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Data-Driven Model to Improve Mechanical Harvesters for Nut Trees

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ABSTRACT. *The economic impact of California's agricultural sector is the most important in the United States. California produces more than 80% of the world's almonds. Currently, the trunk shaker harvesting machine is the most widely used for harvesting almond trees in California. During the harvest, the operator, based on their experience, set the shaking parameters such as duration and shaking frequency. Manual adjustments by operators lead to variability in fruit removal, and in some cases, it could cause tree damage. This study aimed to develop a data-driven mathematical model required to build an intelligent tree shaker machine capable of optimizing shaking parameters autonomously. A sensor system to monitor force distribution throughout the tree canopy was designed and implemented. Data was collected from an almond orchard in California during the summer of 2023. A quadratic mathematical model was developed using machine learning regression methods to estimate relationships between trunk diameter, acceleration, and shaking duration. The findings show that trunk diameter positively correlates with acceleration and shaking time duration. Our research demonstrates the potential for intelligent harvesting machines that can adjust parameters based on real-time sensor data, ultimately improving fruit removal efficiency, and potentially reducing tree damage.*

Keywords. *data-driven model, mechanical harvester, nut tree, sensor, trunk shaker.*

Introduction

Since the 1900s, almond commercial cultivation started expanding in California's Central Valley. By the year 2000, California was the only almond producer in the United States and its largest exporter (Geisseler et al., 2014). According to the California Almond objective measurement report, published by USDA, showed that almond production increased from approximately 2.57 billion pounds in 2022 to 2.6 billion pounds in 2023. Consequently, there has been a 1.5% increase in almond production from 2022 to 2023 (USDA, 2023).

The design of trunk shakers has remained largely unchanged since the late 1970s (Afsah-Hejri et al., 2022). As trunk size increases, kinetic energy transmission from the shaker to the canopy surface decreases (Ma et al., 2022). Studies in California have shown that increasing trunk circumference by over 1.27 m can result in a 30% decrease in final harvester efficiency

(Ferguson et al., 2014). Currently, field managers or machine operators manually set the shaking frequency, and duration for trunk shakers (Pu et al, 2023; Homayouni et al., 2022). While it is theoretically possible to mathematically determine optimal shaking parameters for maximum fruit removal and minimal damage, determining these parameters for every tree is not a practical solution (Ma et al., 2022; Pu et al., 2018a).

To address this limitation, machine learning can be employed to analyze data and generate approximate mathematical models from the fed data (Alizadeh et al., 2023; Malek et al., 2020). This approach can help predict each tree's optimal shaking parameters (Ma et al., 2022; Pu et al., 2018b). However, creating a practical data-driven model for machines requires a massive amount of actual data collected during the harvest season. Earlier studies have utilized various types of wired analog and digital accelerometers to collect in-field data (Pu et al., 2018b; Liu et al., 2018a; Liu et al., 2017). A wireless accelerometer was developed and tested in the field, as well as a quick-mountable independent vibration sensor with GPS capabilities for pistachio harvesters (Ma et al., 2022; Homayouni et al., 2022). A new device enabled the collection of a massive amount of data during the Pistachio harvest season, allowing researchers to manually measure trunk sizes and investigate the trunk size influence on harvester performance (Ehsani et al., 2023).

Each tree's unique natural frequency, determined by its size and branch arrangement (Homayouni et al., 2022), must be considered when designing a trunk shaker. Shaking trees at frequencies mismatched to their natural frequencies can lead to severe damage or even tree failure (Liu et al., 2018b). To address this challenge, there has long been a need for machines that can adapt to individual trees and optimize shaking parameters accordingly (Homayouni et al., 2022). However, simply applying the same shaking settings universally may not achieve optimal fruit removal for each tree. Therefore, further research is needed to develop a tailored approach that considers the trunk size of each tree and yields ideal harvesting results. The objective of this study was to create a practical data-driven mathematical model that estimates the optimal shaking settings required for individual trees based on their unique trunk sizes.

Materials and Methods

To collect a comprehensive dataset for developing a practical, data-driven mathematical model, we enhanced the system introduced by Ehsani et al. (2023) by incorporating a linear position sensor. This upgrade enabled us to simultaneously record GPS coordinates, tagged acceleration data, and tree trunk size measurements. The linear position sensor used in this study, called SP1, was modified for easy mounting on the shaker head of an almond harvester. The output signal from the SP1 sensor was integrated with the Ehsani et al. (2023) system to record GPS-coordinated acceleration data at each elapsed time interval. The system was capable of measuring and recording real-time shaking data at a sampling rate of 4 ms.

In August 2023, we collected data from over 100 almond trees located in a single row of an orchard block at Stevenson, California (Latitude: 37°21'07.2" N, Longitude: 120°54'40.9" E). The trees were shaken using an Orchard-Rite BULLET trunk shaker machine (Figure 1). A total of 90 trees with clean and reliable data were selected for modeling and analysis purposes.

Figure 1. Orchard-Rite BULLET trunk shaker machine.

The Orchard-Rite BULLET trunk shaker machine employs a complex reverse scissor mechanism to grasp and secure the almond tree trunk, allowing it to be shaken. To determine the trunk size based on the installed location of the SP1 sensor, we leveraged Thales' theorem (Buysse, 2023). According to this theorem, Equation (1) was derived to translate the measured distance value (x) into the actual trunk diameter (D).

$$D(x) = 0.7647x \quad (1)$$

Finally, we utilized TensorFlow 1 within a Python programming environment to develop an optimal data-driven mathematical model. The input features included shaking duration (τ), resultant acceleration (a_r), and trunk diameter (D) from the dataset of 90 trees. Values of Goodness of fit (R^2), Sum of Square Errors (SSE) and Root Mean Square Error (RMSE) were reported to evaluate how well the model was able to predict the target value.

Results

Our analysis of the collected data indicated that polynomial mathematical models are the most suitable functions to fit the data. Specifically, a quadratic polynomial (degree 2) effectively describes the relationships between D, τ, and a_r. Figure 2(a) illustrates the results of the suggested quadratic equation, which captures the changes in D as a function of τ. Figures 2(b) and 2(c) show the relationships between D and a_r, and a_r and τ, respectively, using the same quadratic polynomial model.

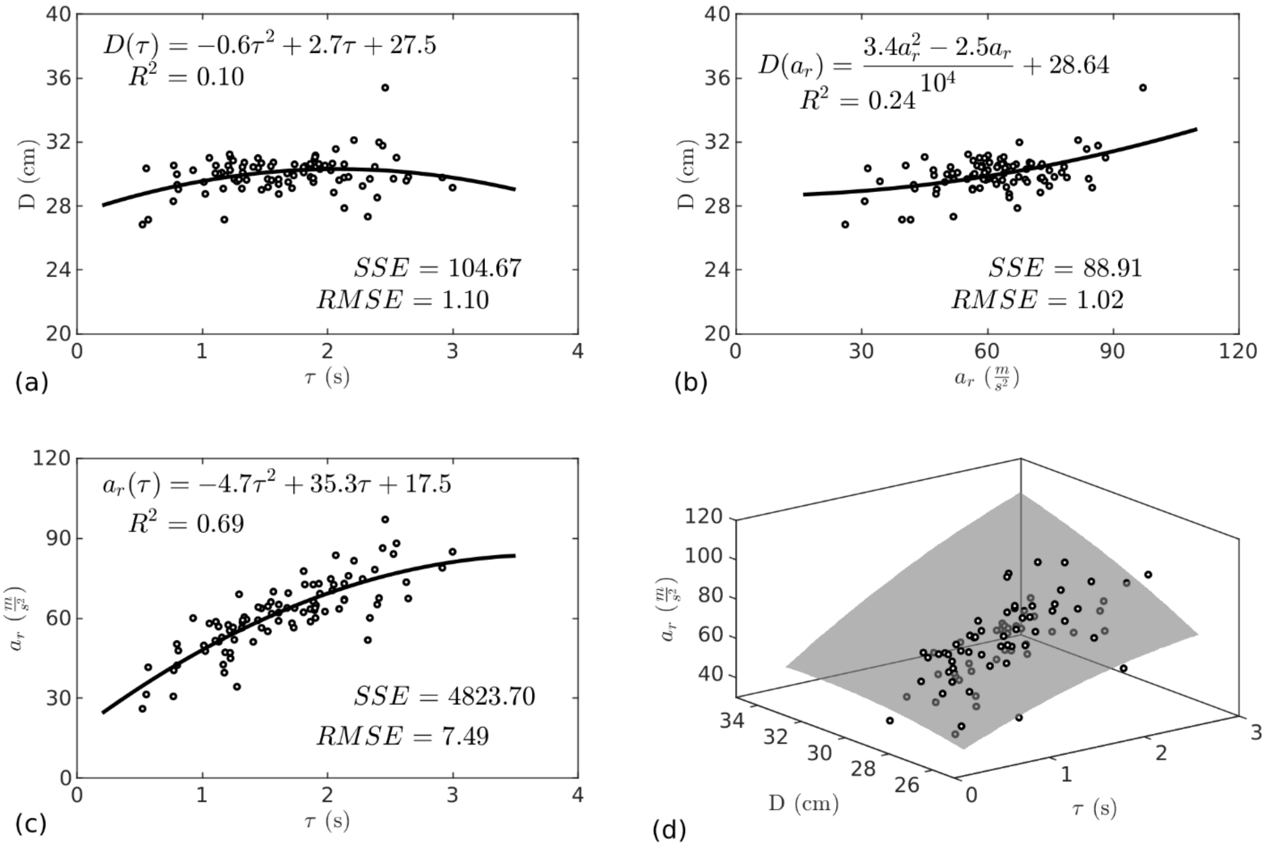

Figure 2. Data-driven mathematical models for (a) trunk diameter as a function of shaking duration, (b) trunk diameter as a function of resultant acceleration, (c) resultant acceleration as a function of shaking duration, and (d) the relationship between resultant acceleration, trunk diameter, and shaking duration.

Ultimately, these results demonstrate that the data-driven mathematical model in Equation (2) can predict the a_r as a function of τ and D, as shown in Figure 2(d).

$$a_r(\tau, D) = \alpha_0 + \alpha_1\tau + \alpha_2 D + \alpha_3\tau^2 + \alpha_4\tau D + \alpha_5 D^2 \quad (2)$$

where

α_i indicates the indexed coefficients of Equation (2) and achieved optimal values for these coefficients are shown in Table 1.

Table 1. Coefficients α_{ij}

		95% confidence bounds	
Coefficient	Optimal Coefficient Value	Lower	Upper
α_0	-164.60	-625.60	296.40
α_1	-16.01	-90.15	58.13
α_2	11.91	-21.04	44.85
α_3	-3.14	-7.26	0.97
α_4	1.50	-1.03	4.02
α_5	-0.19	-0.78	0.40

The R^2, SSE, and RMSE of Equation (2) are 0.76, 3658.30, and 6.34, respectively. Although these reported metrics indicate a reasonable fit, there is still room for improvement. To increase model performance, one could consider increasing the degree of the mathematical model. However, this would also lead to an increase in the number of coefficients and model terms, potentially making it more challenging to optimize the coefficients within predetermined boundaries while ensuring correct optimization. It is notable that further research is needed to verify the model's effectiveness across various nut tree varieties.

Conclusion

In this study, we built upon the work of Ehsani et al. (2023) by integrating a linear position sensor and employing Thales' theorem to develop a mathematical framework that translates measured distance values into actual trunk diameters. Our machine learning-based approach created a predictive model for estimating resultant acceleration as a function of trunk diameter and shaking duration. This methodology has the potential to inform optimal shaking intensity and duration settings for various tree types, but further research is needed to validate its effectiveness across different almond varieties. This method can be utilized in the next generation of intelligent machines for determining the optimal duration and shaking amplitude based on each tree's trunk diameter. The reported metrics (R^2, SSE, RMSE) provide sensibility into how the suggested models fit the data points. Moreover, we propose that incorporating additional key parameters such as tree natural frequency and morphological information as pre-trained inputs for machine learning could enhance the precision of predicted models.

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