Efficient Seed Volume Measurement Framework

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Abstract—**Modern seed breeding programs require the ability to analyze seeds efficiently to be useful. Even simple measures such as volume and density can be challenging to compute efficiently with modest equipment. Accurately measuring seed volume becomes a highly under-constrained problem. Multiple images from different perspectives are required.**

This paper presents an efficient and affordable 3D single seed volume measurement system to extract image contours and compute volumes using a modified volume carving method in a controlled lab environment. The framework is constructed with a turntable, a stepper motor controlled by an Arduino microcontroller, three orthogonal cameras, and camera control via a modest computer used for data acquisition and processing. For testing, images are captured using only a side camera from different angles by rotating the turntable. Then, the framework processes the multiple images in parallel and reconstructs 3D seed objects to calculate the volume based on the voxel numbers. The proposed framework: (1) generates single seed 3D geometries for visualization, (2) calculates precise seed volumes within seconds, and (3) achieves less than a 3% error rate on a reference ceramic sphere.

Key Words—**Computer graphics, computer vision, image processing, single seed analysis, volume carving**

I. INTRODUCTION

The principle goal for seed property analysis is to identify seed quality by measuring physical and physiological factors that regulate the performance of seeds. Among those physical factors, seed volume and density are among the most crucial aspects to measure since they are highly correlated with seed functionality and quality. There are several existing seed physical property analysis models using image processing including 2D affordable scanning [1]–[3] and commercial software designed for different seed types [4], [5]. These models calculate typical parameters including width, length, and area from the 2D images. They can be used to analyze different seed types such as rice, soybeans, and barley. Other than these specific seed image processing frameworks to measure physical seed factors, we can also apply general image processing models for volume measurement. From a geometric perspective, there are stereo-based techniques, space-carving methods, and newly developed methods based on convolutional neural networks (CNNs). Although CNN methods may use fewer images, effective and accurate solutions typically require multiple images.

For seed property analysis, 3D reconstruction modeling can be applied to solve the volume measurement problem and conduct property analysis. Reconstructing and recovering the 3D shape of a single object is a long standing ill-posed problem, which has been explored by computer vision, computer graphics, and machine learning communities. The single object 3D reconstruction model has made enormous progress and rapid revolution since 2015 [6]. The goal of image-based 3D reconstruction is to infer the 3D geometry and structure of objects from one or multiple 2D images. The recovery of a 3D shape using multiple 2D images has been extensively investigated.

In order to achieve high quality 3D shape reconstruction, volume carving with shapes generated from the silhouette method [7]–[9] is used for reconstruction. A silhouette of an object in an image refers to a contour separating the object from the background. Shape-from-silhouette methods require multiple views of the scene taken by cameras from different viewpoints. For each image, the silhouette of the target objects is segmented using background subtraction. The retrieved silhouettes are back-projected to a common 3D space with projection centers equal to the camera locations [10].

In this paper, we present a novel measurement framework for single seed volume measurement using a modified 3D reconstruction volume carving method. Although existing software and models have been well-known or developed in the literature and in practice, we propose a complete, end-to-end system for the volume measurement of a single seed. Our proposed work achieves high accuracy from multiple images automatically acquired and processed.

To demonstrate the accuracy of the proposed framework, a reference ceramic ball is reconstructed with less than a 3% error rate. In cooperation with collaborators from USDA, the framework is used to measure a variety of seeds, including wheat seeds. The computed results are compared with the results obtained directly using beads and volume displacement measurement. The results indicate that the proposed framework is highly accurate and usable in practice. It is also much faster than physical measurement using volume displacement.

II. SHAPE FROM SILHOUETTE FOR SINGLE SEED RECONSTRUCTION

The shape-from-silhouette method for single seed volume measurement requires multiple images from distinct views. For each image, the silhouette of the target objects is segmented using background subtraction. The retrieved silhouettes are

back-projected to a common 3D space with projection centers equal to the camera locations.

The intrinsic camera matrix K and the distance between the origin of our working volume and the camera center are computed from the calibration. The origin of the working volume is selected to be the intersection point (IP) of the seed bottom horizontal line and the centerline in the image [11]. The system acquires N images of a seed under equidistantly spaced rotation angles a_i where $i \in \{1, ..., N\}$. The rotation is around the vertical axis through IP and is parallel to the y-axis of the camera. A grayscale threshold method is applied on each image and each image is segmented into a binary mask M_i for $i \in \{1, ..., N\}$. For each image, the camera projection matrix P_i is computed from the rotation angle a_i by

$$P_i = K(R_i|T_i) \tag{1}$$

Where R_i is the rotation matrix corresponding to the given angle a_i, and T_i is the translation matrix for the optical center. After that, an equidistantly spaced cubic voxel grid is placed around the world origin, and each voxel size is set to $1mm^3$ for wheat seeds. Different voxel sizes can be used for different types of seeds based on the size of the seed. Each voxel center with homogeneous world coordinates $\vec{X}$ is projected to a point $\vec{x}_i$ in each mask M_i by

$$\vec{x}_i = P_i \vec{X} \tag{2}$$

If a voxel belongs to the foreground object, its value $V(\vec{X})$ is set to 1. If the voxel does not belong to the foreground object, its value $V(\vec{X})$ is set to 0.

$$V(\vec{X}) = \prod_{i=1}^{N} M_i(\vec{x}_i) \tag{3}$$

The mask M_i in this volume carving method is sensitive to misalignment of the object volume. Camera calibration used to minimize misalignment as discussed in the next section.

III. MATERIALS AND METHODS

The hardware design is a relatively simple, convenient turntable design. The system includes a NEMA 23 stepper motor to control rotation of a 3D printed turntable with a minimal step size of 1.8 degrees (a maximum of 200 steps per rotation), three orthogonal cameras, and an LED light as shown in Figure 1.

A. Turntable Framework Setup

- Turntable control: A NEMA 23 stepper motor controls the base and a 3D printed custom-sized turntable is designed to handle a range of seeds at the required camera distance. The seed samples can be placed in the center of the turntable perfectly. The stepper motor is connected to a power supply and controlled using a low-cost Arduino microcontroller using a Synthetos gShield stepper driver.
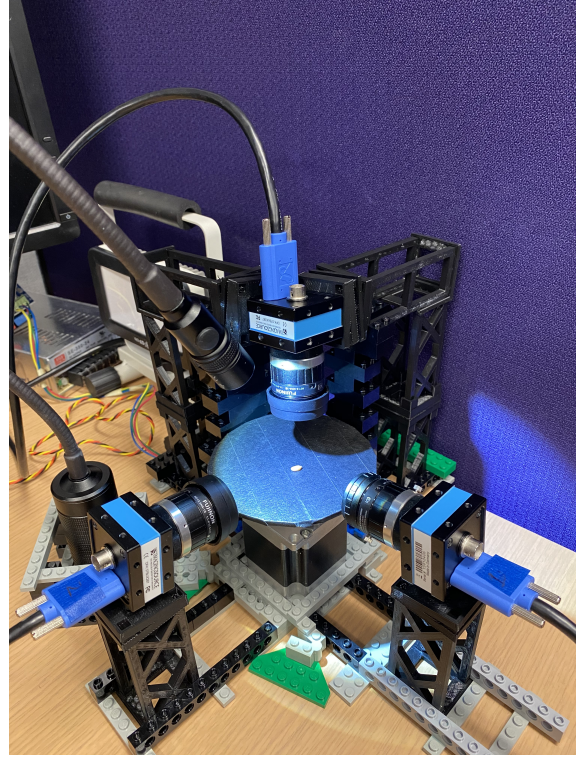- Physical framework: For printing the 3D parts, a MakerGear M2 3D printer is used [12]. For each part, a 3D

Fig. 1: Single seed measurement framework.

stereolithography (STL) model is designed using Cubit 15.2 [13]. The STL 3D camera mounts are shown in Figure 2. All parts are design in millimeters. After the STL model is designed, they are sliced into gcode using slic3r [14]. Finally, 3D parts are printed on the Makergear M2 3D printer using the Printrun [15] software or the Makergear M2 software.

- Image capture: The image capture component is built using three ImagingSource color cameras DFK 37BUX287 [16]. These cameras are mounted orthogonally at three different angles: front, left, and top, each 90 degrees apart. The images are taken using the ImagingSoure IC measurement software.
- Controller and power supply: The stepper motor is controlled by a DFRduino UNO R3 board [17] attached with a Sythetos gShield v5 board [18]. A Universal Gcode Sender (GCS) [19] is used to test the whole system. Then, simple control software is developed to control the system by sending gcode strings. The turning degree and capture rate can be controlled by the user based on their needs. For example, a rotation of 360 degrees requires a step size of 6.4. If $N = 36$ equidistant images are desired, the turntable should rotate 10 degrees on each step; therefore, the rotation is set to a $6.4/36 = 0.178$ step size for 10 degrees.
- Mounts and stands: All camera mounts are 3D printed, the base is built using simple Legos to stabilize the whole system. The mounts and parts are designed to be

assembled together. For example in Figure 2f, the length of the pillar is 76.00 mm, the width is 32.50 mm, and the height is 4.60 mm, and in in Figure 2a,2b,2c,2d, the length of the square is 5.00 mm to fit the pillar leg which length is 4.60 mm.

B. Camera Calibration

The acquired images without appropriate parameters, adapting camera pose, and adjusting lighting sources are known to be particularly sensitive to calibration errors. Therefore, controlling the precise positioning of the cameras, determining the accurate photo parameters, and adjusting light intensity are crucially important for accurate image analysis. For the framework setup, three cameras are mounted at the same distance as the object. From the top view, side view, and front view. The distance d from object to cameras are set to be fixed. To reduce glare and focus on the turntable, the camera angle is rotated by 10 degrees as shown in Figure 2c,2d. For the testing phase, only the front camera is used to capture multiple images when rotating the turntable. Future testing will involve all three cameras.

- Camera Position: As shown in Figure 2, the cameras are mounted at different angles, but they are all orthogonal to each other. To better capture images without glare from overhead lighting, the front camera is rotated 10 degrees along the x-axis towards the turntable, the side camera is rotated 10 degrees along the y-axis towards the turntable, and the top camera is rotated 10 degrees along both the x and y-axes away from the turntable.
- Camera Parameters: The image properties and camera properties of the framework are shown in Table I. ImagingSoure IC measurement software is used to capture raw image data. The camera settings for the software is shown in Table I.
- Light Source: One goose-neck LED light is placed next to the left side camera, the light source is set on top at a distance d from the object.
- Calibration Reference Object: To calibrate the camera distance and pixel ratio for each frame, we simply test a ceramic ball of a known fixed size as a calibration object to calibrate the working distance d and pixel ratio for the framework.

C. Software Implementation

The framework software is implemented using Python. When capturing the raw data, the Imaging Source camera is controlled by the IC Measurement Software. For each experiment:

1) Determine the number of images N taken by the front camera. Therefore, the degree between adjacent images is $D = \frac{360}{N}$.
2) Crop and trim images in the input sequence, and save the offset for each image for image matching using normalized cross correlation.
3) Convert each image to the HSV color space. HSV (hue, saturation, value) is a better alternative representation
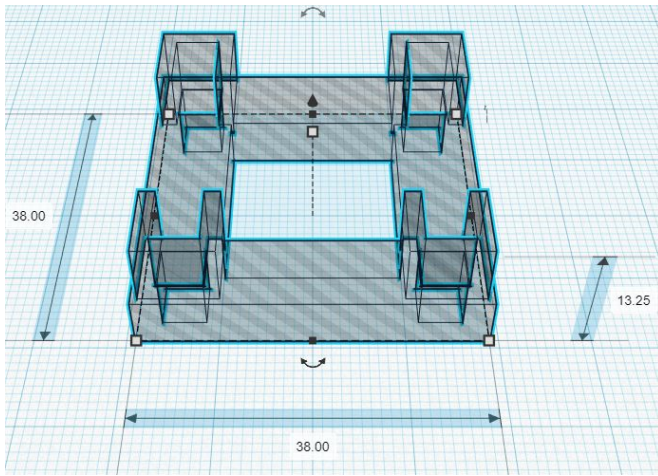
TABLE I: Camera calibration settings

Auto ROI	
Auto Functions ROI	Enabled
Preset	Center 50%

Exposure	
Brightness	0
Gain(Top color camera)	0 db
Exposure	1/30 sec
Auto Reference	128
Auto Max Value	1/30 sec
Highlight Reduction	Enabled

Image	
Sharpness	0
Gamma	100
Denoise	0
Image size	720 x 540
Pixel per mm at working depth	145/5.74
Pixel size	1/0.0062
Focal Length	12.5

Color	
Hue	0
Saturation	64
White Balance	Auto Disabled
White Balance mode	Temperature
Auto-Preset	Auto Daylight
Temperature Preset	Cool White LED
Temperature	7500

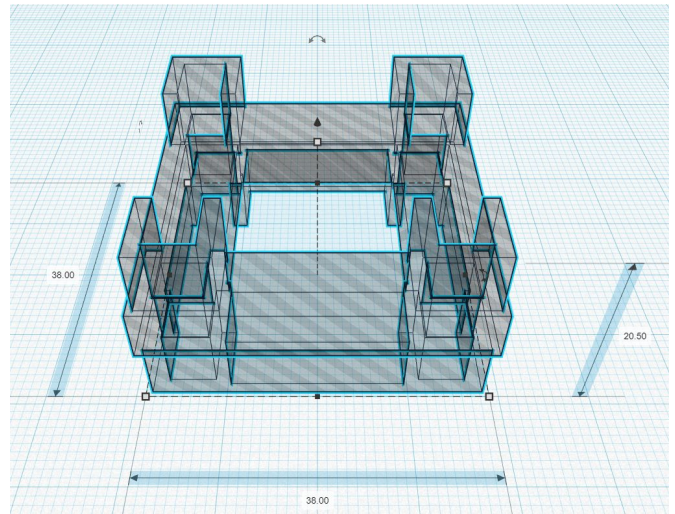used in place of the RGB (red, green, blue) color space for better thresholding.

4) Adjust the threshold of the HSV image to filter out the background from the seed object, and apply a threshold to the HSV image to obtain a binary mask image.
5) Get the total number of images N, and set the turntable center using pixel coordinates.
6) Apply volume carving method to reconstruct seed shape.
   - First, the software finds the center of the reconstruction cuboid by finding the intersection point (IP) of the seed bottom horizontal line and the center line in the image. A cuboid is constructed outside of the object defined by voxels. Each voxel size is $1*1*1$, and initially, we fill the cuboid with the voxels.
   - Then, for each image of a different angle, the software trims, crops, and generates the mask image from raw input. The projection matrix [20] for each image is computed and the background is carved out.
   - The reconstructed 3D shape is the object that remains after carving out all $N = 36$ images.
7) For each voxel, the volume is $v_i = 1*1*1$, the total voxel volume of the 3D reconstruction seed is $V = \sum_{i=1}^{n} v_i$. The total volume of the seed is calculated by multiplying by a factor, which is the cubic volume of a pixel per mm in camera properties.
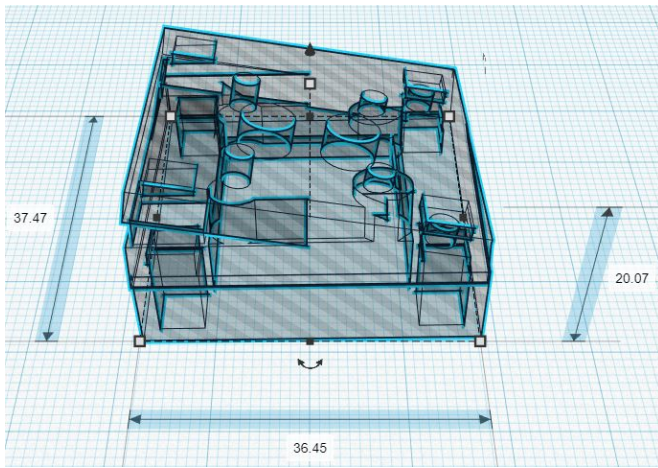
IV. RESULTS AND ANALYSIS

After implementing the code and setting up the turntable framework, results are computed from many wheat samples. But, before applying our framework to small seeds, reference
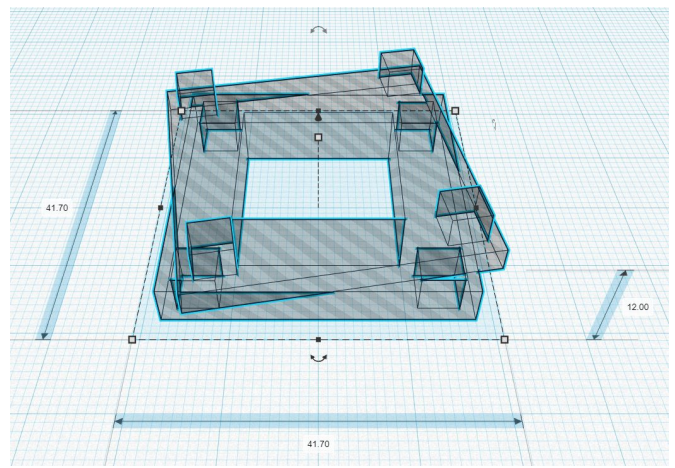
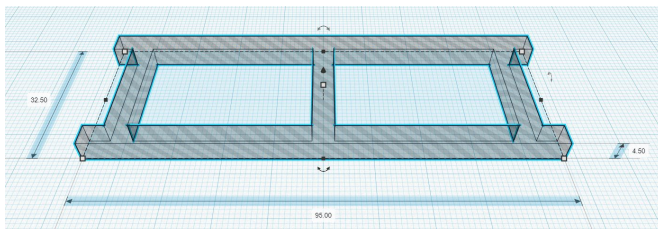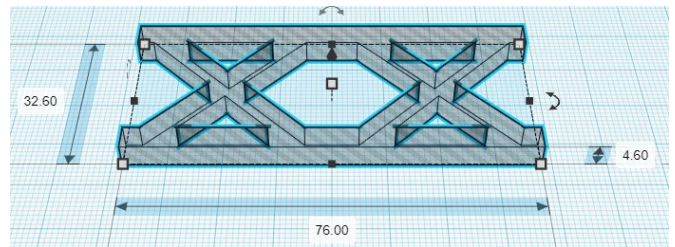(a) Mount bottom

(b) Mount join

(c) Rotate 10 degrees in X and Y direction

(d) Rotate 10 degrees to the left

(e) Pillar

(f) Pillar

Fig. 2: Selected camera mount 3D models.

objects are used to test the accuracy of shape reconstruction from the silhouette volume carving method. Shapes reconstructed from the silhouette 3D reconstruction using a finite set of objects images results in an approximated visual hull of the object. The object obtained by the visual hull is guaranteed to enclose the object in 3D space. However, some surplus volume is typically produced in the visual hull by the finite set of objects images shown in Figure 4 because the seeds are not totally concave, they also have convex regions. The four cameras project the orthogonal visual hull in 2D space. The brown region represents the wheat seed object, and the light brown region represents the 3D reconstruction volume from the visual hull. It is challenging to engrave the surplus region using only four images.

To further investigate the relationship between the number of images captured and volume measurement accuracy, an experiment is conducted using a reference ceramic sphere with radius $r = 1.975mm$, the theoretical volume is $32.75mm^3$.
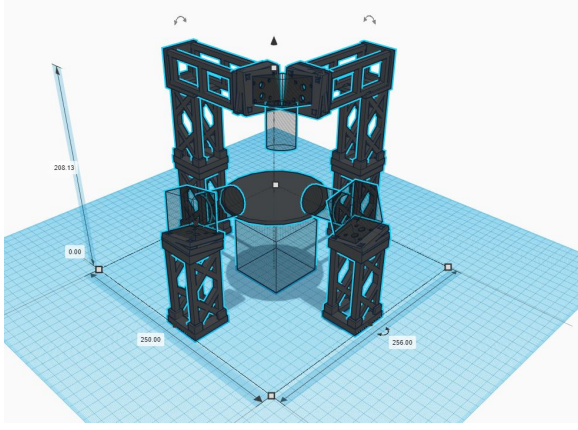
Fig. 3: Turntable setup with all 3D printed camera mounts

For the experimental design, different numbers of images N are acquired from rotating the turntable at a $D = \frac{360}{N}$ degrees in each step. For example, if $N = 5$,the turntable is rotated $\frac{360}{5} = 72$ degrees for each step and a total of 5 images are captured.
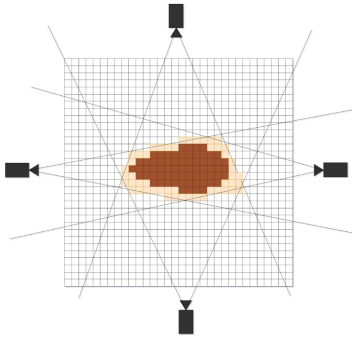

Fig. 4: 2D view for volume carving method using voxel grid

Before the experiment, the theoretical volume of the reconstructed object is computed assuming that a central projection with a point camera is used. If $N = 4$, the reconstruction object is exactly a Steinmetz solid [21], and the volume is

$$V_{Steinmetz} = \frac{16r^3}{3} \qquad (4)$$

and the actual volume of a sphere is

$$V_{sphere} = \frac{4\pi r^3}{3} \qquad (5)$$

Therefore, the theoretical reconstruction volume is given by

$$V = \frac{4N}{3}(tan(\frac{180}{N}))r^3 \qquad (6)$$

Different numbers of images N have been selected and to evaluate the performance of the volume measurement using a ceramic ball. The 3D reconstruction object is shown in Figure 5 and the line chart is shown in Figure 6.

To test the reconstruction shape and volume measurement using the different numbers of images N, the number of images captured ranges from 5 to 12. Figure 5 shows for $N = 12$

number of images yields much better reconstruction than for $N = 6$. This is in full agreement with the measurement error in Figure 6. From the experimental data, we observe that for the $N = 12$, the theoretical error rate is below 3%. As the number of images goes up, the error rate goes down. When we select $N = 36$, the error rate is also below 3%. In practice, other error sources may dominate when we select a higher number for N. For the number of images selected, we want to achieve higher accuracy in the controlled environment. Therefore, based on the N parameter analysis of the reference ceramic sphere, we achieve an experimental error rate of less than 3%, and we apply $N = 36$ as the number of images value to the experiment samples including wheat, soybean, and corn seeds.
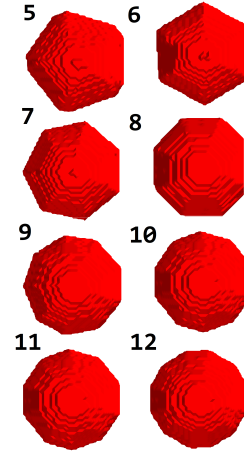

Fig. 5: Different number of images N for the 3D volume reconstruction using the reference ceramic ball
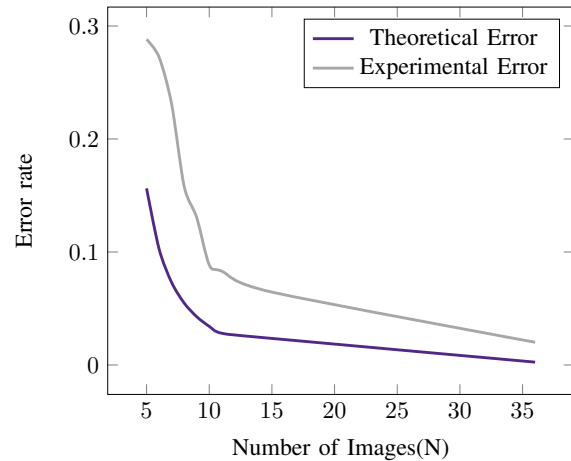

Fig. 6: Error rate when using different number of images N.

The framework is tested on different seeds, the 3D reconstruction and volume measurement data for wheat, corn, and soybean seed is shown in Figure 7.
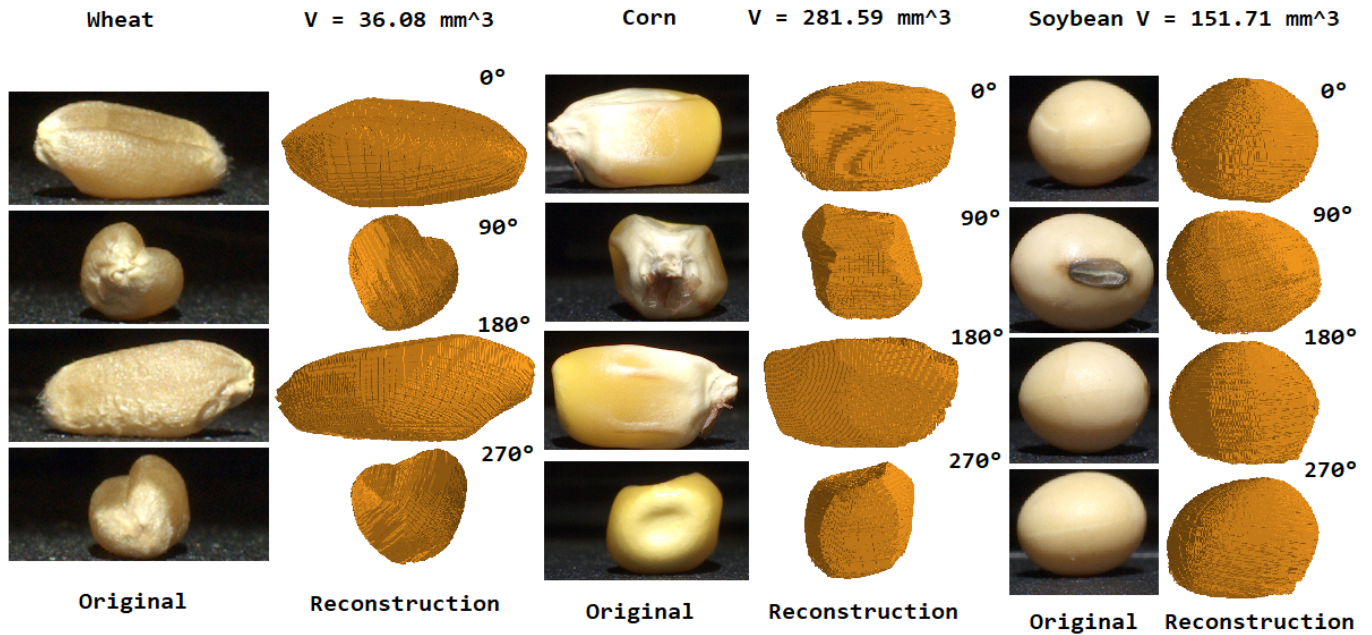
Fig. 7: 3D reconstruction and volume measurement for wheat, corn and soybean seed.

Four pictures of each seed from 0, 90, 180, and 270 degrees are selected to show the comparison between original seed pictures and reconstruction 3D models. For wheat seed, the framework is able to accurately calculate the volume and also capture the brush end and germ end details from the seed shape property. Also, for the corn seed and soybean seed, the overall performance of 3D reconstruction is great except for the imperfection for the concave and dark region as shown in the 270-degree picture for corn.

V. Conclusions and Future Work

This paper presented an inexpensive, efficient computer vision system to simplify the image capture and analysis process for single seed volume measurement. The simple volume carving method combined with an inexpensive 3D printed, affordable turntable setup is sufficiently accurate for volume measurement of most single seeds. To optimize the framework, we are currently testing different numbers of images N and the resulting performance with respect to efficiency, both in space and time, and accuracy. When $N = 36$, for a reference ceramic ball, the proposed framework achieves less than a 3% error rate. For this affordable setup, systematic errors are relatively low. For future work, other factors that influence the accuracy will be further investigated. For example, the system needs to identify the concave and convex regions of the seed and adjust the volume measurement for concave regions. There is a need to add a more precise stand to hold a seed. Our volume carving algorithm assumes the bottom part of the 3D object is a flat surface due to the lack of information from the bottom. We will improve this by using the top camera and changing the orientation of the single seed with a more sophisticated seed holder. Finally, automating calibration to account for camera distances and orientation will allow small perturbations in camera position and orientation to be automatically accounted for. Overall, the framework provides an end-to-end, efficient computer vision system for accurate seed reconstruction for volume and density measurement.

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