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The use of x-ray computed tomography for creating computational models of corn stalks and other plants: advantages, benefits, and common challenges.

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Highlights: X-ray computed tomography (CT scanning) is a powerful tool for evaluating plant tissue, and is commonly applied in the field of biomechanics to obtain 3D representations of bone, arteries, and other anatomical data. We have applied this technique to the development of computational models of corn stalks and bamboo culms. While CT scanning has many advantages, the process of creating parsimonious models based on CT data is often challenging since this technique often produces several gigabytes of data for each scan. This paper provides an overview of the advantages, benefits, and common challenges associated with the use of computed tomography in plant modeling in the context of modeling corn stalks.

Keywords: computed tomography, CT, data, 3D modeling, corn

INTRODUCTION

Corn (Zea mays L., Figure 1) is the leading grain crop globally. In the US, over 300 million tons of corn are harvested annually from 80 million acres (135,000 mi2) (Hondroyianni et al. 2000). Only 4 US states (Alaska, Texas, Montana, and California), have a greater land area than that devoted to corn production. Corn is susceptible to late season crop failure (called stalk lodging), with yield losses due to stalk lodging range from 5 to 25% (Nielsen and Colville 1988). These losses affect the productivity of farms, negatively impact individual farmers, and may eventually affect the overall crop supply, thus affecting commodities trading and even the broader economy (Hagenbauch 2007). Reasons for crop failure have been challenging for plant geneticists to identify, measure, and control (Esechie et al. 1977, Loesch et al. 1963), largely because most plant research focuses on biology, not structural mechanics.

From an evolutionary perspective, the purpose of grain kernels is to propagate the species. The species known as Zea mays resulted from millions of years of optimization for this purpose. But humans have adopted corn for an entirely different purpose than nature intended. In the last 100 years, aggressive breeding programs have increased corn yields by over 400% (Gardunia, private communication). As a result, the highest-yield varieties currently suffer from persistent stalk failure, and further increases in crop yield are limited by the ability of the stalk structure to support such large kernels. This proposal is based on the concept that an understanding of the biomechanics of corn stalks can be used by plant breeders to develop breeding strategies that will produce stronger stalks, thus enabling further advances which would not otherwise be possible without the application of biomechanical principles. The objective of this research project is the identification of key geometric and material properties that influence structural attributes of corn stalk. Once these factors have been identified, plant breeders can use this information to develop varieties exhibiting stronger stalks. As a first step toward this long term objective, we require detailed 3D descriptions of corn stalk geometry. This paper desribes our efforts to develop a method for obtaining this information in an efficient manner using computed tomography to produce detailed digital models of corn stalks (see Figure 1).

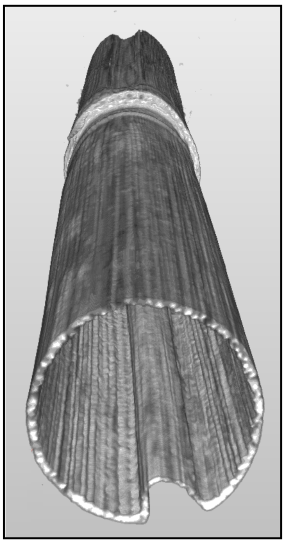


Figure 1: Digitized, three-dimentional corn stalk model.

SCAN METHODOLOGY

CT scanning was performed on multiple corn stalk samples using an X-5000 scanner from NorthStar Imaging (Rogers MN, USA). This scanner is capable of producing CT reconstructions ranging from 10μm to 127µm. All CT scanners operate on a principle of combining a number of 2D x-ray to mathematically reconstruct a 3D representation of the scanned object. Typically, between one and two thousand images are required for an high quality scan.

The quality of CT reconstruction depends upon many factors, including x-ray intensity, frame-rate of data acquisition, rigidity of the holding fixture, the number of 2D radiographs, density variation within the object, and scan type (continuous or intermittent).

We constructed a holding fixture which consists of a central post, around which 5 corn stalks were arranged, attached by inserting the ends of each stalk into lightweight foam (first image in Figure 2). Scans were conducted using from 1000 to 2500 2D radiographs. To determine the effect that number of radiographs has on reconstruction quality, we have conducted an experiment involving 2400 scans. These scans were combined to create a 3D reconstruction. Half of the same set of radiographs were then used to create a second 3D reconstruction.

SEGMENTATION

While there are many software programs which utilize high-power computing resources to automatically generate 3D models based on CT data, there are several practical problems with this approach. First, these software are not affordable, especially for those just starting to explore this technology. Second, the models produced by such software are often highly complex, and require a great deal of computational resources (CAD, meshing, and finite element software) to fully utilize. Our institution recently purchased Simpleware, one of the leading software products in this category. This software cost approximately $20k. In using this software, we realized that it was not optimized for the extraction of the relatively simple shapes of corn stalks. Although the software is relatively easy to use, the models produced in this way required a great deal of computer memory to manipulate. Over the course of one week, we were able to develop a segmentation process based on freely available MATLAB routines. Our approach involved much less computational power and resources, and successfully extracted relevant data regarding the corn stalk geometry. This process is outlined below.

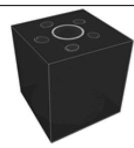
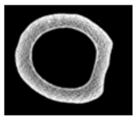
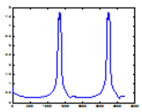
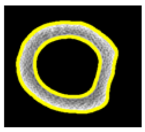
Process	Time (min)	Data (MB)	Image
2D Radiograph Acquisition	90	10,000	
CT Reconstruction	25	8,000	
Axial image decomposition	30	4,000	
Node Identification	15	9,000	
Edge Detection	20	0.06 (60 KB)	
Surface/CAD Generation	15	1-2	

Figure 2: Process utilized in creating digital stalk models. Note that the relevant geometric data requires only 60KB of the original 10GB data set.

RESULTS AND DISCUSSION

One of the challenges associated with corn and other plant stalks is their inherent aspect ratio. The corn rind is approximately 1mm in thickness. Adequate resolution of the wall structure therefore requires a scan resolution of approximately 100µm, which provides approximately 10 pixels across the rind thickness. The stalk diameter is usually an order of magnitude larger, typically 15-23mm. Individual nodes are 10-20 cm in length and the entire stalk is around 1 meter in length. Thus, the data set required for CT reconstruction of a single stalk will consist of approximately 3.2 billion voxels. Of these 3.2 billion, perhaps 5%-10% are corn stalk, while the rest are background data. The first challenge is to segment the images, selecting only those portions that are relevant.

Of the many segmentation algorithms, we have found good success with a technique called the level set method (Li et al. 2001). While many other methods will split each image into two regions (corn tissue and air), the level-set technique is particularly useful for identifying the boundary between regions, which is our primary interest. The drawback is that this method is computationally intensive, usually taking approximately 10 seconds per analyzed 2D image. However, because the corn stalk (and many other plants) have a relatively constant geometry and structure along the length of the stalk, we can attempt to reduce the number of 2D images that are analyzed. One nodal section of corn stalk may consist of around 1500 axial CT images, but not all need be analyzed. We developed an algorithm that uses a relatively crude thresholding measurement to estimate the number of pixels in each 2D image that represent corn tissue. Since the nodes contain more stalk tissue than the internode regions, this data allows us to infer the locations of the nodes. A sampling scheme is then derived which determines the number, spacing, and location of sample images.

This approach requires that edge detection be performed on a small subset of all axial CT images. In our experience, a set of 1500-1800 axial slices can be adequately approximated using 50-100 judiciously chosen images. This process results in a dramatic reduction in the amount of data (data reduced by a factor of 14,000), while successfully extracting the most important data (geometric boundaries), which can then be used independently, or as starting points for more advanced analysis.

Edge detection and surface generation images are shown in Figure 3. We are now proceeding to create finite element models based on the digitized models, as well as performing geometric analysis on various geometric features of the corn stalks that have been digitized. Finally, this information will be used to create virtual populations of corn stalk models for sensitivity analysis.

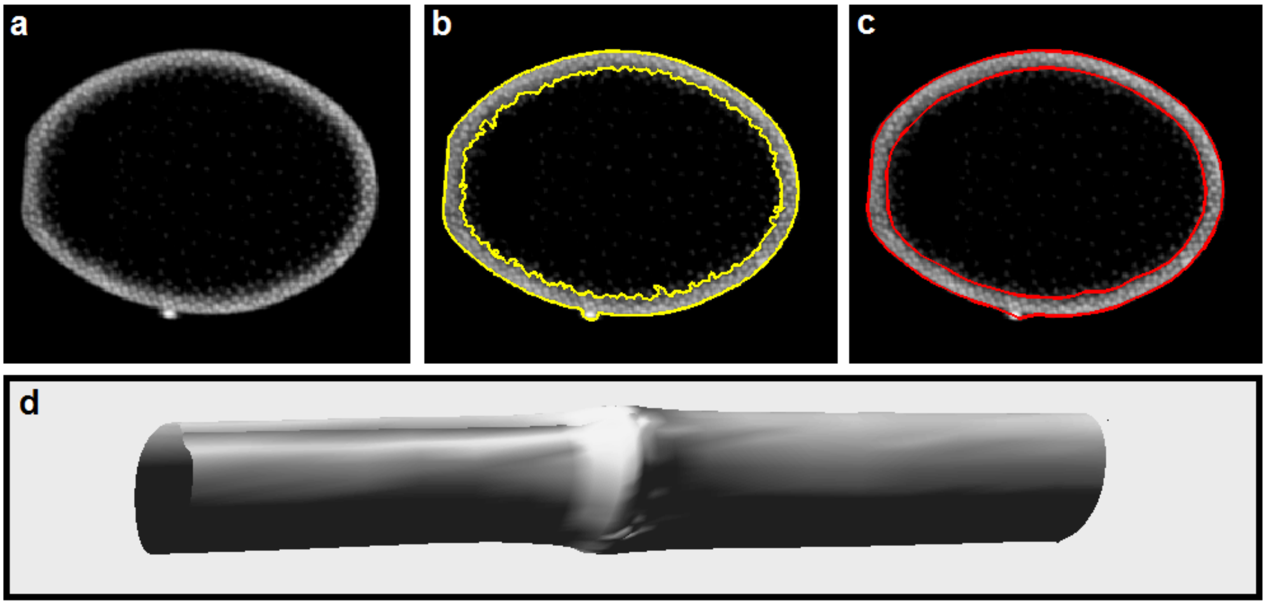


Figure 3: Representative corn stalk cross-sections: (a) axial CT image (179KB); (b) image overlayed with edges detected by level-set method (edges require 16KB); (c) smoothed & simplified edges contours (requiring less than 1KB total); (d) digitized surface model (15KB for shown geometry).

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