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Estimation of fruit locations in orchard tree canopies using radio signal ranging and trilateration

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ABSTRACT

The development of novel robotic harvesters could benefit significantly from a model-based design approach, in which harvesting performance metrics—such as fruit reachability and average pick-and-place cycle—are calculated via simulation, and are used to guide mechanical design. The actual spatial distributions of fruits on orchard trees are necessary for such an approach. Reported methods for measuring the locations of all fruits require several minutes per fruit, and, consequently, have been used only for very small numbers of trees. The novel method presented utilizes high-frequency radio signals and trilateration to measure the locations of all fruits in canopies, at speeds that are significantly higher than those of existing methods. More specifically, a fruit picker wears gloves on which an antenna has been attached. A mobile trailer carries four radio beacons that measure and log their distances from the antenna on each glove, every time a fruit is grasped to be picked. The coordinates of each glove are computed with respect to a coordinate frame attached to the trailer, and the fruit position is approximated by these coordinates. Data from an RTK-GPS and an inclinometer on the trailer are used to compute georeferenced fruit coordinates. Data were collected for 32,193 fruits in eight California pear and cling peach orchards. The measurement rate varied from approximately 8–12 fruits per minute, with an average of 10.8, which is a magnitude faster than existing reported methods. In open space, the root mean square error between the estimated and true distance (DRMS) in the system's measurement volume was measured to be 10.3 cm. The error's 90th percentile (R90) was 13.1 cm. In the periphery of and inside canopies, these errors were calculated via Monte Carlo simulation to be equal to 15.7 cm and 24.9 cm respectively. The horizontal accuracies (across and along the row), and the vertical accuracy were 9.6 cm, 4.3 cm and 5.7 cm respectively. The corresponding worst-case relative accuracies were 2.7%, 1.6%, and 3.4%, and were calculated by dividing each accuracy component by the distance between the fruits that were as far away as possible from each other along the corresponding axis. Finally, fruit position statistics, such as fruit elevation and horizontal distance from the row centers were computed and reported for a set of pear trees. Such data can be very useful for growers and for model-based design of harvesting machinery.

1. Introduction

In this paper, a novel method is presented that utilizes Ultra-Wide-Band (UWB) radio signals and trilateration to measure the locations of *all* fruits in tree canopies, at speeds that are significantly higher than those of existing methods. The motivation behind this work is that fruit distributions, together with digitized branch geometries, will be used as inputs to software design tools that predict harvesting performance metrics and guide the design of novel robotic harvesters, thus enabling a model-based design approach. Together with purchase price, fruit reachability and harvesting throughput performance metrics have been shown to constitute the most important factors in deciding the economic feasibility of a robotic harvester (Harrell, 1987). Of course, a robotic harvester's actual performance in the orchard will depend on the complex interrelationships among orchard layout, tree canopy structure, spatial fruit distribution, harvester kinematics and dynamics, fruit detection and localization, and actuator control. For this reason, performance is evaluated using physical prototypes in orchards during the short harvesting season. This fact renders the iterative process of designing, building, testing and modifying fruit-harvesters expensive and slow.

The development of novel robotic harvesters could benefit significantly from a model-based design approach, in which

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harvesting performance metrics are estimated by simulating the parts of the harvesting operation that are essential and meaningful for design purposes. A major goal of model-based design would be to guide toward a *mechanical* design that *maximizes* performance in terms of fruit kinematic reachability and average pick-and-place cycle for trees of certain architectures. This goal can be achieved by assuming perfect perception and control. In other words, predicting harvesting performance for mechanical design should incorporate the constraints imposed by the tree geometries and fruit positions, but not the constraints that may arise due to poor fruit visibility, under-powered actuation, or non optimal control. The use of model-based approaches for robotic harvester design and optimization has been very limited. Edan et al. (1991) modeled a specific robot arm type and measured fruit locations on a few small trees, in order to calculate optimal picking sequences for the robot, and to study the effect of link masses on maximum throughput. Sivaraman and Burks (2006, 2007) used canopy volume estimates to perform robot manipulator kinematic design, with maximum fruit reachability as a design criterion. Van Henten et al. (2009) used workspace and manipulator specifications stemming from cucumber harvesting operations to optimize the kinematic structure, and link parameters of a three-link robot arm.

This paper focuses on the measurement of spatial distributions of all fruits on trees. Branches certainly affect fruit accessibility and harvester throughput (and, consequently, optimal mechanical design); therefore, their geometries would need to be incorporated, too. Measuring the locations of *all* fruits on trees can be a very time-consuming and expensive process. The first documented attempt to map fruit spatial distributions on trees was by Schertz and Brown (1966), who adopted a cylindrical coordinate system and measured the coordinates of citrus fruits. More specifically, the longitudinal axis of the coordinate system was oriented vertically and collinearly with the trunk of the tree. The height of each fruit was measured by lowering a plumb bob on a calibrated tape. The point of intersection of the plumb bob with a polar coordinate board at ground level gave both the angular and the radial positions of each fruit. This approach was very time-consuming, and required one to two days to map all the fruits on a single tree, depending on yield and tree size. Measurement accuracy could not be assessed, but it obviously depended on user skill, because branches might also cause the tape to deflect and deviate from a straight vertical line. Other researchers, such as Juste and Lee and Rosa, have also used this simple approach (Juste et al., 1988; Lee and Rosa, 2006).

Smith et al. (1992) used a theodolite to record the three-dimensional coordinates of kiwi fruits on vines and sample the geometric structure of the vines themselves. The accuracy of the readings was reported to be within millimeters of the position of each point. This method was limited, in that it required unobstructed Line-of-Sight (LOS) between each fruit and the theodolite. This, however, is impractical for trees with dense canopies and fruits hanging deep inside them. Also, fruit position measurement was slow: each fruit required approximately 60 s, resulting in an effective rate of one vine per one-to-two days, depending on yield and vine size. Smith and Curtis (1996) used a three-dimensional position tracking system (Polhemus FastTrak™) to digitize tree structure and measure fruit locations. This system used a low frequency magnetic field emitted by a transmitter to measure the 3-D coordinates of the tip of a stylus; coordinates were relative to a coordinate system defined by the transmitter. The RMS static accuracy of the system in the absence of metal objects is approximately 1 cm, within 1 m from the transmitter. The system's operational radius was limited to approximately 1.5 m; digitizing large trees was made possible by re-locating the transmitter to various positions, while keeping at least three points from the previous position within range. As a result, an appropriate coordinate transformation matrix can be computed. Data collection without moving the transmitter was reported to take place at approximately 10 points per minute. However, digitizing 1300–1500 points on a larger kiwi vine with this system required 10–12 h.

Edan et al. (1991) measured fruit locations on twenty orange trees using a robotic manipulator on a mobile platform as digitizer. The data were collected manually, by placing the arm tip at each fruit on the tree, and storing the readings of each joint encoder at this position on a computer. Furthermore, the exact location of each fruit was calculated via the robot's forward kinematics. Accuracy and data collection rate were not reported. Relocating the robot tip – and possibly the platform – to reach each new fruit position should have required non-trivial effort, resulting in low collection rates. Also, larger trees would require a large robot, while branches could interfere with the robot links, thus rendering the task very difficult.

In contrast to manual methods, vision-based approaches use multiple cameras and points of view to detect and triangulate fruits from images. Takahashi et al. (2002) used stereovision to measure the range of apple fruits. The camera's position and Euler angles could be combined with the range to compute 3D fruit location. The range estimation errors were reported to be ±5% (average of -1.3% and standard deviation of 3.5%) at a distance range of 1.7–5.2 m for non-overlapping fruits. Fruit localization has also been performed in yield estimation systems, such as the one developed by Wang et al. (2013), in order to avoid double counting of fruits in sequences of images. The authors do not report the position accuracy of the system, although they mention that fruits closer to 5 cm are counted as a single fruit. Here, it is important to note that their goal was yield mapping and not fruit localization. The major problem with vision-based approaches is that many fruits – especially those deeper into the canopy – are occluded by other fruits, leaves, or branches, and are not visible from the camera's viewpoints. For this reason, they cannot be localized.

In this paper, a novel method is presented, which utilizes Ultra-Wide-Band (UWB) high-frequency radio signals and trilateration to measure the locations of *all* fruits in tree canopies, while the fruits are being picked. UWB uses short pulse radio frequency waveforms over a large bandwidth (GHz) to measure precisely the time-of-flight of a signal between a transmitter and a receiver. Trilateration combines the measured ranges into an estimated position. UWB radios have been proposed for localization in work environments associated with construction (Cheng et al., 2011) and mining (Chehri et al., 2009). To the authors' best knowledge, the use of UWB technology for localizing points close to, or inside, tree canopies has not been reported in the literature. Results from data collection in several orchards with different tree architectures are presented. These results establish that an average throughput of the system is approximately 10.8 fruits per minute, which is at least one order of magnitude faster than existing reported methods.

Another contribution of this work is the investigation of the effects of foliage on trilateration accuracy. It is known that the water contained in vegetation attenuates radio signals, and that signal reflection on the ground, as well as scattering at tree branches introduce multipath effects (Vougioukas et al., 2013) that reduce UWB ranging accuracy. A novel trilateration error assessment method is also presented, which uses the statistical distributions of range errors to estimate the trilateration error inside foliage. The method is validated by means of experimental results, which are used to characterize the accuracy of the measuring system. Finally, as an example of using the fruit position data, some spatial statistics that could be relevant to machine design are calculated and presented.