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Identification of pruning branches in tall spindle apple trees for automated pruning

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ABSTRACT

Pruning is a labor intensive operation that constitutes a significant component of total apple production cost. As growers are adapting simpler, narrower, more accessible and productive (SNAP) tree architectures such as the tall spindle fruiting wall system, new opportunities have emerged to reduce pruning cost and labor through automated pruning. This work focused on identification of pruning branches on apple trees in a tall spindle architecture. A time-of-flight-of-light-based three dimensional (ToF 3D) camera was used to construct 3D skeletons of apple trees. Pruning branches were identified in the reconstructed trees using a simplified two-step pruning rule; (i) maintain specified branch spacing and (ii) maintain specified branch length. Performance of the algorithm was optimized using a training sample of 10 trees to achieve human worker's pruning level. With a selected branch spacing (28 cm) and branch length (20 cm), the algorithm achieved 19.5% branch removal with the training dataset and 19.8% of branch removal with the validation dataset (10 trees) compared to 22% average branch removal by workers. Root Mean Square Deviation (RMSD) between human and algorithm in number of branches identified for pruning was 10% for the training dataset and 13% for the validation dataset. The algorithm and the human pruning resulted in similar average branch spacing. The algorithm maintained an average spacing of 35.7 cm for validation set whereas the average spacing for three workers was 33.7 cm. RMSD in branch spacing between the algorithm and the workers was found to be 13%. The algorithm removed 85% of long branches whereas the overlapping branch removal was only 69%. With some additional work to improve the performance in terms of overlapping branch removal, it is expected that this work will provide a good foundation for automated pruning of tall spindle apple trees in the future.

1. Introduction

Pruning refers to removing old and/or damaged parts of trees, especially unproductive shoots and branches. It is essential to improve plant health and appearance, to control plant size and to increase fruit quality and yield. Pruning is labor intensive and could cost 20% or more of the annual pre-harvest production cost for crops such as cherries (Galinato et al., 2010), apples (Gallardo et al., 2010) and pears (Galinato and Gallardo, 2011). Automated pruning of fruit trees has a potential to reduce labor demand and cost, which will help to increase the long-term sustainability of fruit production.

Researchers have been working on mechanization of fruit tree pruning for several decades. Early research work in pruning focused on mass pruning in which a cutting tool was run over rows in orchards while maintaining a certain distance from the tree canopy center (Moore, 1958; Davies and Crocker, 1994; Gautz et al., 2002). These mass mechanical pruning systems have limited ability to ensure the quality of pruning and therefore may lead to reduced quality and yield of fruit (Moore-Gough and Gough, 2007; Jensen, 1980; Carbonneau, 1979; Sevilla, 1983; Velazquez and Gonzalez, 2010). Therefore, an automatic machine for selective pruning, which can identify the branches on the tree that need to be pruned, is essential to reduce manual labor while maintaining or improving the quality and productivity of fruit crops.

Apple orchards are evolving towards simpler, narrower, more accessible and productive (SNAP) systems that are friendlier to mechanization and automation. These architectures represent various training systems that create very narrow two-dimensional canopies in which the majority of branches and fruit are visible and accessible to machines. These systems could increase profitability by improving yield and/or reducing labor cost (Robinson, 2008). One simplified architecture that lends itself better than

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conventional orchard systems to mechanization is the tall spindle fruiting wall system. In this architecture, trees are planted at smaller intra-plant spacing compared to classical architectures and the branches are not allowed to grow multiple secondary and tertiary branches. This simpler tree architecture opens up an opportunity for automated pruning.

A proper sensing technique is essential to identify unwanted branches in fruit trees for automated, selective pruning. Machine vision technology can be used to obtain such information non-destructively. In the past, some researchers have investigated the use of 2D machine vision systems to locate grapevines to guide an automated pruning device. Naugle et al. (1989), Ochs and Gunkel (1993), McFarlane et al. (1997), and Gao and Lu (2006) used a single 2D camera and image processing techniques for identification of pruning points in grapevines. However, extracting three-dimensional (3D) information of objects from a single two-dimensional (2D) image is difficult. It is essential to accurately represent objects and scenes in 3D to support the development of automatic pruning machines.

Researchers have been attracted by 3D technologies such as stereo vision and structured light for general use in 3D sensing and object reconstruction. However, only limited studies have been reported in their application to 3D reconstruction and pruning of fruit trees. One such study was conducted in a laboratory setting using multiple images of a dormant apple tree (Tabb et al., 2009). A shape-from-silhouette method was used to reconstruct the shape of the tree from the images captured from multiple orientations. Though the method showed promise for generating a 3D tree structure for pruning, the method is complex and has challenges for practical use in the orchard environment. Recently, a 3D reconstruction method based on a low cost video gaming sensor was explored by Wang and Zhang (2013) for potential application in apple tree pruning. This preliminary study indicated that a high resolution 3D structure of fruit trees can be generated using RGB-D cameras (Wang and Zhang, 2013). However, the technique requires further work on understanding its accuracy and robustness in outdoor orchard environment.

In the past several years, time-of-flight-of-light-based cameras (called 3D camera in the following text) have also been used for 3D reconstruction of plant structures. These 3D cameras have shown to be more accurate than stereo vision systems for such reconstruction (Beder et al., 2007). Lindner et al. (2007) also used a 3D camera with high resolution color images to present an efficient way of identifying false mappings due to hidden surfaces in 3D reconstruction. Nakarmi and Tang (2012) used a 3D camera for interplant space sensing in natural illumination conditions. These studies showed that 3D camera-based systems can be used to construct skeletons of apple trees in field environments, which then can be used to identify pruning branches for automated pruning.

The main goal of this research was to detect and identify branches that need to be pruned in apple trees using a 3D machine vision system, which is the first step towards automated pruning of apple trees. Specific objectives were to:

- Develop an algorithm to detect and identify pruning branches in apple trees in tall spindle orchard architecture.
- Optimize input parameters of the pruning branch identification method to achieve desired level of pruning and compare the results with actual human pruning.

2. Materials and methods

2.1. Study site

This study was conducted on a test plot in a commercial apple orchard near Prosser, WA. The test plot consisted of four rows of Pacific Rose cultivar apple trees in their fourth year. These trees were planted in high density tall spindle fruiting wall architecture (Fig. 1). The intra-plant spacing was 0.46 m and between-row spacing was 2.44 m. Maximum canopy height was 2.74 m. A tree in this architecture consisted of a single central trunk with lateral branching. The images were captured in the late dormant season on April 05, 2012.

2.2. Branch identification

A machine vision system was used to develop 3D structure of apple trees and identify branches. Four different steps were involved in processing the images captured by the 3D camera to identify branches; (i) image acquisition, (ii) image pre-processing, (iii) skeletonization, (iv) and skeleton analysis. Descriptions of each of these steps are provided below. Additional details of equipment, methods and algorithms used in these steps can be found in Adhikari and Karkee (2011) and Adhikari (2012).

2.2.1. Image acquisition

A 3D camera (CamCube 3.0, PMD Technologies, Siegen, Germany) was used to capture 3D information of the apple trees (Fig. 2). The camera generated 3D coordinates of objects with reference to the imaging plane of the camera. The imaging system was mounted on a pan-and-tilt system (PTU-D48 E, FLIR Motion Control Systems, CA, USA). Using the pan-and-tilt system, a total of 20 different images at different positions were captured for each of the 20 trees randomly selected for this study. The pan-and-tilt system was rotated vertically at the rate of 1.285° per second between [−30° and 30°] with reference to horizontal. The camera captured image frames at two-second intervals (i.e. at 2.57° interval). The platform was located approximately 1.27 m away from the center of the row of trees being imaged.

2.2.2. Image preprocessing

First, the noise in 3D images was filtered out using two different parameters; (i) the flag and (ii) the amplitude data. The time-of-flight (TOF) 3D camera provides a parameter called *flag* to indicate the quality of distance estimation at each pixel. Any pixel whose

Fig. 1. Image of the tall spindle fruiting wall apple orchard in Prosser, WA that was used in the study.