Determining shape of strawberry crops with spherical harmonics

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***Abstract*—Shape descriptor and shape reconstruction are two challenges found in computer vision and graphics as well as in perception for robotics, especially for some fields such as agri-robotics (robotics for agriculture). Being able to offer a reliable description of shape that can also translate directly into an high fidelity model of the shape, would be of high importance for a lot of applications such as phenotyping or agronomy. In this paper we report on our work on using spherical harmonics to offer efficient representation of strawberry shapes and we validate them by reconstructing the fruits. The reconstruction achieve extremely close results to the original shape (less than 1% deviation) and the representation reduce the complexity and improve compactness by a large factor (minimum 100).**

***Index Terms*—3D, spherical harmonics, point clouds, phenotyping**

I. Introduction and Related work

An accurate description of crops shape is an important challenge in horticulture. Automating their creation and allowing a complete 3D reconstruction of the objects from it, would improve greatly phenotyping or other agronomy tasks. In this work, we use the mathematical concept of spherical harmonics to create a representation of strawberries' shape and study their fidelity and accuracy by reconstructing the fruits with them. Furthermore, this new representation offers a more compact and efficient representation of the shape than using directly points.

The use of spherical harmonics as a 3D shape representation was first proposed in [1]. The practical use of that representation as a rotation-invariant feature descriptor was later introduced in [2]. Some of the drawbacks related to poor results with discontinuous surfaces were addressed by the introduction of weighted spherical harmonics [3]. Applications of Spherical Harmonics as shape descriptors include [4] who applied them to summarise shapes of sand particles obtained from X-ray micro-tomography. In [5] the authors propose to use Spherical Harmonics to represent the 3D shape of agricultural materials such as grains and show this representation to be a more compact and efficient representation than previous methods and meshes/point clouds. Our work takes inspiration from [5], reducing the process complexity to match the symmetrical characteristics of strawberries.

II. Methodology

To explain our approach we detail in this section how spherical harmonics transformations are computed and implemented.

Spherical harmonics represent a solution to Laplace's equation,defining a complete set of angular functions in spherical coordinates. We can use it to define the surface f of an object as described in Equation (1). In this equation the surface is formulated as the combination of all spherical harmonics $Y_l^m(\theta, \phi)$ with their respective coefficients c_l^m. In [4] they are computed over three components : $c_l^m = (c_{xl}^m, c_{yl}^m, c_{zl}^m)^T$, and each point of the shape are associated to its spherical coordinates with smoothing methods over each of these components.

$$f(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} c_l^m Y_l^m(\theta, \phi) \tag{1}$$

We detail in Equation. 2 the spherical harmonics for degree l and order m, with P being the Legendre functions associated with it. Spherical harmonics are computed on θ (azimuthal coordinates) between $[0, 2 * \pi]$ and ϕ (polar coordinates) between $[0, \pi]$.

$$Y_l^m(\theta, \phi) = \sqrt{\frac{(2l+1)(l-m)!}{4\pi(l+m)!}} e^{im\theta} P_l^m(cos(\phi)) \tag{2}$$

To go from the spherical mapping of an object to its spherical harmonics representation we need the forward transformation defined in Equation (3). The implementation of these integrals varies from paper to paper [6], [7]. We use the representation of these harmonics as detailed in Equation (4). All the harmonics for a given position on the sphere can be represented as a Matrix $\hat{Y}$ for all degree and orders up to m and l. Using the definition of the inverse spherical harmonics in Equation (1), we can define the dot product of the coefficient by the harmonics matrix. Finally, these coefficients can be expressed as the dot product of our mapping on the sphere by the inverse of the harmonics matrix. Also efficient in terms of memory and simplicity, the forward spherical harmonics transform is not computationally efficient but can be accelerated through lookup tables and down-sampling of our point clouds.

$$c_l^m = \int_0^{\pi} \int_0^{2pi} d\phi d\theta f(\theta, \phi) Y_l^m(\theta, \phi) \tag{3}$$

Fig. 1. Example of strawberry point clouds (left example for each pair) and their reconstructions(right example for each pair), for two particular shapes.

$$
\begin{aligned}
\hat{Y} &= Y_l^m(\theta, \phi) \\
f(\theta, \phi) &= \widehat{C}\hat{Y} \\
\widehat{C} &= \widehat{Y}^{-1} f(\theta, \phi)
\end{aligned} \tag{4}
$$

As spherical harmonics are intrinsically symmetric over ϕ, one can, similarly to [5] we take separated portions of the shape and generate their spherical harmonics representation independently for more precise control over the shape and its details. We align the strawberries over their principal axis along the horizontal axis and recreate the two halves separately. To recreate each strawberry we change their points to spherical coordinates and using the forward harmonics transform, compute the coefficients up to an arbitrary degree. We then use them to recreate the strawberry shape from the unit sphere. Our sample set is composed of 15 3D point clouds of strawberries from [8], representing all the different shapes as described in the industry phenotyping reports.

III. Results

In this section, we present some of our results and analyse them toward their possible applications.

In Table I we show the quantitative results obtained using spherical harmonics for the reconstruction of our set of strawberries. We compare the average volume and the average surface area, with their deviation. With such a high degree of harmonics, the deviation is very small for most of our samples and his coming from fined details rather than important shape features.

In Figure 1 we present some qualitative results of two different strawberries point clouds reconstructed using spherical harmonics. We use 30 degrees of harmonics, for a very precise and detailed reconstruction (seed bumps and calyx shape with a lot of details). At this level, only a few details are smoothed out and only very sharp angles and edges are not recreated.

In Figure 2 we present an example of the coefficients for one of the strawberries. We showcase the coefficients responsible for most of the shape of the strawberry omitting the one influencing more fine details. As per our way of processing both halves of the strawberry independently, we have them separated by the centre of the chart. We also omit the first coefficient, associated with the first harmonic as it is responsible for the round shape of the strawberry, present in every strawberry and non-discriminative other than for scale. The first twenty harmonics are more important for the shape and specificity of the global strawberry, while the following one corresponding to more fine details. This representation offers a compact (maximum a thousand parameters for high precision reconstruction) way to represent the strawberry shape with relatively close fidelity, compared to the hundreds of thousands points composing the object.

TABLE I
THE VOLUME AND SURFACE AREA ESTIMATION RESULTS FROM THE RECONSTRUCTION PROCESS OF 15 3D MODELS OF STRAWBERRIES (NOTE THE OBJECTS WERE SCALED DURING CAPTURE PROCESS).

	Original	Reconstructed	Deviation
Volume $(\mu \pm \sigma)$ cm^3	45 ± 46	45 ± 46	$\sim 1\%$
Surface area $(\mu \pm \sigma)$ cm^2	280 ± 160	277 ± 160	$\sim 1\%$

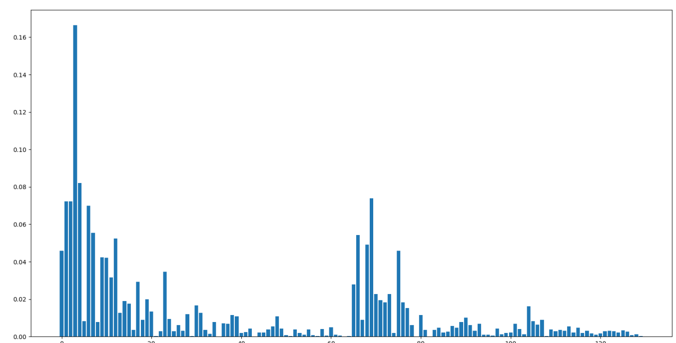

Fig. 2. Spherical harmonics coefficients responsible for main shape information

IV. Conclusion and discussion

We have presented an efficient way of describing and reconstructing strawberry shape information. It offers a compact way of representing the shape of such objects and simplifies future work done on processing this shape information. Future work would include reconstruction from partial view, automatic phenotyping from the compact representation, generation of new fruit models etc.

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