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## **Production,**

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## **Remote Estimation of Intra-Parcel Grape Quantity from Three-Dimensional Imagery Technique Using Ground-based Microwave FMCW Radar**

Dominique Henry, Hervé Aubert, Thierry Véronèse and Éric Serrano

For better benefits and yields, a good estimation of the quantity of grapes in a vineyard is necessary. In this paper, a three-dimensional (3D) imagery technique using conventional 24 GHz frequency-modulated continuous-wave (FMCW) radar is applied for detecting and remotely estimating the intra-parcel quantity of grapes. An estimation is possible even in the presence of natural or artificial clutters such as leaves, wood, or irrigation hoses. The microwave sensing is performed from the radar beam scanning of a vineyard, and an estimator is defined to derive the quantity of grapes in grapevines from the radar echoes distribution in the interrogated 3D scene. An algorithm based on contour detection is applied to the 3D radar image and a new parameter, called the *spread factor*, is defined for classifying the echo levels of grapes. The quantity of grapes is finally deduced from an appropriate estimator. This remote sensing approach brings a new and flexible solution for precision viticulture by estimating the grape quantity even for grapes hidden by leaves.

Currently, precision agriculture (PA) is mandatory to optimize crop yields, particularly for very large field areas. It requires an understanding of crop science and environmental impacts. When it concerns specifically the study of vineyards, PA refers to precision viticulture (PV). Two main technologies applied to PV can be identified:

- variable-rate-technologies (VRT) which use agricultural machines controlled by data from sensors and Global Positioning Systems (GPS)
- monitoring technologies, which focus on the observation of biological or structural parameters such as the leaf area index (LAI) [1], [2], the canopy and vigor (that is, leaf area and pruning weight), the chlorophyll content and the anthocyanin concentration [3], the sugar content [4], or the soil properties [5].

These technologies are usually integrated in satellites [1], [2], airborne [6] or un-manned aerial vehicles (drones) for multi-parcels monitoring while sensors based on the ground, such

as low frequency ground-penetrating radar (GPR) [7], LiDAR [8] or optical cameras [9], are good candidates for intra-parcel monitoring.

The major challenge addressed in this paper is how to monitor the quantity of grapes on grapevines. Being able to know the volume of grapes in advance, that is, before the crop harvest, offers many economic advantages: it allows predicting the appropriate quantity of materials to rent several months before the grapes are harvested, and it could estimate grape losses to be fairly compensated by insurance in case of severe weather conditions. Detection of grapes has already been investigated, mostly from optical technologies (see, e.g., [9]). The main drawback of such an approach is that grapes may be partially or completely hidden by leaves or wood and consequently, they cannot be easily detected by optical sensors. Moreover, volume estimation of grapes is difficult since only 2D images are available from such sensors.

In this paper, the objective is to estimate the volume of grapes on grapevines using a ground-based FMCW radar operating at 24 GHz. Compared to optical systems, the microwave radar technology allows remotely sensing the scene in depth and detecting most hidden grapes. Microwave frequencies, especially super high frequencies from 3 to 30 GHz, are advantageously used here for grape quantity estimation since the water in the grapes is highly reflective at these frequencies. We show here that the estimation of grape volume can be derived from the proposed microwave sensing even in the presence of natural or artificial clutters such as leaves, wood, and irrigation hoses. The sensing is performed by radar beam scanning of a vineyard. An appropriate estimator is proposed for deriving the quantity of grapes in grapevines from radar echoes distribution in the 3D scene.

### Measurement Setup

A 24 GHz FMCW radar used in the experiment generates a frequency-modulated signal with a carrier frequency  $f_0 = 23.8$  GHz and a bandwidth  $B = 2$  GHz. The bandwidth is a crucial parameter leading directly to the theoretical depth resolution:

$$d = \frac{c}{2B} = 7.5 \text{ cm}$$

where  $c$  denotes the speed of light in vacuum. The signal is transmitted using a horn lens antenna (Tx antenna) with a gain of 28 dBi and a beamwidth of  $6^\circ$ . Electromagnetic waves backscattered by the grapevines are received by a 1x5 patch array antenna (Rx antenna) with a gain of 8.6 dBi and a beamwidth of  $60^\circ$  in azimuth and  $25^\circ$  in elevation. The backscattered signal is received by the radar antenna and is converted into a beat frequency spectrum,

which gives the echo level of the grapevine in a given direction as a function of the interrogation range. The power transmitted by the radar front-end is 20 dBm (100 mW). The radar and antennas are mounted on a mechanical platform controlled by a computer unit (Fig. 1). The system performs a rotation of the Rx and Tx radar antennas with an accuracy of  $1^\circ$  in azimuth  $\theta$  and in elevation  $\varphi$ . This rotation allows performing the mechanical scanning of the radar beam, and the 3D representation of the grapevine echo level distribution can be derived.

**Insert Fig. 1 here**

### **Vineyard Clutter Response**

3D 1.5 m radar images are taken in a vineyard in Gaillac, France. The microwave FMCW radar is ground-based and moves between rows of grape vines. A beam scanning is performed in front of each plant at a distance of 1.0 m with angles of  $\pm 30^\circ$  in azimuth and  $-10^\circ$  to  $30^\circ$  in elevation. This scanning allows measuring the beat frequency spectrum in 2501 directions in the interrogated scene. As an illustration, the cut plane of the obtained radar image is shown in Fig. 2. Vine rows are easily detectable in this image because of their specific geometrical and physical properties. Rows are separated by a distance of 2.5 m while the separation distance between grapevine plants is 1 m. These plants are composed of leaves, grapes, and wood. The water inside grapes and leaves has a relative permittivity around 30 at a frequency of 24 GHz and generates high reflection of the incident microwave field. Non-organic clutters (such as iron wires or irrigation hoses) also create strong electromagnetic echoes.

**Insert Fig. 2 here**

### **3D Scanning of Grapevine Plants**

For the estimation of grape volumes, the electromagnetic echo levels are measured from 0.5 m to 1.5 m in front of various grapevine plants. Two varieties of grapes are studied here: Gamay and Black Manseng (Fig. 3). Radar measurement of three plants of each variety is performed before and after the grapes are harvested. As observed in Fig. 3, these varieties have many leaves, and consequently, a detection of all grapes from optical sensors is highly problematic, while the microwave 3D scan allows sensing in depth within the plants and 1.5 m detection of hidden grapes. For fixed volumetric mass density of grapes, the grape volume increases linearly with the mass and the water content. Consequently an estimation of the volume of grapes on a plant can be derived from the measurement of the echo level generated by the water content in the grapes.

**Insert Fig. 3 here**

The measured data from the 3D radar beam scanning are originally obtained in spherical coordinates. A Cartesian conversion is applied and 93324 voxels are then derived for each grapevine. The resulting volume resolution depends on the size of the voxel  $s$  defined by:

$$s = d_x \times d_y \times d \quad (1)$$

where  $d_x$  and  $d_y$  denote, respectively, the x and y cross-range resolutions defined by the interpolation during the coordinates conversion. Here,  $d_x = d_y = 1.75$  cm and consequently, the volume resolution is  $s = 23 \text{ cm}^3$ . Fig. 4 shows the resulting 3D scan of a Gamay grapevine plant. The echo levels are displayed by using isosurfaces, which represent layers of echo levels sharing the same value. These layers are stacked together and provide a convenient way to display the 3D distribution of echoes. It can be observed that regions with higher echo levels are located near leaves and grapes above a height of around 60 cm. The trunk is also easily detectable at  $x = 0$  m with a height below 60 cm. The identification of regions containing leaves and grapes is not easy at first glance. However, the analysis reported in the next section will allow estimating the volume of the grapes on the plant.

**Insert Fig. 4 here**

### **Grapes Quantity Estimation**

To estimate the quantity of grapes from the measured radar echoes distribution in the interrogated 3D scene, the analysis of each echo level generated by the clutter is performed. The objective is to determine if echoes are due to the electromagnetic backscattering by grapes or by the clutter such as, e.g., the leaves, trunk, wood or iron wire. Knowing that grapes grow at heights from 60 to 90 cm from the ground, the proposed analysis considers only echoes located between these two heights. For classifying these selected echoes, a standard marching squares contour algorithm is applied [10], and 2D contours are obtained by defining an initial echo level in all xy-planes. The initial echo level is computed as a function of the mean echo level in the 3D scene. This level depends mainly on the grape variety but also on the density of the leaves. For both Gamay and Black Manseng grapes, initial echo level contours are of -80 dB. In a given xy-plane, only contours enclosing a surface between  $10 \text{ cm}^2$  and  $100 \text{ cm}^2$  are considered. This surface restriction removes from the clutter undesirable (very high or very low) echo levels. As a matter of fact, surfaces that are smaller than  $10 \text{ cm}^2$  may generate false detections while surfaces higher than  $100 \text{ cm}^2$  may be due to multiple electromagnetic scatterers. The contour algorithm is iterated with higher echo levels until no contour encloses a surface larger than  $100 \text{ cm}^2$ .

**Insert Fig. 5 here**

Fig. 5 shows contours computed from the previous Gamay grapevine plant in a cut-plane at  $z = 0.825$  m. Echo levels are identified from their positions, and red, green, purple, brown, and black dashed contours illustrate the trunk, leaves (or other), grapes, ground, and echoes that are not analyzed, respectively. Contours of each xy-plane are combined to make a list of echoes in the interrogated 3D scene. For each echo, different parameters are calculated:

- its position (or barycenter);
- its mean value;
- its standard deviation value;
- its maximal value;
- its *shape*, e.g., the height, width and depth; and
- its *volume*, that is, the number of voxels contained within the contour multiplied by the volume resolution  $s$  given by (1). Data associated with the purple contours in Fig. 5b are potentially generated by the electromagnetic scattering of grapes, and consequently, they must be analyzed to avoid eventual false detections of grapes. A new parameter to perform the echoes classification is defined here as follows:

$$\chi = \frac{C_{Max}}{\hat{C}} \quad (2)$$

where  $C_{Max}$  denotes the maximal value of measured echo levels, and  $\hat{C}$  designates the arithmetic mean of the echo levels. We call this parameter the *spread factor*. 3D contours with close spread factors have very similar distribution of echo levels. To highlight the physical meaning of this new parameter, Fig. 6 reports the computed values of  $\chi$  for Gamay and for Black Manseng grapevine plants before and after the grape harvest. For example, for the Gamay variety, the number of contours such that  $\chi > 0.95$  is higher before the crop harvest than after the crop harvest. Moreover, for the Black Manseng variety, the number of contours such that  $0.98 > \chi > 0.94$  is higher before the crop harvest than after the crop harvest. Consequently, grape varieties are characterized by a specific spread factor, which can be used for classification purposes. If you let:

$$V_{EST} = N_{EST} \cdot s \quad (3)$$

be an estimation of echo volume, where  $N_{EST}$  is the number of voxels for which  $\chi \geq 0.95$  in the case of the Gamay variety (or for which  $0.94 < \chi < 0.98$  in the case of the Black Manseng variety). Note that a correction factor must be applied to  $V_{EST}$  for each grapevine by

determining the number of voxels in a region without grapes (for example, at a height higher than 0.9 m). Fig. 7 reports the estimator  $V_{EST}$  as a function of the mass of the grapes. The mass has been measured just after the crop and radar interrogation. We observe that  $V_{EST}$  increases linearly with the grapes' mass with a slope of  $0.17 \text{ g/cm}^3$  (the coefficient of determination is found to be  $V_{EST}$  and a standard error of 0.02g). This convenient linear variation is obtained from detected grapes but also from undesirable scatterers in the 3D scene such as leaves and wood. The volume of grapes can be estimated by using a unique grapevine for calibration purpose. Assuming that the volumetric mass density of grapes is known for a given variety, the physical volume of grapes can then be remotely derived directly from the computation of  $V_{EST}$ .

**Insert Fig. 6 here**

**Insert Fig. 7 here**

## **Conclusion**

In this paper, a solution to remotely estimate the volume of grapes is proposed by performing a 3D beam scanning of a ground-based 24 GHz FMCW radar. A new parameter called the spread factor is defined to perform a classification of the measured 3D echo levels. By choosing the appropriate spread factor for a given grapevine variety, an estimator based on the number of voxels is computed to derive the quantity of grapes (mass or volume, if the volumetric mass density of grapes is known) in each grapevine, even if the grapes are hidden by leaves. This estimation has been applied with success to two grape varieties and to six grapevines. The sensitivity of the estimator is found to be  $0.17 \text{ g/cm}^3$  for a linear model with  $R^2 = 0.947$  and a standard error of 0.02g. This model will be applied to numerous radar data for reaching the targeted accuracy (<10%) of grape volume estimation.

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### **Figure Captions:**

**Fig 1.** Ground-based microwave FMCW radar proposed for precision viticulture.

**Fig 2.** Two-dimensional polar plot of electromagnetic echoes from the vineyard (cut-plane  $\phi = 0^\circ$ ). High echo levels allows locating the vines rows.

**Fig 3.** Grapevines of (a) Gamay and (b) Black Manseng.

**Fig 4.** Three-dimensional representation of echo level distribution of a Gamay grapevine. The region of height comprised between 0.6 and 1.2 m corresponds to the location of grapes, wood, and leaves.

**Fig 5.** Echo level contours (a) in a cut-plane  $z = 0.825$  m and (b) in the interrogated 3D space.

**Fig 6.** Number of 3D contours as a function of the so-called spread factor  $\chi$  for (a) Gamay and (b) Black Manseng grape varieties, after and before the crop harvest.

**Fig 7.** The grapes mass for three grapevines as a function of the estimator  $V_{EST}$ . The mass of grapes has been measured after crop and radar interrogation.