

# Plant Leaf Surface Mesh Fitting Using RGB-D Sensors

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## Abstract

Plant phenotyping is an emerging science that assesses plant growth and development from the interactions between genetic variations and environments. Automatic plant phenotyping relies on sensors to measure plant leaf shape and pose in limited growth spaces. We propose a new method to significantly improve the accuracy of plant phenotyping by detecting and modeling the leaf 3D surface with inexpensive close-range time-of-flight RGB-D sensors. While these sensors provide dense depth, the noise in the depth is large compared to the surface features, making high-fidelity surface estimation challenging. Our method seeks to maximize the resolution and accuracy of the estimated surface by combining features from multiple modalities of the sensor including dense depth and color. The result is an automated surface mesh that captures leaf boundary and shape information and filters out much of the noise. Experimental results on known shapes and real plant data show that our method is clearly better than the existing solutions.

## 1. Introduction

In order to meet the increasing needs for food and materials, researchers aim to produce sustainable plants with high yield and high resource-use efficiency by testing approaches ranging from molecular biology to field management [28]. In this process high-throughput plant phenotyping is the major bottleneck [6]. New automated methods to non-invasively measure plant phenotypes including growth, plant structure, leaf layout and orientations, photosynthesis and productivity, are highly expected [13, 19, 28].

An important step in estimating all of the plant phenotypic properties is to obtain 3D shape and pose for all the plant leaves [19], which has to be measured in a limited growth space with minimum disturbance, making it impractical to use scanning lasers for shape modeling. As an alternative, we propose to mount close-range time-of-flight RGB-D sensors in the growth chambers, acquire color, IR-reflectance and range data, and estimate leaf shape through

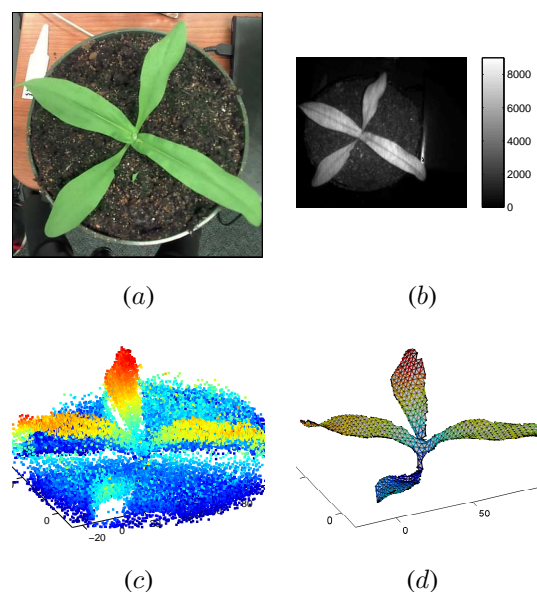


Figure 1: Illustration of sensor data. (a) Portion of color image. (b) IR reflectance image with reflectance values. (c) Portion of a single depth image surrounding plant averaged over 60 frames to reduce noise, and projected into 3D showing significant remaining depth noise. (d) The mesh resulting from the algorithm in this paper using data from the color, depth and IR reflectance images. Units of 3D plots are mm.

building leaf 3D mesh models (see Fig. 1). Mesh fitting to 3D point clouds and depth maps enables visualization and leaf shape analysis by providing a surface topology and geometry to a point cloud [24, 31]. A mesh can efficiently compress dense scanned data and mesh fitting methods have been developed that adhere to the underlying shape and preserve geometric features such as creases [8, 10]. However, while time-of-flight RGB-D sensors are small, inexpensive and provide dense 3D surface sampling of objects, they pose a challenge to surface modeling of small objects due to large depth noise. Specifically, in our leaf 3D mesh modeling ap-

plication, the pixel-depth noise has a standard deviation on the order of the surface feature sizes (see Fig. 3). In this paper, we present a new solution to automatically build precise 3D mesh models of plant leaves using time-of-flight RGB-D sensors. We achieve this through formulating an optimization that minimizes depth noise and adds a curvature-based regularization.

One goal of automated 3D leaf modeling has been to generate realistic foliage for graphics [5]. Here known leaf shapes are fit to 3D structure from motion data producing realistic-looking foliage, but not necessarily a close approximation to the actual plant leaf shapes and poses. In [23] an interactive system enables semi-automatic estimation of complex arrangements of leaves. In [3, 2] plant leaves are automatically segmented and fit using color and time-of-flight data enabling robotic arm inspection. This work is most similar to ours and they use a similar sensor, but the goals are quite different. They automatically segment and estimate poses of densely spaced leaves using simple geometric models (planes and parabolas) to obtain leaf poses and rough shape approximations. Our goal, on the other hand, is not segmenting overlapping leaves, but rather to estimate complex 3D leaf surfaces as precisely as possible from the noisy data.

We propose a new mesh generation algorithm that has the following advantages:

- It resolves complex 3D leaf shapes despite large noise in the range images by leveraging multiple sensor modalities.
- Boundary edge features in the high resolution color image are used to help select and constrain vertices and mesh edges.
- The errors in depth are modeled along camera rays and minimized during fitting to facets.
- A regularization term modeling curvature is incorporated and a linear approximation enables a fast, least-squares shape fit.

## 2. Related Work

This paper builds on past work in the areas of leaf detection, segmentation and 3D shape fitting. Detection and segmentation of leaves can be challenging and there have been numerous research efforts in this area.

One class of approaches to leaf segmentation is through combining many low-level features. Simple cues like color, texture and local brightness and its combination are extensively used in contour and image boundary detections [17, 27]. Active contours can enhance segmentation and boundary regions [18]. LeafSnap [12], identifies leaf species from

photographs of leaves and in segmenting leaves uses Expectation Maximization of color distributions in the HSV color space. Pape et al. [22] segment overlapping leaves using 3D histograms cubes in the Lab color space.

Another class of segmentation methods uses parametric models. Manh et al. [16] use deformable templates in weed leaf segmentation which consists of fitting a parametric models to leaf outlines in image, by minimizing energy term related to internal constraints of the model and salient features of the image, such as color of plant. In related work, Toshev et al. [25] use both geometric properties of object boundary edges and coherent saliency cues distinct from the background.

A third approach includes Wei Ma et. al [15] who proposes modeling leaves using voxels. It aims to deal with the highly cluttered background by extracting the more visible apex features (position, middle axis and neighborhood) of the leaves instead of intelligent segmentation, from the volumetric data recovered from the images. Volumetric data provide pose and position of 3D leaves, and the 3D leaf shapes can be extracted from the optimized voxels.

The focus of this work is accurate leaf boundary and surface estimation, rather than robust segmentation. We restrict ourselves to relatively simple conditions including non-overlapping leaves, low background clutter, and single plant types. On the other hand we do not want to constrain leaf boundaries with prior parametric shape models which could prevent accurate leaf shape estimation for leaves that do not fit the models. Hence we rely primarily on color cues [1] for segmentation.

Mesh fitting to range data has been well studied. Much work address how to combine range maps from different perspectives including early work on zippered polygons [26]. The method developed by Curless and Levoy [7], and built on by later work [9, 20], populates a weighted voxel occupancy grid from the depth data and recovers the surface by triangulating an isosurface. Advantages of this method include that surface topology is automatically determined, additional data can be readily incorporated, and it incorporates directional uncertainty of range data into the models. Recent approaches for environment modeling from RGB-D cameras including [30] and Kinect Fusion [9, 20]. These voxel methods work well on room-size scales where the sensor noise is significantly smaller relative to object size than in our application.

Model-based leaf estimation is another approach to our problem. Some methods [23, 5] fit leaf templates to sparse 3D data. Another method is to fit geometric models, such as parabolas, to leafs[3, 2]. However, none of these models are flexible enough to capture curved leaves with complicated shapes. And it is this task of estimating the surface shape variation of plant leaves that is the focus of this work.

### 3. Sensor Overview

We explore using a new class of RGB-D sensor such as the Creative Sens3D [21] to build 3D mesh models of plant leafs. The sensor contains a high resolution color camera ( $1280 \times 720$  pixels) adjacent and parallel to a lower resolution depth camera ( $320 \times 240$  pixels). A flash IR emitter adjacent to these cameras illuminates the scene and depth sensor measures the time-of-travel for the reflected light as well as its reflectance over its pixel grid. These modalities are illustrated in Figure 1.

In order to gain the most from the sensors, we model effects due to sensor alignment and sensor noise. Pose alignment between the color and depth cameras, as well as intrinsic parameters, are calibrated using Zhang’s method [32]. In the rest of this section occlusion effects between sensors and the depth noise are modeled.

#### 3.1. Occlusion Modeling

The color camera is offset to the side of the depth camera, and so at depth discontinuities, such as leaf boundaries, some pixels visible by the depth camera may be occluded in the color camera. During mesh fitting these occluded pixels may project into the leaf mesh and result in large depth distortions. In [3] an interpolated z buffer is used to detect these occluded pixels. Here we present a visibility analysis method that is closer to the stereo occlusion modeling [4]. We do not require rectification as there is no pixel matching, and we use the known horizontal offset of the color camera from the depth camera.

A row of pixels in the depth camera are projected out into world coordinates, as illustrated in Fig. 2. Then using just the planar position of the color camera (and not its orientation), the angle to the color sensor,  $\theta(i)$ , can be calculated for each depth pixel  $i$ . Starting from the left-most pixel we incrementally step through all the pixels and set  $\theta_{\max}(i) = \max(\theta(i), \theta_{\max}(i-1))$ . This keeps track of the largest angle seen so far in the row traversal. Occluded pixels are then simply:

$$\theta(i) < \theta_{\max}(i). \quad (1)$$

This assumes occluding objects are wide enough not to be seen around. Results of this are shown in Fig. 4(b). The only filtering done on this is to remove single occluded pixels with no neighbors as these occlusion labels are likely to be due to noise.

#### 3.2. Noise Characterization

Depth measurements are performed along pixel rays, and hence depth noise is modeled as a one dimensional random variable,  $\varepsilon$ , along each pixel ray direction. We observe significant noise correlation between sequential measurements

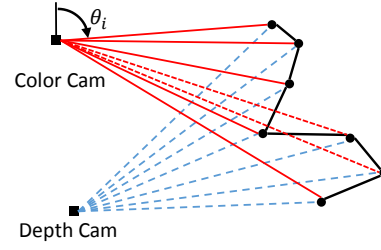


Figure 2: Occlusion modeling. The red dotted lines indicate pixels measured by the depth camera that are not visible to the color camera, as predicted in Eq.(1).

of a given pixel, and so do not assume sequential measurements are independent. On the other hand averaging multiple measurements reduces the noise. To capture partial correlation we propose the following simple noise model.

The depth noise,  $\varepsilon$ , is modeled as the sum of an image-varying term,  $\varepsilon_I$ , and a scene-varying term,  $\varepsilon_S$ :

$$\varepsilon = \varepsilon_I + \varepsilon_S. \quad (2)$$

The term  $\varepsilon_I$  models the random change in depth for camera pixels of subsequent images of a static scene from a static camera. To quantify this term we measured the standard deviation  $\sigma_I$  in depth of each pixel for a batch of 300 images of a fixed scene containing a flat matte surface. We repeated this at different poses and depths, and with different surface albedos. While target depth, inclination, albedo, and pixel position are all correlated with  $\sigma_I$ , we found that the best predictor for  $\sigma_I$  was the IR reflectance intensity, as shown in Figure 3. For typical scenes the single measurement noise in depth is roughly 5mm, although for low reflectivity objects or objects at long range this noise can increase significantly. Fortunately plant leafs are good IR reflectors.

Averaging depth measurements of a fixed scene will reduce the noise from  $\varepsilon_I$ , but will not reduce the noise from  $\varepsilon_S$ . This latter scene-varying term is constant for a static scene, but changes when the scene changes. To characterize this noise we first eliminated (approximately) the image-varying noise contribution by averaging over a large number of images (300). Then assuming  $\varepsilon_S$  is independent and identically distributed between pixels, we measured the variance of the pixel depth errors between a known flat surface and the estimated surface. In our experiments we obtained  $\sigma_S = 6.5mm$ , and found that it was insensitive to changes in depth.

The total pixel noise can be estimated assuming independence of  $\varepsilon_I$  and  $\varepsilon_S$ , and is given by:

$$\sigma^2 = \frac{\sigma_I^2}{N} + \sigma_S^2, \quad (3)$$



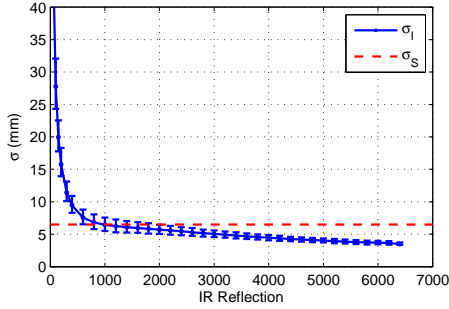


Figure 3: Image-varying noise,  $\sigma_I$ , is predicted well by the IR reflectance in raw units returned by the camera, see Figure 1(b). The scene-varying noise,  $\sigma_S$ , is plotted for comparison.

where  $N$  is the number of images averaged over. When averaging 5 or more depth images the scene-varying contribution,  $\sigma_S^2$ , will dominate. There are additional sources of noise not modeled by this. These include object specularities, and mixed-depth pixels on object edges.

#### 4. Color Image-Based Mesh Creation

For simplicity, and since the focus of this work is on accurate individual leaf surface modeling, we assume leaves are not overlapping. This allows us to rely primarily on the color image for leaf segmentation. Initial segmentation is done using the K-means clustering on the a and b channels of the Lab color space. We found that the a and b channels contain good discriminatory information on the leaf pigments [22]. Using three clusters on these two channels in the k-means clustering was sufficient to obtain a rough mask of the leaf regions. To refine the segmentation accuracy we then use simple linear iterative clustering (SLIC) superpixels [1] to split image into multiple homogenous regions. In most cases the boundaries of these superpixels adhere closely to the leaf boundaries. To detect whether each superpixel belongs to the leaf pigments or not, the initial batch of superpixels are selected by computing the centroid of each of them and checking whether it falls within the initial mask developed by K-means cluster. Any non leaf superpixels that are chosen in the first selection are then filtered out by thresholding on the ratio of 'a' and 'b' channels of the Lab color space. The selected superpixels are then merged to create the segmented leaf segment.

The boundary of the segmented leaves is found and a polygonal approximation formed [14]. Straight lines are permitted a maximum deviation of one pixel the original boundary [11]. We then sample the polygonal boundary with a uniform spacing of  $\ell$  pixels on each side of the polygon. Uniform grid of points with a spacing of  $r$  are also

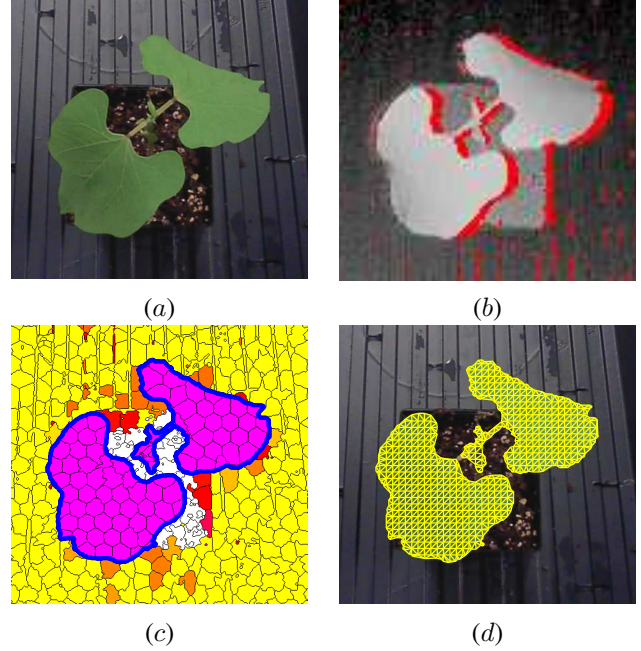


Figure 4: Initial algorithm steps. (a) Color image portion on plant. (b) Depth image, where red pixels are those that are masked out using the method in Fig. 2 as they are not visible in the color image. (c) SLIC superpixels on LAB color space. Each of the superpixels are colored with the mean L, a and b values of that particular superpixel. The leaf boundaries obtained by integrating the superpixels having the leaf pigments are shown in green dots. (d) A mesh is defined in the color image with evenly spaced vertices within and along the leaf boundaries.

created in the entire image, and the grid points which fall within or on the mask built by integrating the leaf superpixels are only selected. Points falling within  $\ell \leq r$  are removed from the set of selected grid points. Both the selected grid points and the sampled points on the boundary are then used to create a Delaunay triangulation on the plant mask. Facets that lie outside the polygonal shape are removed by determining whether their midpoints of the line fall within the polygonal shape or not. The final meshes on a typical color plant image looks like that in Fig. 4 (d).

#### 5. Mesh Fitting

In mesh fitting we seek the most likely surface that generated the measured depth points. This is achieved by minimizing a noise model and by incorporating prior surface assumptions through regularization. Methods that fit mesh models to 3D points often minimize the perpendicular distance of points to facets [24]. This makes sense when point-cloud noise is equal in all directions or else the point noise is

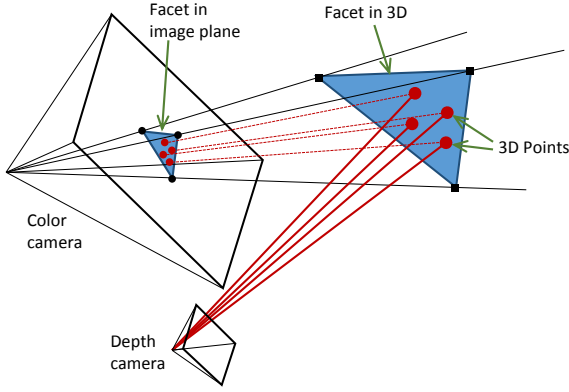


Figure 5: The parallel and adjacent color and depth cameras are shown as pyramids denoting their fields of view, and their size difference illustrates their relative resolutions. Three vertices in a color image define the rays on which the vertices of the corresponding 3D object facet must lie. This facet is fit using the 3D points projected out from the depth camera.

small compared to the facets. For our data the measurement noise is large and is not equal in all directions, but rather is along the depth camera rays. Our method to minimize this noise is described below.

### 5.1. Notation

A vertex,  $v_j$ , is a vector in 3D. In a given camera coordinate system, it projects onto a pixel on the unit focal-length image-plane  $\tilde{v}_j = (u, v, 1)^\top$ , where the “ $\sim$ ” indicates a homogeneous vector, and  $u$  and  $v$  are the coordinates in this plane. Now  $\tilde{v}_j$  defines a ray from the camera origin, and the original vertex is obtained by scaling the image-plane vertex by its depth,  $\lambda_j$ , along the ray, namely:  $v_j = \lambda_j \tilde{v}_j$ .

### 5.2. Facet Model

Mesh fitting for an individual facet is illustrated in Figure 5. The 2D vertices and edge connections of the mesh are initialized in the color image. Then to project these facets out onto the real surface requires associating depth pixels with facets.

To associate depth pixels with facets, pixels in the depth camera are projected along their rays out into 3D, and then they are projected into the color image. A depth pixel,  $p_i$ , is associated with the facet,  $\mathcal{F}_i$ , into which it projects in the color image, as illustrated in Figure 5.

To estimate the facet parameters from depth measurements we will express the depth points,  $p_i$ , after they have been projected out and transformed into color camera coor-

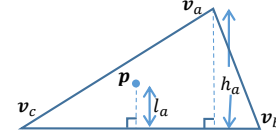


Figure 6: The coordinates of a point on a facet described by Eq. (4) are the weighted linear sum of the three vertex coordinates. The weight,  $\alpha_a$ , for vertex  $v_a$  is given by  $\alpha_a = \frac{l_a}{h_a}$ , the ratio of its perpendicular distance  $l_a$  to the opposite edge to the vertex perpendicular distance  $h_a$ . Analogous expressions describe  $\alpha_b$  and  $\alpha_c$ .

ordinates, as a linear function of the vertices of its facet:

$$p_i = \sum_{j \in \mathcal{F}_i} \alpha_j v_j. \quad (4)$$

Here  $\mathcal{F}$  is the set of three vertex indices belonging to the facet, and  $\alpha_j$  is the coefficient of vertex  $v_j$  as illustrated in Figure 6, and  $\sum_{j \in \mathcal{F}} \alpha_j = 1$ . This linear sum is valid if we make a local orthographic approximation for the projection of a facet. It will be a good approximation as long as the facet size is small compared to its depth from the camera, which is true for most applications. Substituting in depth-scaled homogeneous vectors, and taking the third row, we obtain an equation for the point depth,  $\lambda_i$ , in the color image:

$$\lambda_i = \sum_{j \in \mathcal{F}_i} \alpha_j \lambda_j. \quad (5)$$

### 5.3. Least Squares Depth

Equation (5) gives the modeled depth of a point in terms of its facet vertices. The depth camera will provide measured depths for each pixel, indicated as  $\bar{\lambda}_i$ , along with a standard deviation estimate  $\sigma_i$  obtained from Eq. (3). Now this noise is along the depth ray, rather than the color camera ray, but since the depth and color cameras are close together compared to the distance to target, these rays are close to parallel and we assume  $\sigma_i$  is a good measure along the camera ray. With this approximation, the weighted least squares cost between measured and predicted depth is:

$$E_{\text{depth}}(\lambda_v) = \sum_{i \in \mathcal{D}} \|\bar{\lambda}_i - \sum_{j \in \mathcal{F}_i} \alpha_j \lambda_j\|_{\sigma_i^2}^2, \quad (6)$$

where  $\mathcal{D}$  is the set of depth pixels that project onto the target. The L2 norm is weighted with the inverse variance of each point. Minimizing this for  $\lambda_v$ , the set of all vertex depths, is a straightforward linear calculation.

### 5.4. Regularization

Prior models on surface properties can be incorporated into the mesh via regularization and in so doing reduce the

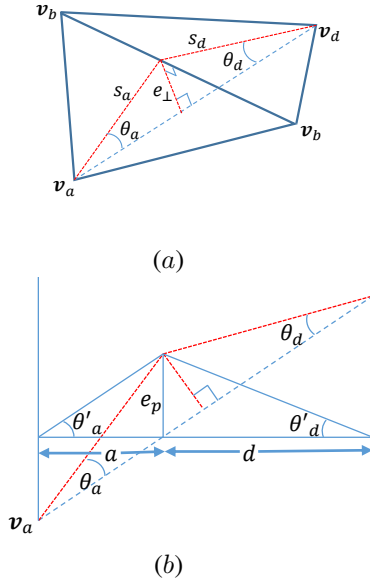


Figure 7: (a) The angle between adjacent facet normals used in Eq. (7) can also be calculated as the sum of the angles subtended by  $e_{\perp}$ , namely:  $\theta = \theta_a + \theta_d$ . (b) An alternative is to use  $\theta'_a$  and  $\theta'_d$  as these can be calculated using the image projection of the facets, along with the depths of the vertices.

impact of noise. In our application leaf surfaces are generally smoothly curved with few sharp edges. We propose a regularization term that penalizes an approximate measure of curvature between pairs of facets:

$$E_{reg}(\lambda_v) = w \sum_{adj(i,j)} \left\| \frac{\cos(\hat{n}_i \cdot \hat{n}_j)^{-1}}{s_a + s_b} \right\|^2. \quad (7)$$

Here the sum is over all pairs of normals,  $\hat{n}_i$  and  $\hat{n}_j$ , whose facets share an edge and hence are adjacent. The numerator is the angle between the facet normals,  $\theta$ . The denominator is made from components shown in Fig. 7(a) and it approximates the arc length,  $s$  in the formula for curvature  $k = \frac{\theta}{s}$ .  $w$  is a weight controlling the level of smoothing. By penalizing high curvatures the mesh can filter out strong noise.

It is also useful to have a linear regularization function. Some vertices are insufficiently constrained the matrix inversion suffers from loss of full rank. This tends to happen when facets are small enough that a number of them have no depth pixels projecting into them. Adding a linear regularization term between pairs of facets will ensure that the coefficient matrix maintains full rank during least squares.

We created an alternative linear regularization that uses an approximation to the angle between adjacent facets. Figure 7(a) illustrates that the angle between two adjacent

facets is given by  $\theta = \theta_a + \theta_d$ , the angles subtended by  $e_{\perp}$ , the perpendicular distance between lines through opposite vertices of the (non-planar) quadrilateral formed by the two facets. Instead we use the projection of the quadrilateral in the image, find the intersection of the lines between opposite vertices, and calculate the depth distance along this intersection ray  $e_p = \frac{a\lambda_a + d\lambda_d}{a+d} - \frac{b\lambda_b + c\lambda_c}{b+c}$ , where  $a$ ,  $b$ ,  $c$  and  $d$  are image distances along the edges joining the intersection point to the respective vertices. Finally we use the tangent of the angles in the regularization to obtain:

$$\begin{aligned} E_{lin}(\lambda_v) &= w_l \sum_{adj(i,j)} \|\tan(\theta'_{ai})\|^2 + \|\tan(\theta'_{di})\|^2 \\ &= w_l \sum_{adj(i,j)} \left\| \frac{e_p}{a_i} \right\|^2 + \left\| \frac{e_p}{d_i} \right\|^2. \end{aligned} \quad (8)$$

Again the sum is over all pairs of adjacent facets, and  $w_l$  is the weighting term. We found that these pairwise regularization terms performed better than Laplacian smoothing [10].

## 5.5. Algorithm

The algorithm steps are:

1. Filter pixels occluded using Eq. (1)
2. Segment and build a planar mesh, see section 4
3. Perform linear least squares for vertex depths,  $\lambda_v$ , by minimizing  $E_{depth}(\lambda_v) + E_{lin}(\lambda_v)$ .
4. Refine  $\lambda_v$  by minimizing  $E_{depth}(\lambda_v) + E_{reg}(\lambda_v)$ .

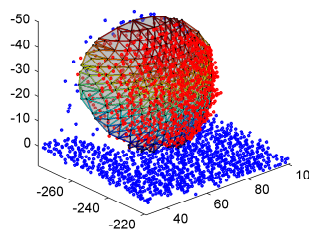
## 6. Results

Mesh reconstructions on a number of plants are presented. In all 3D plots the units are millimeters. Figure 1 shows image and 3D data, along with the estimated mesh of a potted plant. Detailed shapes are recovered. The estimated mesh is compared to a laser scan of the same plant in Fig. 9. This shows overall good accuracy of the shape, with the main error being an extension of the leaf tip area. It appears the lower leaf shifted in position between the laser scan and the camera image, and this may be a result of the turntable required by the laser.

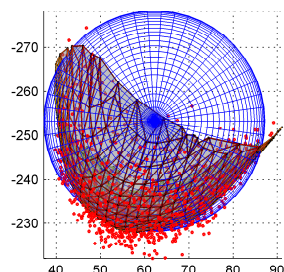
Another way to quantitatively evaluate the surface is to estimate a known 3D object. In Fig. 8 a 50mm diameter sphere is imaged and the aligned to the points on the surface. The 3D point offsets from the sphere changes with the slope indicating that there are some inherent depth biases in the sensor. Nevertheless the mesh smooths the data noise and approximates the sphere surface well. The standard deviation of the raw points fit to the sphere is 2.3mm and the mesh vertices is 1.3mm. This does not account for absolute depth error, only shape error, as the sphere center was aligned.



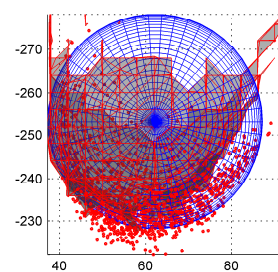
(a)



(b)



(c)



(d)

Figure 8: (a) Color image of a 50mm diameter sphere. (b) Estimated 3D mesh. (c) Known sphere shape with center fit to data points shows how well the mesh captures the real surface. (d) The isosurface is much more jagged and does not fit as well.

Surface estimates for the bean plant from Fig. 4 are shown in Fig. 10 and from a soybean plant in Fig. 11. The 3D points have been averaged over 30 frames to reduce noise, but still are noisy. Despite this mesh is able capture the leaf features well. A comparison is made to the Marching Cube algorithm from an isosurface [7] in Fig. 4(c). We used a modified implementation from [29] along with the Matlab isosurface command. This shows the voxelization generating large artifacts, and using smaller voxels simply leads to surface holes. Fig. 10(d) compares the mesh surface with a parabolic fit [3]. The latter gives rough shape but not a detailed model as we are able to obtain with our mesh fitting.

## 7. Conclusion

This work presents a new method for estimating high fidelity plant leaf surfaces from RGB-D data. Our mesh model is flexible enough to capture a wide variety of complex leaf surfaces, and at the same time can filter out significant depth noise from the sensor. Robustness to noise is achieved by constraining the mesh vertices to fit along the color pixel rays, by minimizing the depth error, and through a curvature-based regularization term. Results show significant improvement in shape estimation of complex leaves

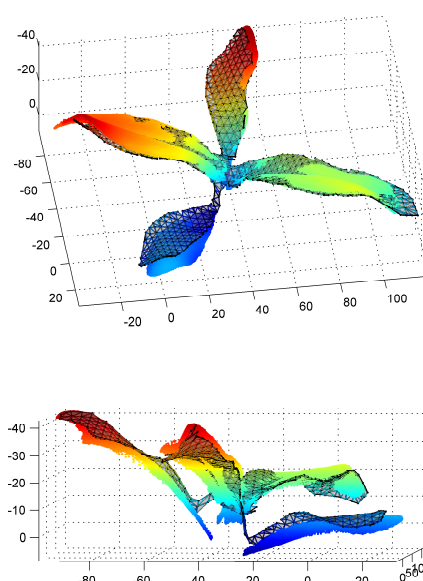


Figure 9: The 3D reconstruction from Fig. 1 is aligned to a laser scan of the plant image. The laser scan data are shown as smoothly-colored surfaces plotted in the same axes as the mesh. The two views show good overall agreement including feature curves. Errors are seen near the ends of the left and right leaves. The lower leaf has likely shifted between the laser scan and the depth data collection.

over alternative methods that use voxel models and that use single-leaf geometric primitives. We anticipate this method will enable automated plant growth observation and further research into improved crop varieties.

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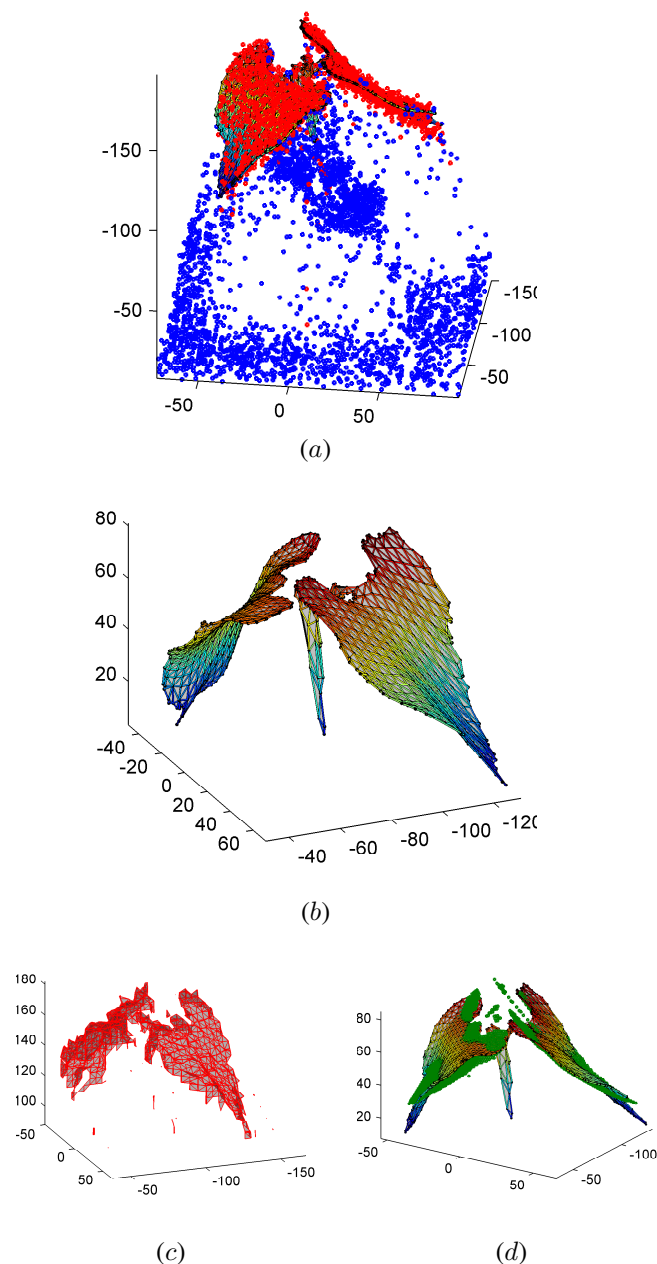


Figure 10: Result of fitting the mesh to the bean data from Fig. 4. (g) The 3D points are red for those on the mesh and blue for the remaining. (h) A more detailed view of the mesh revealing detailed curves of the leaves. (c) A comparison with an isosurface created using marching cubes [7]. (d) A comparison with the use of parabolic fits to leaf surfaces (dark green points) as used in [3, 2]. Clearly parabolic models cannot capture complex bean leaf structures or the leaves in Fig. 9.

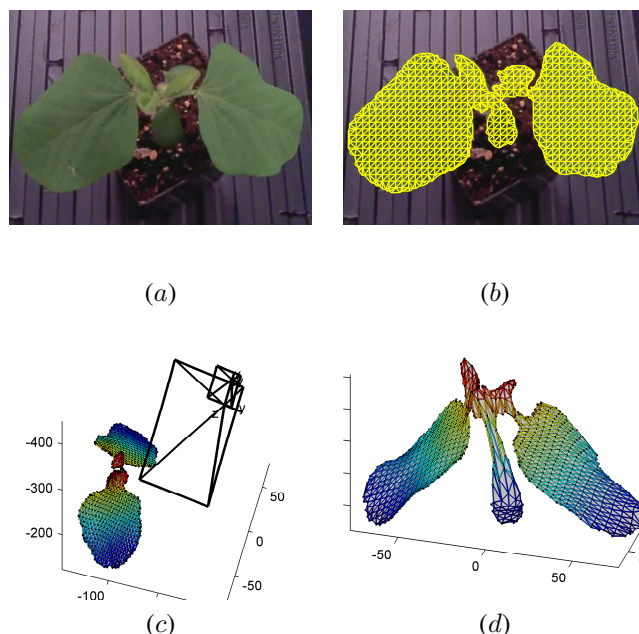


Figure 11: (a) Color image of a soybean plant. (b) Mesh on the color image. (c) 3D mesh along with camera poses. (d) Close-up of 3D mesh.

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