UFEEL: USING HAPTICS AND STEREO TO PLACE LANDMARKS IN THREE-DIMENSIONAL VOLUMETRIC IMAGES

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ABSTRACT

This paper is concerned with extracting 3D models from volumetric images. Building models of 3D shape relies on placement of landmarks and in many biological and medical applications automatic landmark placement is impractical. We introduce a system, called *uFeel*, which allows manual placement of landmarks in 3D using a combination of stereo and haptics. This system is used to capture and analyse data on growing Arabidopsis leaves.

1. INTRODUCTION

Organisms grow from simple to complex forms through the actions of genes with feedback from shape (morphology). Understanding growth is a challenge that requires the capture of detailed three-dimensional (3D) shapes from volumetric images and the extraction of quantitative growth data. Our aim is to develop software tools that allow these 3D volumetric images to be visualised and analysed. In computer vision statistical shape models are often used to quantify changes in shape and size. The barrier to building statistical models of 3D shape lies in accurately and efficiently marking the shape of 3D objects in volumetric images. Not only is this needed for biological and biomedical research but also for 'ground truthing' prior to developing automatic segmentation. The placing of landmarks is difficult for many reasons. For example in Figure 1, organs are complex; are tightly embedded among many others; and edges are indistinct. As a result marker placement requires specialist biological or medical knowledge. Furthermore, placing points in 3D using standard 2D pointing devices is cumbersome.

We have developed a system that: (1) displays volumetric images in stereo; (2) enables landmarks to be placed in the image using a 3D pointer; (3) that provides haptic (force) feedback; and (4) provides input to a 3D shape model toolkit. We call it *uFeel*. We have analysed Antirrhinum leaf shape [1, 2] in 2D but such an approach would ignore the strong 3D curvature in early development of Arabidopsis leaves. Therefore we illustrate our system by collecting data for modelling the growth of young Arabidopsis leaves.

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2. DATA ACQUISITION AND SHAPE CAPTURE

Confocal microscopy is widely used for imaging biological systems in 3D but it is limited to imaging only fluorescent signals to a depth of approximately 1mm. We acquire our 3D volumetric images using a new technique known as optical projection tomography (OPT) [3, 4]. OPT allows scanning of larger organs with greater tissue penetration (15mm) and is able to visualise internal structures down to the resolution of large cells. An example OPT image which shows both the external and internal structures is shown in Figure 1.

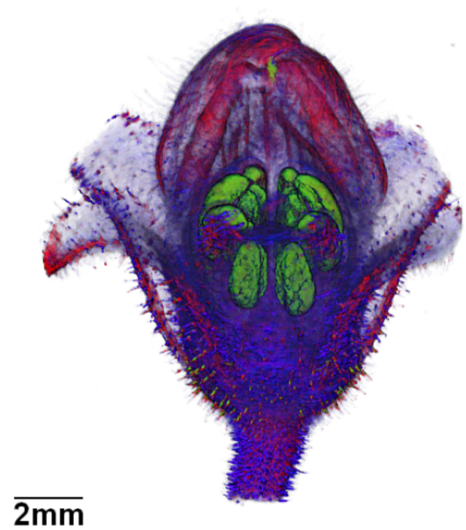

Fig. 1. Combined volume view of an Antirrhinum flower virtually dissected using clipping planes to reveal internal floral structures. Information from three optical projection tomography (OPT) channels were superimposed to give a combined 3D volumetric image [4]. The first channel (transmission) highlights petals and sepals shown in red. The second (autofluorescence) highlights the anther lobes shown in green. The third (autofluorescence) highlights petals and sepals shown in blue.

2.1. Design

We aimed to create a tool that allows intuitive interactive exploration of volumetric images using the senses of vision and touch. The particular goal was to allow expert biologists to place landmarks from which statistical models of 3D shape and size can be formed. In addition, we aimed to make the functionality of *uFeel* available through a MATLAB software interface, enabling integration into larger software packages without exposing the complexity of haptic software.

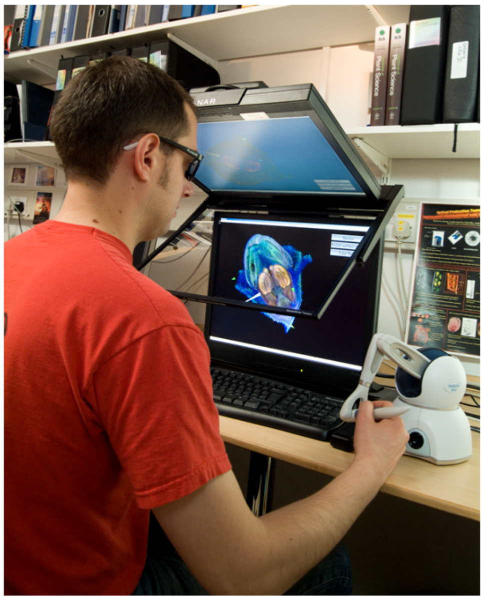

Fig. 2. Haptic device and stereo display setup.

2.2. Haptics

Haptic devices do not fit into the user interface paradigms available in standard operating systems. They include: 2D mice that generate tactile feedback; joysticks that generate force feedback with 2 degrees of freedom (DOF); and human-scale devices used for sports training and rehabilitation. We used a 6 DOF-in 3 DOF-out haptic desktop device known as a PHANToM Omni, manufactured by Sensable Inc. [5]. This device registers translations and rotations along and around the x-, y- and z-axis as input. Output takes the form of force feedback along the three spatial axes and is specified programmatically using three-dimensional force vectors. In contrast to graphics, the haptic input-output loop must be run at approximately 1000 Hz [6]. Thus, in practice the two rendering systems are implemented in two different threads, locking access to shared data when the scene is changed (thread synchronisation). The high rate is necessary to maintain a stable feedback loop and to ensure smooth perception of forces by users. This constrains the amount of computation that can be performed in one haptic frame. When working with mesh models the time consuming problem lies in determining when the pointer moves through a surface - detecting collisions. However, when feeling volumetric image data, the feedback system does not have to perform collision detection as it senses the voxel features at the pointer position directly. The technical problem lies in deriving an intuitive feel (force feedback) from the image features.

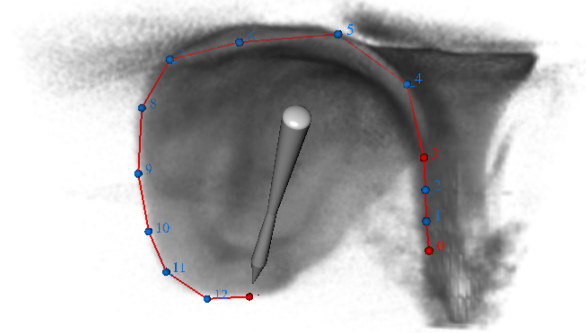

Fig. 3. Constructing a 3D point model template for leaf shape using *uFeel*.

2.3. Application

uFeel is partly based on components of H3DAPI [7] which contains implementations of haptic algorithms introduced in [8, 9]. *uFeel* renders the images as stereo pairs on a 3D screen. Figure 2 shows *uFeel* running on a workstation equipped with a haptic device and a StereoMirror™ display manufactured by Planar Systems Inc. [10].

To place landmarks, as shown in Figure 3, the user starts approaching the leaf by moving the stylus through the low intensity areas of the volumetric image. Based on the force feedback relayed through the device the user can feel when the device tip touches the leaf. Having found the starting point at the start of the petiole using both the sense of vision and the sense of touch the user starts placing landmarks whilst following the edge of the petiole and the blade. Haptic force feedback enables the user to feel their way along the edge, augmenting visual navigation and thereby improving accuracy and speed. This is a simple case of marker placement which may also be approached with more automatic methods. However, it demonstrates functionality required in more complex cases like the flower bud shown in Figure 1 where manual marker placement by a specialist user is required to identify internal organs. Primary markers in red designate points where material correspondence between samples is assured. The blue intermediate points are placed and then distributed evenly along defined edges approximating material correspondence points.

The time required for manually fitting a template depends on the number of model points and sample complexity. For instance an experienced user requires 15 to 30 minutes to manually fit a model of 67 points to a sample as shown in Figure 4.

uFeel allows users to define point model templates and then manually fit them to further volumetric images (Figures 3 and 4) to allow the building of statistical models of 3D shape and size. Our point model templates also contain the connectivity of the points, the red lines in Figures 4. These provide visual guidance. In our implementation all the scene objects have haptic identity. For example, in addition to force feedback from the volumetric image, lines and points have 'magnetic properties' guiding users by feel when manipulating a template to fit a sample (Figure 4).

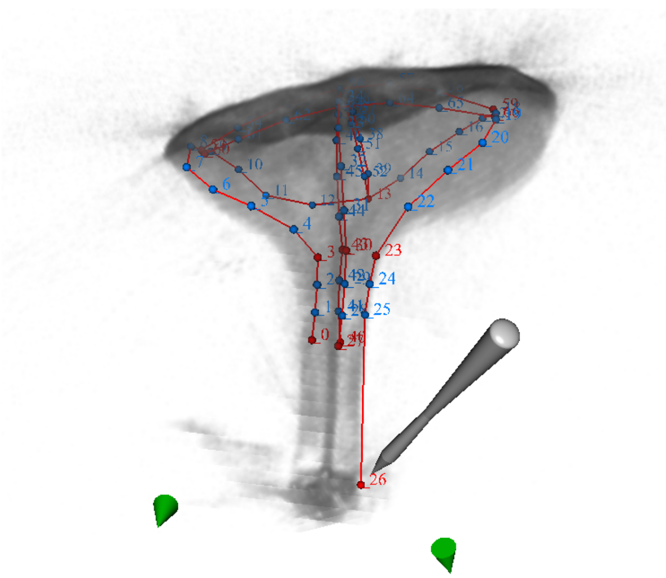

Fig. 4. Fitting the complete template to a sample: The stylus is used to move individual points to fit the petiole part of the template to the sample. In addition to the force feedback from the volumetric image, the 'magnetic' properties of points and line segments guide users by attracting the haptic device tip. The green cones, also positioned using the stylus, represent clipping planes used to clip away the remaining part of the seedling contained in the image.

3. SHAPE AND GROWTH ANALYSIS

After the landmarks have been placed using the haptic device and stereo screen, we analyse and model variations across shape. To do this we use *point distribution models* (PDM) [11]. The shapes within a dataset are normalised using Procrustes alignment via translation, rotation and optionally scale.

To illustrate a practical application we use *uFeel* to capture the change in 3D morphology of growing young Arabidopsis leaves. A total of 17 wild-type Arabidopsis (Landsberg erecta background) metamer 2 leaves were scanned using OPT [4]. The 17 leaves were grouped into six classes based on days from sowing: Day 4 (3 samples); Day 6 (4 samples); Day 7 (5 samples); and Day 17 (5 samples). A template was developed and fitted manually to each OPT leaf scan, as described in Figure 4, and a 3D PDM calculated from the normalised point models using principle component analysis(PCA)[11]. Example OPT scans with fitted templates for each class are shown in the top row of Figure 5.

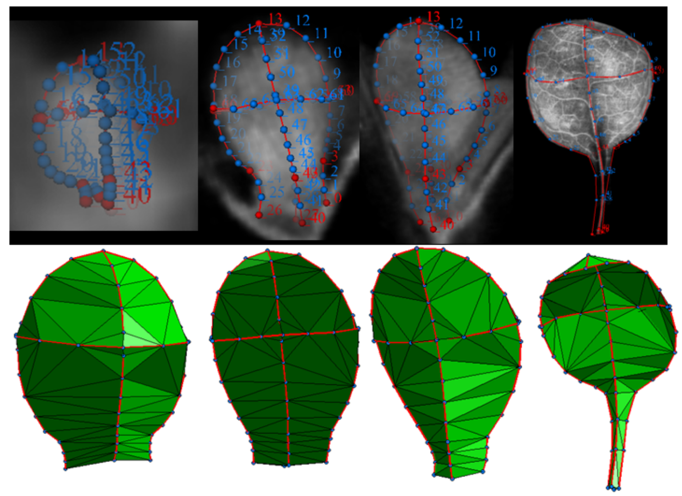

Fig. 5. Top row shows example OPT scans and fitted point templates for each class: Day 4, Day 6, Day 7 and Day 17 (columns left to right). The average leaf width of Day 4 samples was 0.06mm, Day 6 0.21mm, Day 7 0.49mm and Day 17 4.51mm. Bottom row shows the mean shape for each class normalised for size (denoted as diamonds in shape-space within Figure 6).

To interpolate the development of shape between stages we use shape-space. Figure 6 shows a plot of first two principle components (PC) of the shape model feature vector for each sample normalised for size. The mean shapes for each class are also shown as diamonds in Figure 6. The bottom row of Figure 5 shows these means projected back into world coordinates. The vectors in Figure 6 represent the interpolated developmental trajectory through Day 4 to 17 in PC shape space. This developmental trajectory through shape-spaces for wild type Arabidopsis now serves as a basis for comparison with other Arabidopsis mutants. Since Arabidopsis mutants often have very different leaf shapes compared to the wild type, developmental trajectories can be used to quantify and identify genes that result in differences in morphology.

4. CONCLUSIONS

In this paper we introduce a system for marking up volumetric images using a 3D display and haptics: *uFeel*. The value of this tool was established by capturing and analysing data

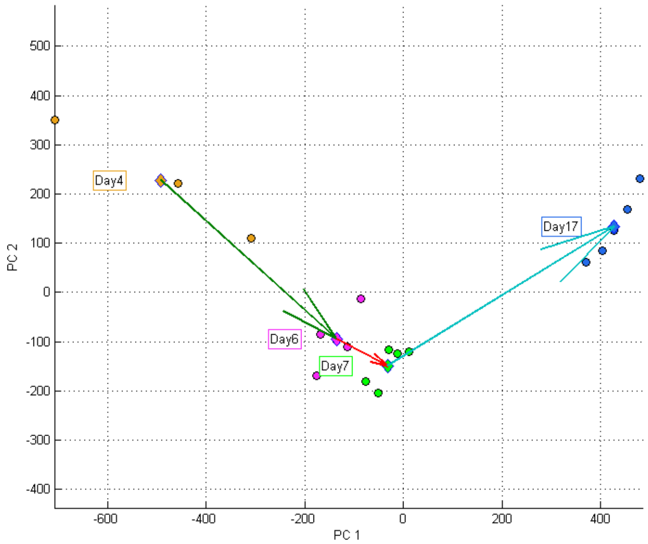

Fig. 6. The shape space obtained by analysing size normalised leaves. Individual leaves sampled at Days 4 to 17 are projected into the space (circles). They form a cluster about their respective means (diamonds) which when projected back into real-world coordinates are the size normalised mean shapes in the bottom row of Figure 5. The means are joined by growth vectors which form the developmental trajectory of young wild-type Arabidopsis leaves.

on the development of Arabidopsis leaves. Our haptic software has been in use by biologists in a number of projects for approximately a year. It forms part of a larger application allowing biologists to construct and visualise 3D statistical shape models of plant organs, such as leaves and flowers.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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