Viticultural Mapping by UAVs, Part 1

Unmanned aerial vehicles provide data for precision viticulture

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Wine composition and quality are related to several vineyard variables that can be observed and managed in the field. However, vineyards are variable with respect to soil texture, moisture and depth and other variables such as organic matter, cation-exchange capacity and major and minor elements. As a result, vineyards also vary in vigor, yield, and fruit composition. Such variability within and among vineyards has been recognized for centuries and can be ascribed to a combination of soil, local climate, vine vigor, and other factors that ultimately affect wine quality. This is referred to as the *terroir* effect.[34]

EDITOR'S NOTE

This is the first installment of a two-part series on using unmanned aerial vehicles (UAV) to obtain data to help vineyards implement precision viticulture. The authors look at the different UAV platforms, hardware, sensors and image processing. The second article will review the use of UAVs in viticulture and will include the results of a study done in Ontario vineyards.

Traditional viticulture aims to maximize wine quality by tailoring variety selection and cultural practices to this local *terroir*. *Terroir* can be characterized in the field by mapping bedrock, soil, and vineyard meso-climate, and, at a finer level,by mapping variables such as soil moisture, vine water status, yield components and berry composition. Much of this mapping must be ground-based (including below the soil surface in trenches and drill holes). However, many of these variables now can be measured or estimated from the air using standard aircraft or satellite remote sensing technology.

Research in Ontario vineyards since 1998 has produced spatial maps and quantified spatial variability in soil composition, vine elemental composition, vigor, vine water status, vine winter hardiness, yield and berry composition.[15, 16, 25-28] These variables have been analyzed to determine relevant spatial relationships among them. Maps showing clear zones of different vigor, yield and vine water status have allowed wineries to produce wines from these unique zones that are different chemically and sensorially.[15, 16] Also, researchers have accumulated evidence of relationships between vine vigor and vine water status vs. wine sensory properties, and by doing so, with efforts of others elsewhere,[34] have helped explain the essence of the *terroir* concept.

Tools and methods have been developed relatively recently to observe and measure this inter- and intra-vineyard variation, and then to use the information for more efficient vineyard management.[5] These tools and methods can be used for the implementation of "precision viticulture" techniques. Simply defined, precision agriculture in general is informed agricultural management at a fine spatial scale. Its purpose is to enable targeted crop management due to the understanding and accurate mapping of the variations of crop or canopy properties of interest.

The implementation of precision viticulture involves three main steps:

1. Observation of vineyard variables associated with vineyard performance (data collection);
2. Interpretation and evaluation of the data;
3. Implementation of targeted vineyard management practices and/or selective harvesting strategies.[5]

Targeted vineyard-management practices might include timing and rate of application of fertilizer, water, pesticide or herbicide

KEY POINTS

The images produced by unmanned aerial vehicles (UAVs), or drones, have a higher spatial resolution than those produced by satellites and conventional aircraft. UAVs have other advantages: a higher flexibility of use, lower operational costs, and they are not affected by cloud cover.

The potential application of the acquired data should determine which remote sensing platform is chosen. When the goal is accurate mapping of intra-vineyard variability so that precision viticulture practices can be implemented, UAVs are the best choice.

UAVs equipped with appropriate sensors can collect useful information such as leaf temperature, vine water status, and canopy vigor. Those sensors can gather thermal, visible, hyperspectral and/or multispectral images. Hyperspectral sensors, for example, can gather a broader range of wavelengths; a thermal camera can gather image data to determine canopy variables such as water stress.

Acquired images are first orthorectified to remove the effects of tilt and terrain. The raw images are also georeferenced using ground control points previously measured with a ground-based device or UAV's onboard GPS. At that point, images can be mosaicked, or stitched, together using georeferenced-based stitching software.

sprays, and/or the use of mechanical or hand labor for pruning or harvesting.

The basic premise of precision agriculture is that inputs to farming practices are in response to information gathered with the intent of affecting outputs through an "information feedback-loop system."[5] Applied to viticulture, there is a focus on understanding the spatial and temporal (time-based) variability in wine grape production.[9] Grape growers traditionally have accepted variability within vineyards as normal, which is a basis for the *terroir* effect. With years of experience, zones in vineyards can be subdivided into individually rated vineyards of higher or lower quality. Increased availability of geomatics software has allowed grape growers to apply information from vineyards to precision agriculture, and to target inputs to specific regions of their vineyards.

Precision viticulture has been evaluated in New World regions California,[12] Australia[5] and New Zealand,[32] as well as Old World regions such as Spain[35-38] and France.[1] In Ontario, geomatic technologies were used to identify zones of different water status in Cabernet Franc,[28] Pinot Noir[15] and Riesling.[25-27] Zones of lowest water status were associated with highest monoterpenes in Riesling berries[16] and highest anthocyanins and phenols in Cabernet Franc.[25-27]

Data acquisition is central to the implementation of precision viticulture. Traditionally, data were acquired on the ground by thorough sampling of various canopy and/or soil variables. This kind of extensive sampling is both time-consuming and expensive. As with any sampling, the accuracy of the data is dependent on the size of the sample population. Remote sensing techniques have been developed to help mitigate drawbacks of traditional sampling.

Early remote sensing "platforms" were satellite- or conventional aircraft-based. These were used to acquire visible, multispectral, hyperspectral and thermal aerial images of vineyards utilizing various cameras and sensors. Multispectral sensors have several band measurements (e.g., green, red, near infrared [NIR]) in each pixel of the images they produce. Hyperspectral sensors measure energy in narrower and more numerous bands (up to 200) than multispectral sensors, which provide a continuous spectral measurement across the electromagnetic spectrum. Hyperspectral sensors are more sensitive to subtle variations in reflected energy, but they are also very expensive.

The usefulness of traditional aerial images initially was limited because of the images' low spatial resolution. Conventional aircraft, and to a lesser extent satellites, still are being used for research and precision viticulture, but the newest, very promising remote sensing technology that has emerged over the past decade, is the unmanned aerial vehicle (UAV) or drone. Drones can collect much more detailed information, and sometimes at a lower cost, than is possible from aircraft or satellites, mainly because they allow for acquisition of aerial images of a higher spatial resolution than other remote sensing methods. Once data from UAVs are gathered and processed, it can then be used along with ground-based measurements for precision viticulture. This is revolutionizing precision agriculture and promises to assist in defining wine-quality zones at lower costs compared to traditional remote sensing methods.

Proximal sensing

A simpler technology also might have potential use in vineyards and other crops. The recent introduction of GreenSeeker and other proximal sensing (ground-based) technologies could allow growers to identify unique zones within vineyards without use of aircraft, satellites or UAVs.[19] If these zones can be identified easily from the ground, and associated with clear differences in berry composition, it is possible that different wines of varying price points could be created from these zones at minimal cost. Data validation is still necessary, as with remote sensing, to determine if there are relationships between proximally sensed data and other variables of agricultural relevance, but the proximally-sensed data are relatively easy to access.

These ground-based technologies generally have been limited to agronomic crops such as corn.[3] In Ontario, GreenSeeker was used in six vineyards to find relationships between the normalized difference vegetative index (NDVI) values and variables such as yield, berry composition and vine water status.[25-27] Relationships were apparent between NDVI data collected by GreenSeeker vs. soil moisture and leaf water potential (Ψ), in addition to yield components and berry composition.

Furthermore, zones indicative of virus infection such as grapevine leafroll-associated virus 3 (GLRaV3) and grapevine red blotch virus (GRBV) could be defined using this technology. Leafroll is one of the most destructive and widespread diseases in all grape-growing regions, causing poor color development, and significant reductions in vine growth, size of clusters and berries, and Brix.[8] Red blotch is a recently discovered virus characterized by reddening of the leaf area between the main veins.[17] There has been limited experience in measuring unique vegetation indices ("spectral signatures") beyond NDVI in virus-infected plants, including one study for GLRaV[22] and another with GRBV.[20]

Remote sensing–UAV platforms

UAVs have been used for agricultural purposes only relatively recently. Satellites and manned aerial vehicles are still used to obtain aerial images for research and agricultural purposes. There are advantages and disadvantages to each of these types of remote sensing.

The time flexibility varies for the different types of remote sensing platforms. Use of manned aircraft depends on the availability of aircraft, and satellites are limited by their coverages.[3] Manned aircraft flights have fewer time constraints than satellites but can be expensive and difficult to organize.[4] The spatial resolution of the airborne platforms is also of great importance, depending on the application of the aerial images. Satellites can take

Figures 1a and 1b show examples of UAVs. Figure 1a (left) is a fixed wing SenseFly eBee; Figure 1b (right) is a multi-rotor type UAV flying over a vineyard.

images of large areas, but the resolution is generally not detailed enough for precision viticulture applications.[18] The spatial resolution of aerial images acquired by satellites or manned aircraft is optimally 20-50 centimeters per pixel.[33] UAVs have a higher flexibility of use and lower operational costs, and due to a UAV's ability to fly lower to the ground than other airborne platforms, the resolution of the aerial images can be much higher than with conventional aircraft or satellites. The resolution of UAV-acquired images can be as high as 1 cm. per pixel.

Matese et al.[18] compared three remote sensing platforms (UAVs, aircraft, satellites) in terms of their technical, scientific and economic performance. Aerial surveys were performed by all three platforms to access their ability to assess spatial variability of vegetation in two vineyards in the Veneto region of Italy. They characterized advantages and disadvantages into two main categories: *mission* and *processing*.

The *mission* category covers planning and execution of the aerial surveys. These include: ability to deal with different weather conditions and the scheduled practices of the vineyard; ability for the platform to reach the site being surveyed; the need for multiple flights to acquire the whole area of interest, and reliability of the platform. Compared to satellites or aircraft, UAVs operate closer to the ground (90-120 m; ≈400 ft.), have more flexibility in scheduling, and are not affected by cloud cover. However, UAVs have a much shorter range and less endurance than aircraft and satellites.

The *processing* category includes computation factors needed to transform the raw images into a final product. These factors include payload, resolution, precision, mosaicking (whereby a single image is created from multiple images) and geocoding efforts and processing time. The advantages of UAVs over aircraft or satellite are higher resolution and precision of the aerial images, but depending on the size of the area being flown, a greater number of images might be required to survey a given area. The increase in the number of images required to survey an area increases the cost and processing time due to increased mosaicking and geocoding.

Aircraft require fewer images to cover a survey area, so both processing cost and processing time are decreased, whereas satellite images require no mosaicking or geocoding but have a much lower spatial resolution. As for cost, an economic breakeven point between UAVs and the other remote-sensing platforms exists between 5 and 50 hectares of area coverage; use of aircraft remains at a similar cost with satellites over a large range of survey areas.

The choice of remote sensing platform depends on the anticipated application of the acquired data. The higher the spatial resolution of the image, the better it will represent the potential intra-vineyard variability of the survey area. Accurate mapping of the intra-vineyard variability is essential for appropriate implementation of precision viticulture practices. Thus, UAVs are the best choice for remote sensing in regard to precision viticulture implementation.

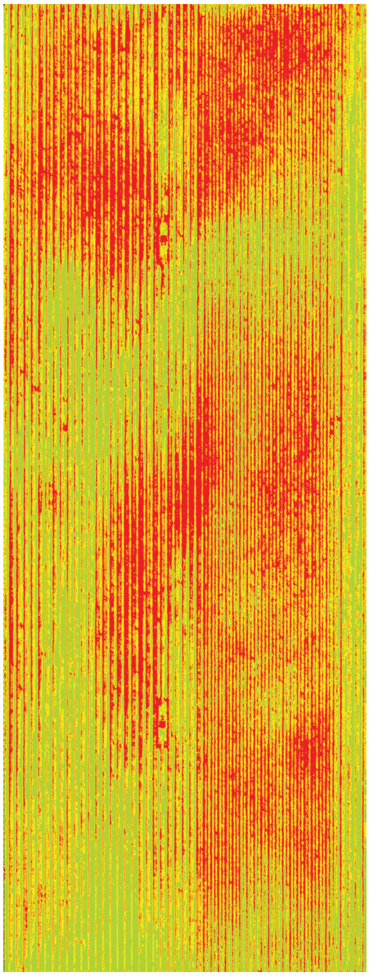
UAV hardware

UAVs are either a fixed-wing type platform (see Figure 1a) or a multi-rotor type platform (Figure 1b). The two different platforms allow for different payloads. For example, Zarco-Tejada et al.[37] used two fixed-wing UAVs, one with a 2-meter wingspan with a 5.8-kilogram payload and a UAV with a 5-m wingspan with a 13.5-kg payload. In comparison, a multi-rotor UAV platform used by Santesteban et al.[29] had a 2-kg payload, while a multi-rotor UAV platform used by Turner et al.[33] had a 1-kg payload. The payload dictates the length of flight and what sensors a UAV can carry. UAVs utilize both hardware and software to ensure that the UAV can retrieve data. The UAV hardware uses various components for flight navigation and accurate determination of the UAV's relative position. A flight control board consists of a pressure sensor and accelerometers to calculate and align the UAV in relation to gravity.[24] The navigation system, consisting of a digital compass[29] or a magnetometer[35] and a GPS module, allows a UAV to be programmed to fly autonomously and bring itself back to the operator.

Aside from hardware required for flight and accurate positioning, the hardware used for measuring of canopy variables of interest must be considered. Of crucial importance, UAV platforms have a camera mount for attaching a sensor or multiple sensors. The UAV "Viptero" had servomotors that compensated for the pitch and roll of the UAV.[24] They also used an elastic suspension system to decouple the camera from the UAV platform to dampen the vibration caused by the UAV's rotating propellers.

UAV sensors

UAVs equipped with appropriate sensors can collect useful information (leaf temperature, vine water status, canopy vigor, etc.) and the



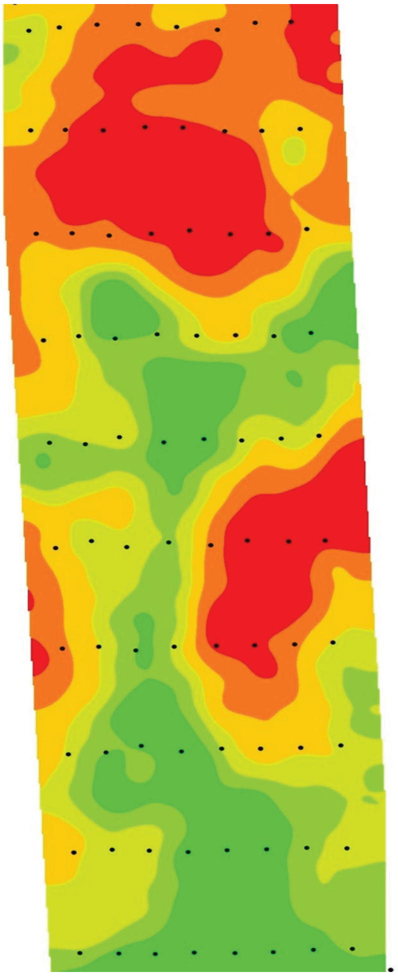


Figure 2a (left) is a normalized difference vegetative index (NDVI) map produced by mosaicking all the data points from a UAV flight. The NDVI map in Figure 2b (right) was produced by extracting UAV data from specific GPS locations adjacent to sentinel vines (indicated by the black dots) in the same vineyard.

resulting maps are more detailed and useful than those compiled using conventional aircraft. The sensors (cameras) can gather thermal, visible, hyperspectral and/or multispectral images for processing to obtain data on various canopy variables. A multi-camera array (MCA) is commonly used to obtain raw images needed to produce multispectral images.[2] Depending on the number of sensors, several specific light wavelength bands can be measured. An MCA is generally used to measure visible to NIR wavelengths, which allows for measurement of reflected light from the canopy in those spectral regions.[6]

With better resolution, the quality of the acquired data has improved due to the ease of determining the actual crop canopy data in the visible or multispectral image as well as the ease of removing the soil or cover crop data from the respective visible, thermal or multispectral image.

Image processing

Raw images taken by the thermal, multispectral, visible, or hyperspectral sensors require processing with help of computer software before being used for research or precision agriculture. Calibration is done first, and recovers focal distance, point coordinates and lens radial distortion of the camera.[4] Several images are taken from different locations and orientations, which allow for the calculation of the variables of the camera and the exterior orientation.

The images acquired by different sensors (e.g., thermal, multispectral, visible, hyperspectral) commonly used with UAVs also must be calibrated to avoid possible errors in the data.

A hyperspectral sensor can measure a much broader range of wavelengths than the 3 to 6 wavelengths measurable with a standard MCA.[36] For example, a hyperspectral sensor could have a range of 260 bands between 400-885 nanometers (one-billionth of a meter).[37] Drones also can utilize thermal cameras to gather image data to be used to determine canopy variables such as water stress.[29] An example of thermal camera had spectral range of 7.5-13 micrometers (one-millionth of a meter) and a -45° to 120° C dynamic temperature range.[4]

As sensor technology has evolved, so has the sensor's resolution of images. The resolution depends on the elevation of the UAV over its respective target; therefore, resolution can range depending on the aims of the study or application. For example, the resolution of an MCA can be as low as 0.056 m/pixel at an elevation of 150 m above the study vineyard,[24] a thermal camera can have a resolution as low as 0.13 m/pixel at 100 m above the study vineyard[29] and the resolution of a hyperspectral camera is 0.4 m/pixel at 575 m above ground level.[8]

Then the pictures are *orthorectified*, a process by which the effects of tilt and terrain of the image are removed. This can be done with a computer program and digital contour maps[24] or by a computer program using an inertial measuring unit installed on the UAV that is synchronized with the respective imager.[36] The raw images also require *georeferencing*, which can be accomplished by using Ground Control Points (GCP) that have been measured with a survey grade GPS device,[33] or by using the data acquired by the UAV's onboard GPS device. Errors in the accuracy of the data point locations are larger without use of GCPs. Once the images are orthorectified and georeferenced, the images can be mosaicked (stitched) together using georeferenced-based stitching software.[33] An example of a stitched image is shown in Figure 2a.

As UAV platform use is increasing, single computer programs are

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able to perform all calibration steps with minimal input by the user. These programs can take a set of images and automatically align them by feature identification, matching and bundle adjustment, which is refining a set of initial camera and structure parameter estimates to predict locations of observed points in a set of images. Previously, bundle adjustment, matching and feature identification were performed manually or semi-manually through a variety of computer programs.[4]

The images acquired by different sensors (e.g., thermal, multispectral, visible, hyperspectral) commonly used with UAVs also must be calibrated to avoid possible errors in the data.

In one example, two 2 x 2 m leveled dark and white targets were placed in a central location within the UAV flight pattern.[2] These targets were measured in the field with a calibrated field spectrometer at the same time as UAV image acquisition. Hyperspectral sensors can be calibrated using measurements made with a calibrated uniform light source at several levels of illumination and integration times.[36] All images, particularly hyperspectral, also require atmospheric correction. Aerosol optical depth was measured at 550 nm with a sun photometer in the study area during UAV flights.[36] The aerosol optical depth measurement simulates total incoming irradiance at 1-nm increments, which is then used for the atmospheric correction of hyperspectral images.

Another important factor in the processing of UAV images is the removal of the cover crop data from the space between the rows of vines. The data normally of interest is exclusively the spectral reflectance and/or thermal data of the vineyard canopy. Errors in the spectral and thermal canopy data can be caused by the inclusion of the between-row soil data and/or cover-crop data. In most cases these data can be isolated by setting a threshold spectral reflectance value, below which no data are included in maps. An example of a common error would be the inclusion of thermal bare soil data, since the soil would be expected to have a higher temperature than the vineyard canopy. The high-resolution nature of the images acquired by UAVs allows for the targeting of pure canopy pixels.

Computer programs now can segregate the pure canopy pixels from other background pixels. Santesteban et al.[29] used Agisoft Photoscan Professional (Agisoft LLC, St. Petersburg, Russia) to produce a digital elevation model that differentiates the image into two terms, row (vine canopy) and inter-row. The two terms were differentiated by their respective height, since the vine canopy is of a greater height than the ground or most inter-row cover crops. The extraction of pure vine vegetation pixels in the thermal, hyperspectral and multispectral high-resolution images allows for increased accuracy and precision in the data acquired by a UAV. After the images are appropriately processed, the data can be used to evaluate various canopy variables of interest. An example of a processed image is shown in Figure 2b. &

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