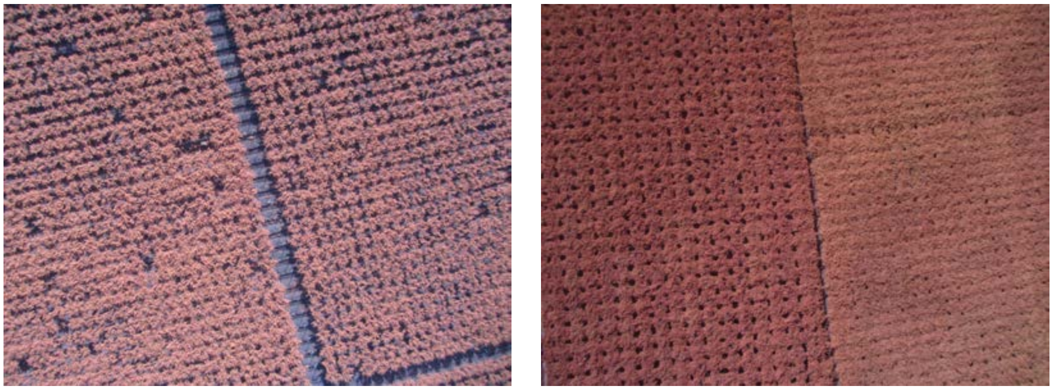

Fig. 3. False color multispectral images of table grape orchard structures at time of flowering (left) and close to harvest (right) taken with a modified Canon SX230 HS camera.

Table 1. Software options used for processing images of tablegrape orchards. Where not listed, default values were used.

Pix4dmapper	Agisoft Photoscan Pro
Aerial nadir / vegetation	**Align images**
Initial Processing	Low accuracy vs. Medium accuracy
Rapid vs. Full	Generic pair pre-selection
Feature extraction ½ vs. 1 scale image	**Optimize alignment**
Point Cloud Densification	**Build dense cloud**
¼ scale image, multiscale	Medium quality, Moderate depth filtering
Optimal point density	
Minimum 3 matches	**Build mesh**
Sharp or medium smoothing	Height field, Sparse cloud, Custom face cloud 5, 10 or 15 million (depending on project size)
XYZ output	
	Decimate mesh
	Face count 0.5, 0.8 or 1 million (depending on project size)
	Build texture
	Mosaic blending mode
	Export model as Google Earth KMZ
Orthomosaic and DSM generation	**Export Orthophoto**
Multiband blending, 0.2 quality	TIFF, WGS84 geographic
Merge tiles	Mosaic blending
Generate Google Earth KML and World files	Write KML and World files
	Export Google KMZ
	Mosaic blending

RESULTS

UAV system performance

To this date we have accumulated about 18 flight hours with the Octocopter-XL. The VTOL multirotor is well suited to take-off and landing in confined spaces, requires less skill to operate most fixed wing UAV, and the flight planning and automatic waypoint capabilities are convenient and easy to use. With the 10-11 min flying time we obtain using a 6600 mAh LiPo under moderately windy conditions (15-25 km h^{-1}) a single flight can cover up to 15 ha, depending on field shape – the 250 m radial range limit imposed by the control software is a major inconvenience, not imposed by new competitors in the high-grade hobby market, and requires the purchase of a commercial license to remove it. We expect that it would be possible to increase battery duration by a couple of minutes with a more aerodynamic camera gimbal and retractable legs. Still, we are procuring other UAVs to obtain flight times of at least 20 minutes, and preferably 45 mins to more efficiently cover larger orchards of 30 – 1000 ha.

Our experience using the Bluetooth (several replacement sets) with this UAV was not a good one. We frequently lost communication, even at very short distances (< 20 m) and the Bluetooth pair was not able to re-established contact over greater distances. Some of the factors affecting Bluetooth performance at close distances were metals in soils (taking off from a raised surface reduced this effect), scattering from nearby tall trees, as well as blind zones in the radiation pattern due to the shape of the antenna. Since replacing the Bluetooth set with the industrial quality wi232 we have not had data link problems.

Despite the generally solid performance obtainable with this UAV and its user-friendly features for automatic operation and data logging, it does require high maintenance. After less than 10 hrs flight time, we had to disassemble the UAV to be able to inspect and repair the connections between the capacitor legs on the motor controller boards and the power supply board, which had come loose due to vibrations. The same problem has been encountered by others with MikroKopters (personal communication, Jon Nielsen, Engineer, Department of Plant and Environmental Sciences, University of Copenhagen).

Mosaicing software performance

None of the image stitching softwares were capable of accurately create mosaics for projects where series of overlapping images contained regular rows of trees without clear features such as buildings and roads or large variations in tree canopy size or spacing, even leaving large areas within a scene unprocessed. Other errors as a consequence of variations in the distances between images and fluctuations in altitude (arising from UAV movements due to wind gusts and vibrations) were also apparent. Figure 4 shows an example of one of the better mosaics produced using Microsoft ICE after applying global scale corrections in Google Earth. Comparing Fig. 4 with Figs. 5-6, important errors in scale and alignment are still evident.

Both Pix4Dmapper and Photscan Pro were able to produce, in most cases, high quality orthomosaics using the low to medium quality settings summarized in Table 1. Each software has its advantages and disadvantages in terms of functionality and performance and areas where one performed better than the other for processing of orchards captured at high resolutions (30-50 mm px^{-1}). Figures 5 and 6 show orthomosaics of a sweet cherry block created using Photoscan Pro and Pix4Dmapper, respectively, and low accuracy settings. Using medium accuracy settings did not eliminate large-scale errors in the orthomosaics. Trees are difficult to model in 3D from high resolution images especially if the images are even slightly oblique because the many branches and canopy surfaces project differently from different view points. This often leads to artefacts like those seen in Fig. 7. These were a problem with both softwares, but slightly more so in Pix4D mosaics. Pix4D has the capability to correct orthomosaic errors using the Mosaic Editor tool, but this feature was not used in this study. Using lower resolution images for alignment and point cloud densification reduced these artefacts considerably. Comparing the figures also highlights differences in the programs with respect to how they calculate orthomosaic boundaries and solutions of the orthorectification system near boundaries where there may be few images in which a keypoint is recognized for triangulation. Flight planning was subsequently used to avoid such edge effects as those seen in Fig. 6.

Figure 8 compares processing times for the two software under low accuracy / rapid settings. The use of mesh decimation in Photoscan Pro was key to obtaining the processing times shown. For example, without the mesh decimation step, processing time for one 127 image project increased from 39 mins to 65 mins. Figure 9 shows that having more precise GPS data reduced full initial processing times in Pix4Dmapper, but made no difference when rapid initial processing was used. Similarly, GPS accuracy did not substantially affect processing time when using low accuracy image alignment in Photoscan Pro, but it was important for a more accurate georeferencing of the mosaic and crucial for automatic chunk merging, which process generally produced unsatisfactory results (e.g. Fig. 10)

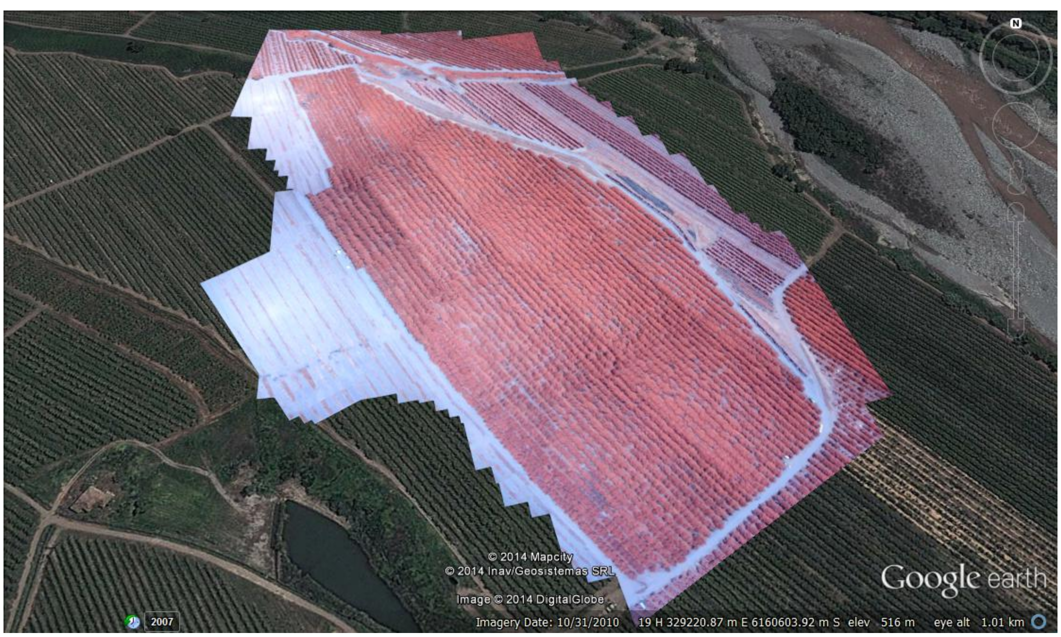

Fig. 4. Orthomosaic of 6 ha sweet cherry orchard using Pronofrut Mosaik and Microsoft ICE to georeference and process 132 images.

Fig. 5. Orthomosaic of 6 ha sweet cherry orchard using Photoscan Pro to process images geotagged with the UAV GPS. No GCPs were used. See Table 1 for settings.

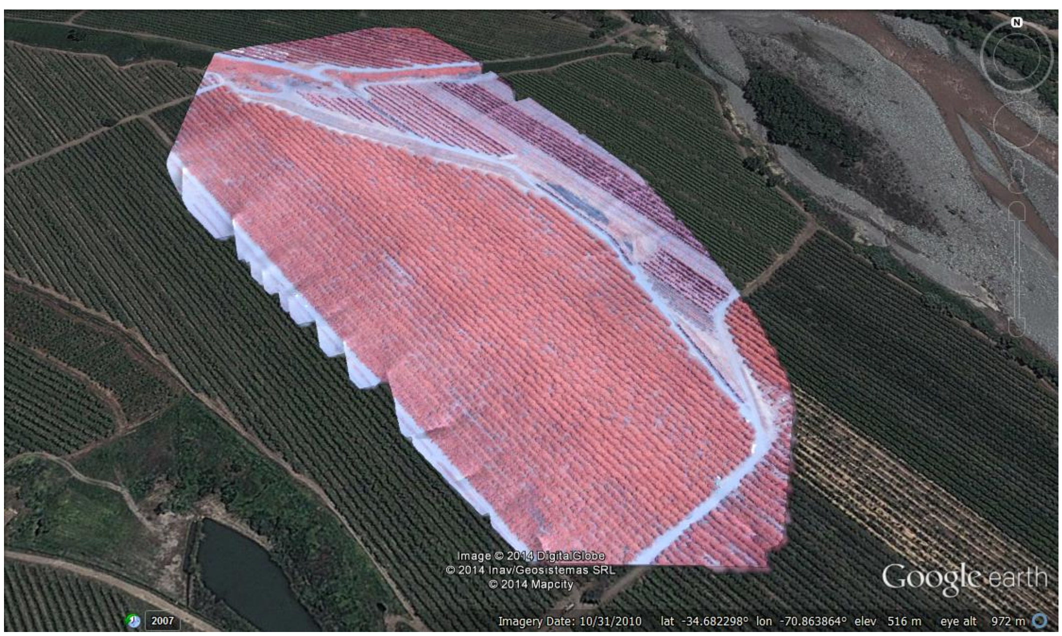

Fig. 6. Orthomosaic of 6 ha sweet cherry orchard using Pix4Dmapper to process images geotagged with the UAV GPS. Full initial processing with feature extraction using full scale image. No GCPs were used. Table 1 lists other settings.

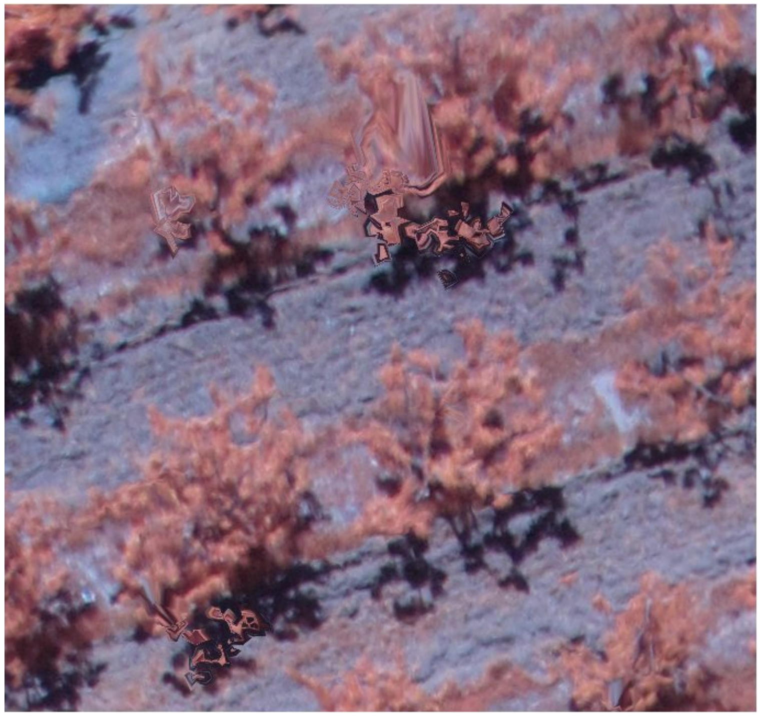

Fig. 7. Artefacts (swirling and smearing effects) sometimes present in high-resolution orthomosaics of trees.

with a few exceptions where there was very little variation in altitude and therefore pixel resolution. Photoscan Pro was also not able to render combined multi-chunk or large projects for viewing on the laptop, due to limitations of the graphics card. In general, Pix4Dmapper produced better merged projects providing that there was sufficient overlapping areas with visible keypoints in the two chunks. The result obtained in Fig. 11 was obtained using full initial processing. Rapid check processing produced significant mosaic errors in the overlapping areas. The recommended Pix4D procedure is to manually identify tie points in the overlapping regions before merging the models, but this was not done here to allow comparison with the Photoscan automatically merged mosaic. For both softwares, combining images from separate flights and treating them as one chunk was our preferred option for moderate sized projects (<200 images).

Results of yield forecasts

A summary of yield forecasts made during the 2012 and 2013 growing seasons is presented in Table 2. The durations of sampling correspond to one two-person survey team and are 20% or less than resource requirements for traditional methods used by the industry. Absolute errors met the goal of 10% in 10 out of 11 surveys (91% rate, i.e. 10% with 90% probability was achieved), and did not exceed 12.1%. The desired error range has been expressed in terms of a percentage, but clearly a high percent error in a lower yielding block could be acceptable, whereas a small percent error in a large, high yielding orchard could have more serious consequences for the business.

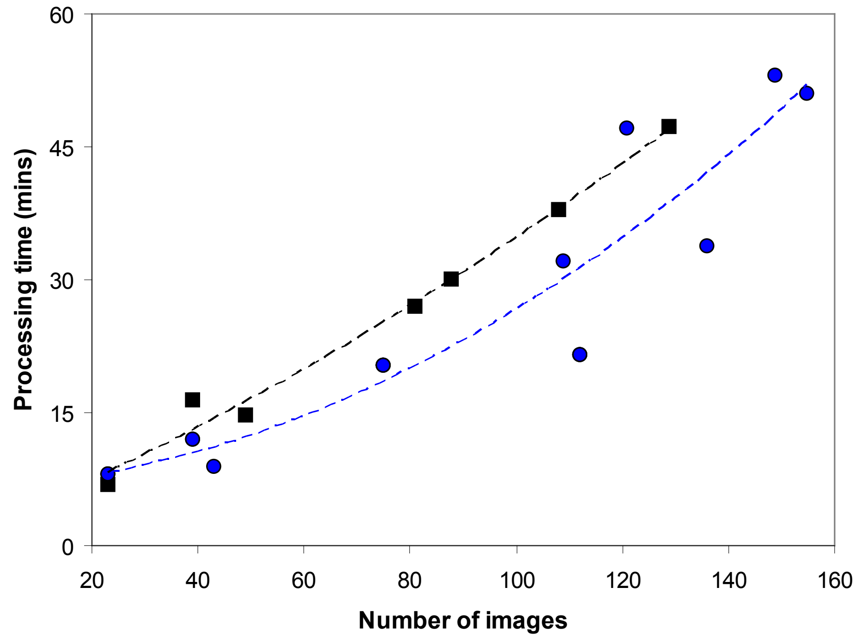

Fig. 8. Number of images versus processing time for multispectral images of table grape orchards using ● Photoscan Pro (low and medium accuracy GPS) and ■ Pix4Dmapper (rapid check using ½ image scale, low accuracy GPS).

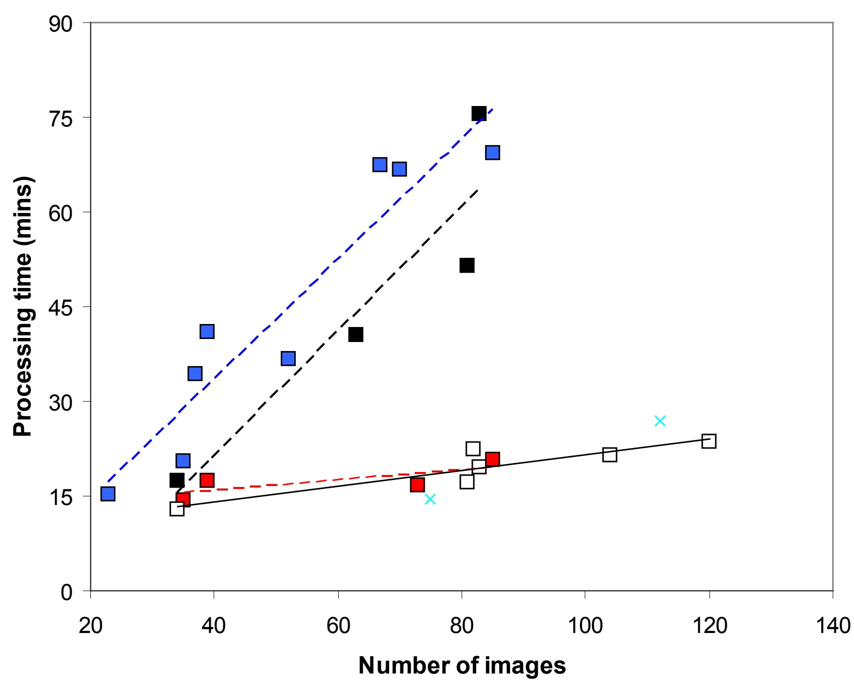

Fig. 9. Number of images versus processing time for multispectral images of table grape orchards taken in March-April 2014 using Pix4Dmapper: Rapid initial processing (½ image scale) and ■ low or medium □ GPS accuracy. Full initial processing (½ image scale) and ■ low or ■ medium GPS accuracy.

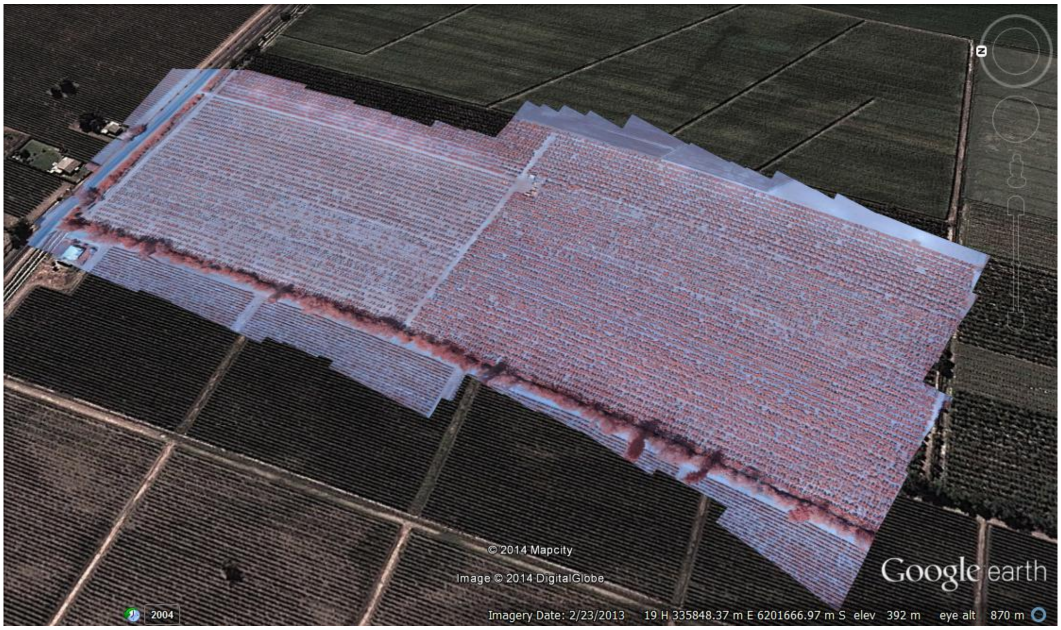

Fig. 10. Photoscan Pro orthomosaic of two blocks of a nectarine orchard created by automatic merging based on points of two projects of 116 and 130 images, respectively. Each project was processed using MK-GPS camera positions and low accuracy photo alignment in Photoscan Pro. Using medium accuracy image or chunk alignment did not improve the merging. No GCPs were used to improve georeferencing accuracy.

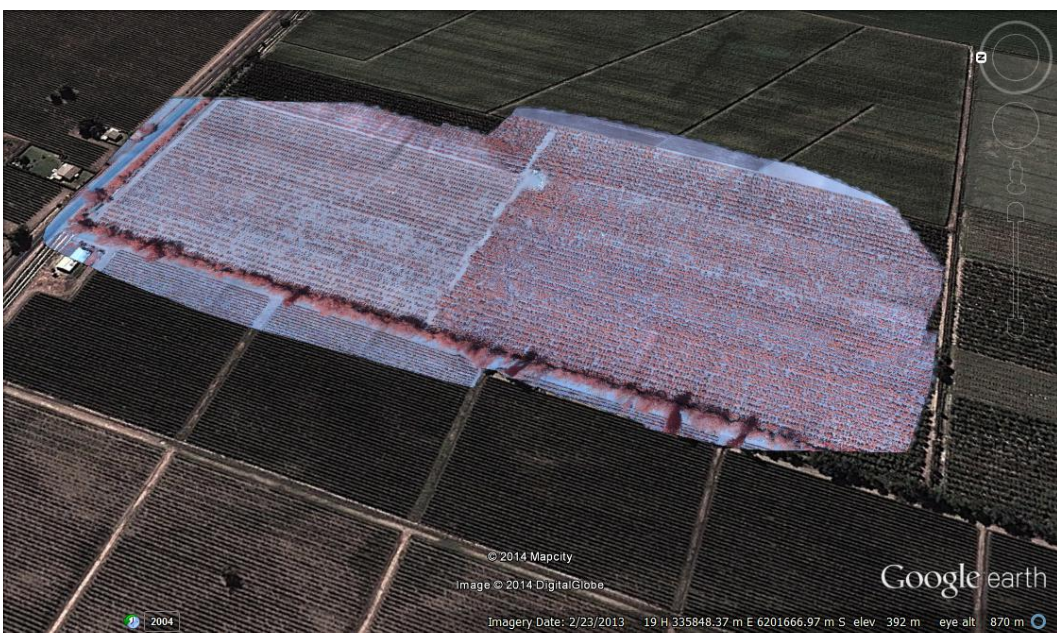

Fig. 11. Pix4Dmapper orthomosiac of the two nectarine blocks. Automatic merging of two projects with the same 116 and 130 images used for Fig. 10. Full initial processing feature recognition at ½ image scale and point cloud densification at ¼ image scale. No manual tie points were introduced to improve chunk alignment. GCPs were not used to improve georeferencing.

Table 2. Summary results of yield forecasts carried out in commercial plantations in Chile during the 2012 and 2013 growing seasons.

Species	Variety	Duration (mins)	Area (ha)	True error (kg)	True error (%)
Sweet cherry	Kordia	200	2.2	-1,702	–10.1
Sweet cherry	Lapins	153	2.4	-311	0.5
Sweet cherry	Bing	185	2.4	-938	–2.2
Sweet cherry	Bing	208	3.6	-120	–0.9
Sweet cherry	Bing	384	6.6	1,600	2.1
Sweet cherry	Tulare	170	1.3	64	3.2
Wine grapes	Carmenere	74	3.1	-1,779	–7.6
Wine grapes	Cabernet Sauvignon	577	50.2	1,279	0.4
Wine grapes	Cabernet Sauvignon	404	50.2	-21,078	–3.3
Apples	Granny Smith	312	11.3	-41,000	–12.1
Apples	Pink Lady	246	5.7	15,425	5.9

CONCLUSIONS

An Oktokopter-XL was evaluated for its suitability during prototype development of a fruit yield estimation service. "Pronofrut" uses high-resolution maps of orchard variability to design tree sampling schemes, followed by fruit counting on small sections of trees, and models to predict the error of estimation. The VTOL and automated waypoint flight capabilities allowed high-resolution remote sensing of small orchards with limited space for take-off and landing, up to 15 ha per 11 min flight depending on field shape. The hobby quality electronics required high maintenance because of loosening of components and damage to soldering due to vibrations under the windy conditions that are a feature of the Chilean geography. Therefore, the Pronofrut service will be based on UAVs equipped with industrial quality electronics and capable of longer flight times.

The performance of two programs on a laptop with 16 GB RAM, Photoscan Pro and Pix4Dmapper, was tested for creating orthomosaics of tablegrape orchards at two stages of growth. The goal was to process images rapidly for practical application in the field, rather than obtain the best possible mosaic. Both systems have their advantages and disadvantages in terms of functionality and performance. Both could be configured to provide good quality mosaics combining up to 160 images per project in less than one hour, or up to 80 images in this timeframe if a better mosaic quality was required. Using more precise GPS geotags reduced mosaic georeferencing errors and also processing times under medium accuracy image alignment settings, but had little influence on processing times using low accuracy image alignment settings.

In commercial yield forecasting trials in sweet cherries, wine grapes, apples and pears over two growing seasons, the goal of an error of 10% with 90% probability was met, seven of 11 projections having absolute true errors under 5%, three cases had errors between 5 and 10%, and one projection had an error of 12%. Survey times and costs in human resources were significantly lower than those associated with traditional methods used by the industry.

ACKNOWLEDGMENTS

The Pronofrut prototype development was partially funded by CORFO, Ministry of Economy, Chile (Project No. 11IEI-12803 2012-2014). Thanks to Reza Ehsani for his generous collaboration, to Jed Roach, Joe Maja and Jon Nielsen for sharing their experience with UAVs of the type used in this pilot study, to Fabian Rubilar and Oded Cohen and Marta Garcia-Fiñana for their contributions, and to field and technical support team members Victor Ahumada, Patricio Triviño and Cesar Gutierrez. Our appreciation is extended to the growers and export companies for access to their farms and production records.

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