Evaluation of an Optimal Approach Direction for a Tomato-Harvesting Robot Using a Digital Twin

Kouya Taitou, Takuya Fujinaga*
Graduate School of Engineering, Osaka Metropolitan University,
1-1 Gakuen-cho, Nakaku, Sakai, Osaka 599-8531, JAPAN

Email: sr25171c@st.omu.ac.jp, tfujinaga@omu.ac.jp
*Corresponding Author

Abstract

In this study, a digital twin environment was constructed to evaluate the optimal approach direction for a tomato harvesting robot. Previous studies have shown that grasping success is strongly influenced by factors such as pedicel orientation and the positional relationship of adjacent fruits. However, testing multiple approach directions with a physical robot is labor-intensive and poses risks of damage. To address this issue, we constructed a virtual environment that integrates a robot model reflecting the structure of the actual machine with a parametric tomato cluster model capable of representing factors related to harvesting difficulty model integration and motion verification were conducted in the virtual environment, enabling systematic evaluation of approach directions. The proposed environment contributes to reducing experimental workload and improving the reliability of the harvesting robot.

Keywords: Digital twin, Agricultural robotics, Tomato harvesting robot, Virtual environment

1. Introduction

In recent years, the agricultural sector has faced severe challenges due to a declining and aging workforce [1], increasing the demand for labor-saving and automated robotic systems. Although harvesting robots have been developed for various crops [2], [3], many systems have yet to reach practical deployment [4]. For tomato-harvesting robots in particular, the diversity of cluster shapes and interference with pedicels or neighboring fruits make it difficult to achieve stable harvesting performance. Geometric factors such as pedicel orientation and fruit arrangement significantly affect grasping success, and the direction from which the robot approaches the target fruit is a key determinant [5].

However, systematically evaluating multiple approach directions using a physical robot is time-consuming, labor-intensive, and poses risks of damaging both the robot and the fruit. Digital twins, which reproduce the robot's structure and motion characteristics in a virtual space, offer a promising solution for safely and efficiently testing harvesting motions [6], [7], [8]. By using a simulation environment, the influence of cluster geometry on approach direction can be analyzed in advance, reducing the burden of physical experiments.

The objective of this study is to establish a foundation for systematically evaluating how approach direction affects grasping success using a digital twin environment. We constructed a robot model in virtual space that reflects the structure and control system of the actual machine. In addition, we designed a parametric tomato cluster model that allows manipulation of geometric factors such as pedicel orientation and neighboring fruit positions. Furthermore, based on the graspability classifications reported in prior work [5], we developed a method to evaluate feasibility by scanning azimuth angles around the classified optimal directions.

The contributions of this study are threefold: (1) construction of a digital twin environment integrating the robot's motion algorithm with a parametric tomato cluster model; (2) development of a model generation method corresponding to multiple cluster shape categories defined in prior research [5]; (3) proposal of a systematic evaluation process for approach direction prior to physical experiments. The proposed framework is expected to reduce the number of trials required in field experiments and support the design of safe and efficient harvesting strategies.

2. Method

2.1. Construction of a digital twin

To reproduce the harvesting motion of the actual robot in virtual space and evaluate how approach direction affects grasping success, we constructed a digital twin environment, as shown in Figure 1. The robot model was based on the actual machine, which consists of a mobile platform, linear sliders along the y- and z-axis, a 4-DOF vertical articulated manipulator, and a gripper-type end effector. Link geometries and mass parameters were imported from 3D data and implemented in URDF format, enabling realistic reproduction of arm motion including physical properties.

In the actual robot, the mobile platform navigates the greenhouse until a tomato is detected, after which the y- and z-axis sliders and the 4-DOF arm perform the approach motion. To reproduce this workflow, we constructed a communication and control structure in the virtual environment that mirrors the node architecture of the real system. Joint angles, end-effector poses, and relative positions to the fruit were obtained to establish a foundation for quantitatively evaluating graspability for each approach direction.

2.2. *Tomato cluster modeling*

To quantitatively evaluate the influence of approach direction on grasping success using the digital twin, we constructed a virtual environment that includes a tomato cluster model and the robot's workspace. The tomato model was designed based on factors reported in prior research [5] to affect harvesting difficulty. That study showed that graspability strongly depends on: (1) whether the pedicel is located on the left or right side of the target fruit; (2) whether the pedicel is positioned in front of or behind the fruit from the robot's viewpoint; (3) whether another fruit exists in the lower-right region of the target fruit. In this study, we designed a new cluster model in which the relative positions of fruits and pedicels can be arbitrarily modified.

The virtual environment was not intended to replicate greenhouse conditions in full detail, but rather to isolate and analyze the relationship between approach direction and graspability under controlled geometric conditions. This allows the results to be applied to real robot experiments conducted in laboratory settings.

2.3. *Definition and evaluation of approach directions*

The approach direction was defined as the horizontal azimuth angle relative to the center of the target fruit. The elevation angle was fixed to 0°, corresponding to horizontal entry, based on the structure of the end effector and typical greenhouse operating conditions.

Candidate approach directions were selected based on prior research [5], which classified the most graspable direction as "front," "left," or "right" depending on pedicel orientation and neighboring fruit arrangement.

For each tomato model, the classified optimal direction was used as the basis for setting approach angles in the virtual environment. For each candidate direction, the robot arm was moved toward the fruit in the digital twin, and graspability was evaluated visually. The criteria were:

- no obvious interference with the pedicel or neighboring fruits,
- the end effector can reach the fruit center without excessive motion,
- a feasible grasping posture can be achieved.

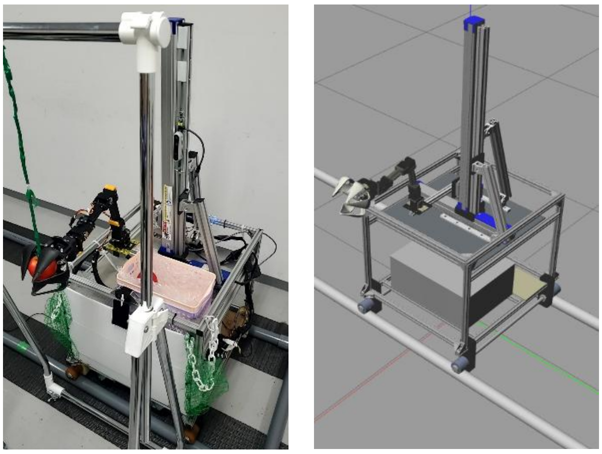

(a) Real environment. (b) Virtual environment

Figure 1 Constructed digital twin of the robot.

If multiple directions were judged graspable, the direction with the smallest absolute azimuth angle—i.e., requiring the least posture change—was selected as the optimal approach direction. This choice is motivated by the expectation that minimizing robot motion reduces operation time and energy consumption in real harvesting tasks.

3. Results and discussion

3.1. *Overview of the simulation framework*

Using the digital twin environment constructed in Section 2, we evaluated how approach direction affects grasping success. The approach direction was defined by the horizontal azimuth angle, with elevation fixed at 0°.

For each tomato cluster model, simulations were conducted within the angle ranges corresponding to the "front," "left," or "right" classifications reported in [5]. Specifically, models classified as "left" were tested from −50° to 0°, and those classified as "right" from 0° to +50°, in 5° increments.

Graspability was evaluated visually rather than using automated collision detection. A direction was recorded as graspable if the end effector could reach the fruit center without excessive interference and if a feasible grasping posture could be achieved.

3.2. *Verification and limitations of the generated tomato cluster models*

We generated tomato cluster models in which fruit size, pedicel length and angle, and neighboring fruit positions could be controlled parametrically. Representative examples are shown in Figure 2.

The generated models corresponded to the classifications reported in [5] regarding pedicel position (left/right, front/back) and neighboring fruit arrangement, confirming that the intended geometric characteristics were preserved. This confirmed that the generated cluster model is appropriate as an input model for evaluating the dependence of approach direction on differences in cluster geometry.

Because multiple models could be generated consistently, the same evaluation procedure could be applied repeatedly across different cluster shapes. However, the current model does not incorporate mechanical properties such as pedicel flexibility or fruit elasticity, as the design prioritizes isolating geometric factors affecting approach direction. Incorporating these mechanical elements will be considered in future work through comparison with real robot experiments.

3.3. Validation of approach directions through digital twin and field experiments

A representative result validating the approach direction derived in the digital twin environment through real greenhouse experiments is presented. For the upper-right fruit in the cluster shown in Figure 2(b) the virtual environment indicated that an approach angle of 0° resulted in significant interference between the lower gripper and the target fruit, making grasping difficult. In contrast, at 5°, interference was reduced and graspability improved, as illustrated by the harvesting motion sequence in Figure 3.

Based on this evaluation, we applied the same approach angle to the tomato shown in Figure 2(a). Harvesting experiments were then conducted in the greenhouse using the real robot, as shown in Figure 4. As a result, harvesting failed at 0°, whereas harvesting was achieved at 5°. This indicates that using the digital twin environment to pre-select approach directions is effective prior to trial-and-error testing in real environments.

3.4. Discussion

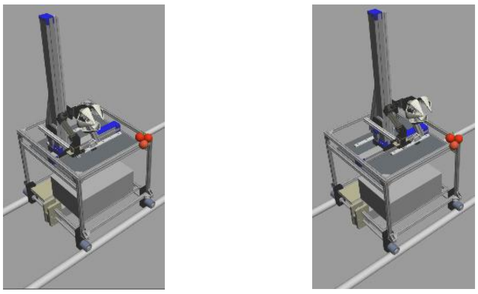
This study constructed a digital twin environment integrating the robot's motion algorithm with a parametric tomato cluster model, establishing a technical foundation for evaluating approach directions. The environment enables analysis of how pedicel orientation and fruit arrangement affect grasping success prior to physical experiments.

The usefulness of the digital twin was confirmed in several aspects:

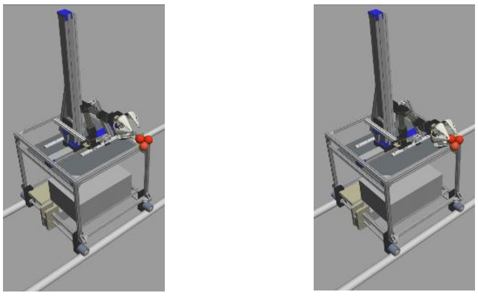
- multiple cluster shapes can be evaluated in advance, reducing trial-and-error workload,
- potentially dangerous pedicel interference can be checked beforehand, contributing to safer harvesting motion design,
- parametric model generation supports generalization of control strategies across diverse cluster shapes.

(a) Origin. (b) Model.

Figure 2 Comparison of tomato clusters.



(a) Initial position. (b) Completion of mobile platform and linear sliders motion.



(c) Approach motion of 4-DOF vertical articulated manipulator. (d) Completion of grasping motion.

Figure 3 Sequence of the harvesting motion in the virtual environment.

(a) Overview camera image after grasping. (b) Camera view mounted on the robot.

Figure 4 Harvesting experiment in the real environment.

Current limitations include the absence of mechanical simulation of pedicel bending and fruit elasticity, reliance on visual evaluation for interference detection, and lack of modeling for the abscission force required for pedicel detachment. These issues will be addressed by incorporating feedback from real robot experiments to build a more realistic harvesting simulation.

4. Conclusion

In this study, we developed a digital twin environment that integrates the robot arm's motion algorithm with a parametric tomato cluster model to evaluate the influence of approach direction in tomato harvesting. This environment provides a foundation for pre-evaluating graspable approach directions across diverse cluster geometries.

Furthermore, the approach angles identified as feasible in the digital twin were directly applied to harvesting experiments in an actual greenhouse, where the virtual evaluation results were successfully reproduced by the physical robot. These findings demonstrate that the proposed method effectively reduces trial-and-error in real environment testing and contributes to the design of safe and efficient harvesting motions.

On the other hand, several challenges remain for achieving higher realism, including modeling the mechanical properties of pedicels and implementing automated interference detection. Future work will incorporate feedback from real environment experiments into the digital twin and extend the mechanical models and evaluation metrics, with the goal of establishing a more reliable framework for harvesting motion design.

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References

1. C. Mitaritonna, et al., "After Covid-19, will seasonal migrant agricultural workers in Europe be replaced by robots?," CEPII Policy Brief, no. 33, 2020.
2. V. Bloch, et al., "A methodology of orchard architecture design for an optimal harvesting robot," Biosystems Engineering, vol. 166, pp. 126–137, 2018.
3. W. Lili, et al, "Development of a tomato harvesting robot used in greenhouse," Int. J. of Agricultural and Biological Engineering, vol. 10, no. 4, pp. 140–149, 2017.
4. C. W. Bac, et al, "Harvesting robots for high-value crops: State-of-the-art review and challenges ahead," J. of Field Robotics, vol. 31, no. 6, pp. 888–911, 2014.
5. T. Fujinaga, "Realizing an intelligent agricultural robot: An analysis of the ease of tomato harvesting," Smart Agricultural Technology, Volume 12, 2025.
6. G. Sætren, et al., "Simulator versus traditional training: a comparative study of night driving training," Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 63, no.1, pp. 1669–1673, 2019.
7. A. M. Khadeir, et al, "Building and validation of a low-cost driving simulator," J. of Physics: Conference Series, vol. 1973, 2021.
8. J. O. Oyekan, et al, "The effectiveness of virtual environments in developing collaborative strategies between industrial robots and humans," Robotics and Computer-Integrated Manufacturing, vol. 55, pp. 41–54, 2019.

Authors Introduction

Mr. Kouya Taitou

He is a master's student in the Graduate School of Engineering at Osaka Metropolitan University, Japan. His research interests include agricultural robots.

Dr. Takuya Fujinaga

He is an Assistant Professor in the Department of Mechanical Engineering at Osaka Metropolitan University, Japan. He received a Ph.D. from Kyushu Institute of Technology in 2021. His research interests include agricultural robots, marine robots and field robotics.