Development of an Automatic Agricultural Fruit Bagging Robot

Tsai-Hsu Wu[†], Ya-Ting Hsu[†], You-Ling Liang[†], and Pei-Chun Lin[*]

***Abstract*—This study aims to develop an automatic agricultural fruit bagging robot that integrates visual recognition and automation of fruit bagging to alleviate the agricultural labor shortage in Taiwan. Using an RGB-D camera, the visual recognition system identifies the young fruits and computes the relative positioning between the fruit and the robot. The automation of fruit bagging is achieved by a custom-designed mechanism that places the young fruit inside a paper bag and secures the bag opening using a twisted cable tie. The process involves lifting the bag to surround the young fruit, securing the bag opening by enclosing two C-shaped jaws, wrapping the bag using a cable tie, cutting the tie, and twisting the tie using a rotating plate. The visual and automatic bagging systems are mounted on a robotic arm for manipulation. A digital twin of the robot is developed for trajectory planning and remote monitoring. The system is empirically built and evaluated experimentally, including visual recognition, robotic arm operation, bagging mechanism design, etc. The experimental results confirm that the system is functional.**

***Index Terms*—agriculture robot, automation, fruit detection, fruit bagging**

I. INTRODUCTION

In recent years, the agricultural sector has been experiencing a significant decline in the labor force, prompting a growing trend of merging agriculture with automation. Among the various agricultural tasks, bagging young fruits has remained a labor-intensive process. Bagging is a standard physical method to protect young fruits while minimizing the use of chemicals. It can prevent diseases, mechanical damage, chemical contamination, and sunburn and avoid pest and bird damage [1, 2]. Due to the popularity of bagging and its various benefits, mechanizing bagging has become an important issue.

Currently, handheld mango bagging machines that create a vacuum using an air compressor are available. These machines use suction cups to remove the bags and manually open them. The fruit is then inserted manually into the bag on the tree. The bag opening is then sealed using a hot-melt Polyethylene (PE) plastic film [3]. Another design utilizes an air pump and suction cups to expand the fruit bag. Then, the fruit is manually placed inside the bag. A linear electric push rod and a linkage mechanism are used to fold the bag opening. A push-pull electromagnet is then used to secure the bag opening with staples [4]. In Japan, there is also a bagging device for grape production. Bags with two leaf springs at the bag opening are used, and an end-effector with two fingers is employed to hold the bag open. The bag naturally closes when the fingers are released due to the leaf springs [5]. However, apart from the grape bagging device above, the proposed semi-automated devices still require human assistance. Achieving complete automation in fruit bagging has yet to be realized. Therefore, this study designs a mechanism for bundling fruit bags. The developed mechanism is positioned beneath the young fruits by a robotic arm, facilitating a rapid and efficient fully automated bagging process.

Due to the wide cultivation area and the frequent practice of bagging mangoes, the current focus is on designing bagging equipment specifically for mangoes. Assuming that the pruning, thinning, and removal of leaves near the fruit stalk have been done manually, this study focuses solely on the bagging step. Comparing the methods mentioned above, hot-melt PE plastic film is time-consuming, and paper bags attached to staples are not reusable and have lower stability. There are also additional costs if specialized paper bags are used. Therefore, this study ultimately chooses a method similar to manual bagging to secure bag opening. The manual bagging procedure involves sealing the paper bag with a wire spiral around the stem when the bag is approximately one-third filled with the young fruit. Here, it is critical to ensure a tight seal around the stem to prevent water from entering the bag. This fruit bagging mechanism references a previously published patent on tying machines [6], and a twist tie is used to tighten the bag. The system uses a feeding mechanism to deliver a winding wire along a guide strip. The winding wire then passes through the space between the upper clip and the movable plate of the clamp, and the clamp descends to grip and rotates the wire, forming a bundled wire. The research outlined in this paper develops an automated young fruit bagging machine. The system utilizes a depth camera for fruit recognition, a robotic arm for precise movement, a dual lead screw mechanism to tighten the bag opening, and C-shaped jaws to propel and securely fasten the twist tie, effectively bagging young fruits. These components work together to achieve successful bagging of young fruits in an automated manner.

The remainder of this paper is organized as follows. Section II presents a brief overview of the bagging process. Section III introduces the training model used for young fruit recognition. Section IV describes the simulation of the virtual system. Section V explains the detailed design of the bagging mechanism and the electromechanical and control systems. The final results are presented in Section VI. Section VII concludes the work.

II. THE BAGGING PROCESS

As shown in Fig. 1, the depth camera first identifies the young fruits and their positions. The bagging sequence is determined from the bottom up and from the inner to the outer side of the fruit tree. Once the young fruits are identified, the

This work is supported by the National Science and Technology Council (NSTC), Taiwan, under contract MOST110-2634-F-007-027-and MOST 111-2634-F-007-010-.

[†]These authors contributed equally to this work.
[*]Corresponding author (email: peichunlin@ntu.edu.tw)
The authors are with the Department of Mechanical Engineering, National Taiwan University (NTU), No.1 Roosevelt Rd. Sec.4, Taipei 106, Taiwan.

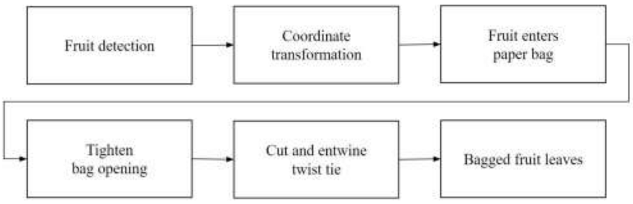


Fig. 1. Flowchart of the automatic fruit bagging process

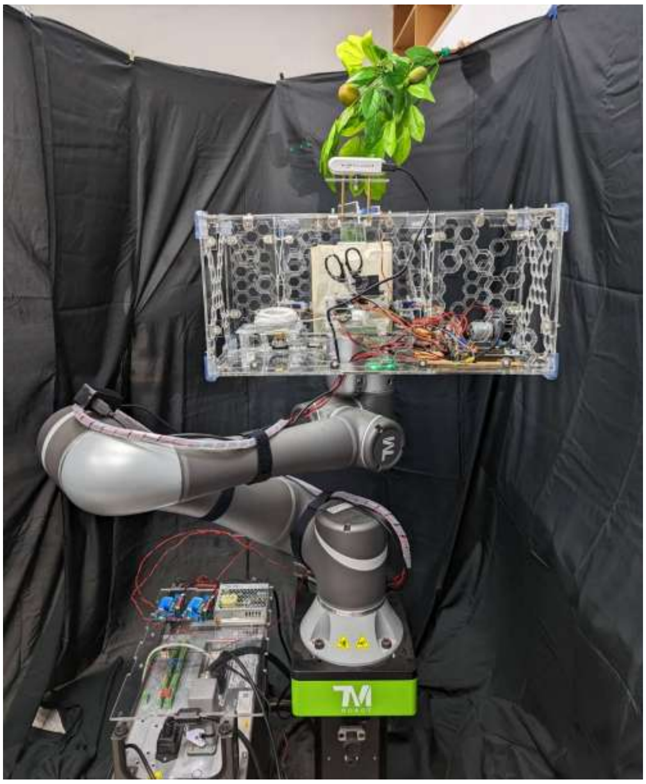


Fig. 2. A picture of the automatic fruit bagging robot

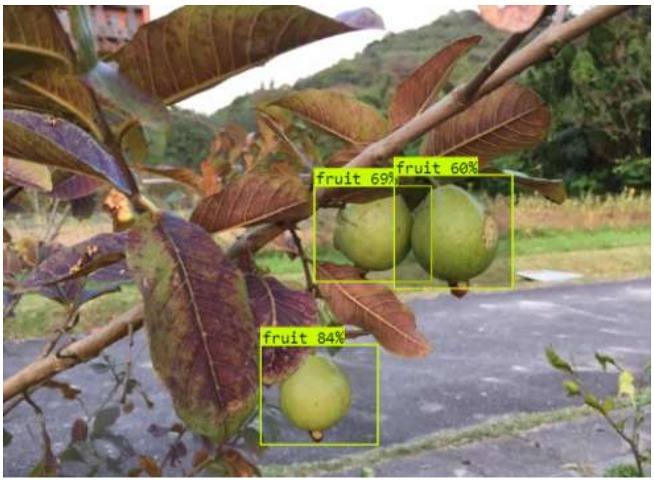


Fig. 3. Fruit Detection test result in real scene

robotic arm moves the bagging mechanism below the young fruit. Then, the entire mechanism moves upward, allowing the young fruit to enter the machine for the bagging process. After bagging, the entire mechanism moves downward, and the young fruit is released, completing one bagging cycle.

III. The Fruit Detection

Accurate fruit detection and identification are critical in agricultural settings for optimizing farming operations, yield estimation, and fruit quality assessment. What follows is a comprehensive overview of innovative research papers that have significantly contributed to advancements in fruit detection methodologies, focusing specifically on lemon and green orange detection.

In an automated lemon detection system based on computer vision techniques [7], preprocessing steps are employed to enhance the visibility of lemon fruits in the images. These steps included image enhancement and noise reduction algorithms, ensuring improved contrast and reducing unwanted artifacts. Enhancing image quality, subsequent segmentation, and feature extraction processes help achieve accurate and reliable lemon detection. RGB-D cameras are used for detection and segmentation [8], particularly targeting green oranges in citrus orchards. Preprocessing techniques are applied to enhance the visibility of the fruits. Color correction and contrast enhancement algorithms are employed to improve the color and texture of green oranges. These preprocessing steps facilitate the accurate separation of the fruits from the background, ensuring reliable fruit detection and segmentation. Another method uses a deep learning-based approach for green-orange detection [9]. Preprocessing techniques are applied to standardize and augment the input images before feeding them into the deep learning model. These techniques included resizing the images to a consistent resolution, normalizing pixel values, and applying data augmentation techniques. These preprocessing steps ensured robust feature learning and generalized well to different variations of green oranges, resulting in accurate and efficient fruit detection. For real-time lemon detection and counting [10], the author developed a real-time lemon detection and estimating system based on deep learning techniques. The preprocessing steps involve noise reduction, edge enhancement, and adaptive thresholding to enhance the visibility and highlight the distinctive features of lemons. By effectively preprocessing the lemon images, the subsequent deep learning model accurately identifies and counts the lemons in real time, even in challenging lighting conditions and complex backgrounds. Nowadays, UAV are popular in the agricultural field for UAV-based multispectral imaging [11], particularly in fruit detection in citrus orchards. Preprocessing of the multispectral images involved radiometric calibration, atmospheric correction, and spectral reflectance normalization. These preprocessing steps eliminate distortions caused by external factors, ensuring reliable multispectral data for subsequent fruit detection algorithms.

The accuracy of fruit detection heavily relies on the performance of the depth camera. Thorough camera testing and optimization are conducted to maximize its capabilities. Through integration with ROS frame, the system receives target points from the depth camera, enabling precise positioning and movement of the robotic arm. This integration ensures effective data acquisition and enhances the overall accuracy of fruit detection. Continual refinement of camera parameters and calibration ensures that the system effectively captures and analyzes fruit-related information. The YOLOv8 model,

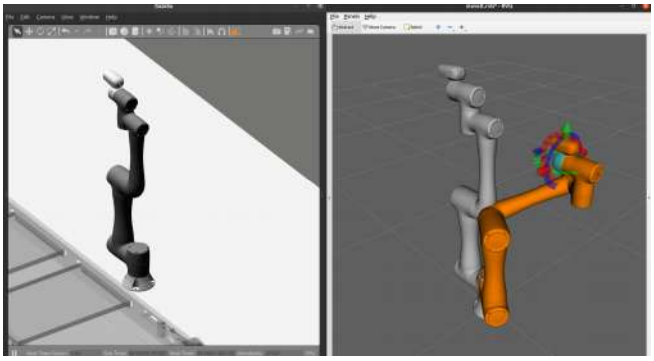


Fig. 4. The manipulator TM5-900 in Gazeno and Rviz

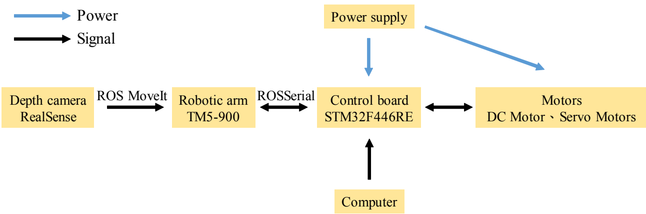


Fig. 5 The overall system diagram

designed for fruit identification and classification, is employed for object recognition. Extensive research and analysis have been conducted on various fruit-related characteristics, especially for fruits with colors similar to those of leaves, such as oranges and lemons. Training the model on diverse datasets and incorporating noise elimination techniques can optimize the fruit identification process. The YOLOv8 model offers advanced features, including improved accuracy, real-time detection speed, and robust performance in various environmental conditions.

IV. THE SIMULATION

To achieve comprehensive system development and evaluation, the concept of digital twins is employed in conjunction with simulations in the engineering field. Digital twins serve as virtual replicas of physical systems, providing real-time insights into their performance. By creating a digital twin of the robotic system, the operation can be accurately simulated in a virtual environment, replicating real-world scenarios. This approach facilitates assessing system functionality, identifying potential issues, and optimizing performance before practical deployment. The integration of digital twins presents a powerful tool for system development, reducing time and cost while ensuring reliable and efficient operation.

Simulations play a crucial role in developing and validating robotic systems within the engineering field. The renowned simulation platforms Rviz and Gazebo provide the capability to create virtual environments that closely resemble real-world scenarios. Within these simulations, the robotic arm, mechanisms, and depth camera D435i are integrated to evaluate their interaction and ensure smooth and accurate movements during fruit detection and pick-and-place operations, as shown in Fig. 4. Extensive simulations are conducted to fine-tune system parameters, optimize control algorithms, and validate

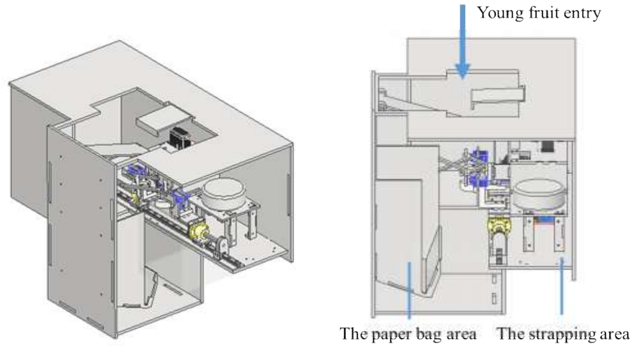


Fig. 6. The CAD drawing of the fruit bagging mechanism

overall system performance. This comprehensive simulation process, combined with the utilization of digital twins, bridges the gap between virtual and physical environments, creating a highly functional and reliable robotic system. By leveraging digital twins and conducting simulations, engineers in the field can thoroughly evaluate the performance, functionality, and efficiency of robotic fruit detection and pick-and-place systems. The virtual replicas offer a tool for testing and refining the system design before physical implementation, reducing the risks associated with potential issues, and ensuring optimal system performance. This approach enables engineers to make informed decisions, optimize control strategies, and validate the system's behavior, leading to a highly reliable and efficient fruit-bagging solution.

In summary, integrating digital twins and simulations in engineering offers a valuable approach to system development and evaluation. Creating virtual replicas provides real-time insights into system behavior and performance, facilitating issue identification and functionality optimization. Platforms such as Rviz and Gazebo provide powerful simulation capabilities, enabling engineers to fine-tune parameters, validate control algorithms, and ensure smooth operations. Embracing digital twins and simulations allows for the development of highly functional and reliable robotic systems, reducing development time and costs while ensuring efficiency in practical settings. Additionally, integrating simulations and digital twins in robotic fruit detection and pick-and-place systems enables remote monitoring and control. Farmers can remotely assess the fruit farm situation and control the robotic arm, observe fruit detection and bagging operations, and make necessary adjustments. This enhances flexibility and accessibility, allowing efficient management of fruit farms from remote locations. Applying digital twins and simulations extends the system's benefits beyond engineering, empowering farmers with greater convenience and control over their fruit farm operations. Overall, this approach offers multiple advantages, encompassing comprehensive system development and evaluation and facilitating remote monitoring and control for efficient fruit farming solutions.

V. THE BAGGING MECHANISM

Figure 6 shows the fruit bagging mechanism comprising the paper bag area and the strapping area. The prototype was constructed using acrylic panels and stereolithography (SLA) 3D printing parts, as shown in Fig. 7. In this study,

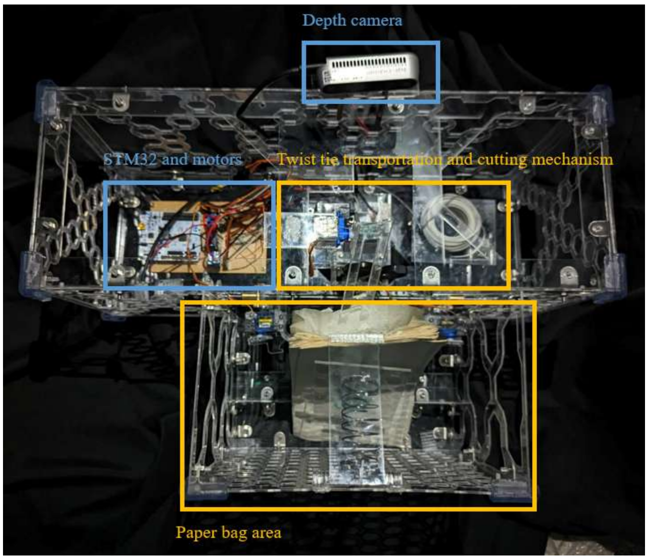


Fig. 7. Photo of the fruit bagging mechanism prototype

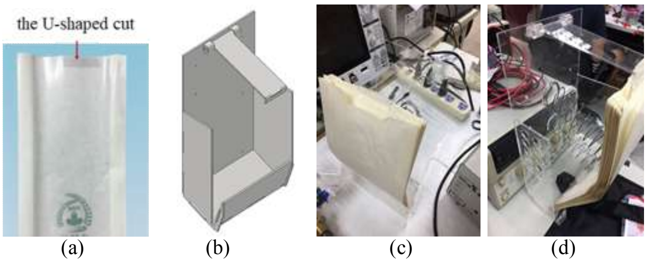


Fig. 8. The paper bag area of the fruit bagging mechanism: (a) The bag for bagging; (b) the CAD model; (c) the L-shaped hook securing bag opening groove; and (d) the side view of the mechanism

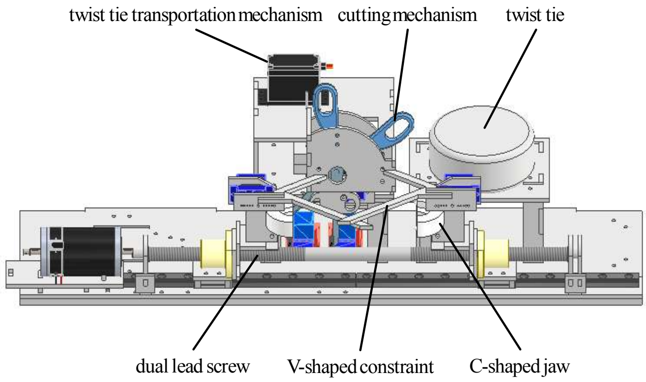


Fig. 9. The strapping area of the fruit bagging mechanism

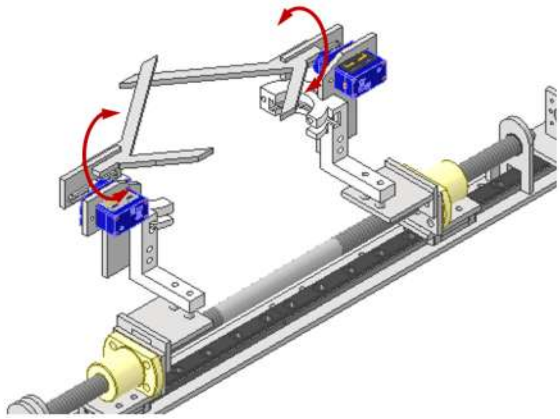


Fig. 10. The V-shaped constraints for securing the bag openings

commercially available mango bagging paper bags with dimensions of 284 mm × 154 mm were used. The young fruits were assumed to have a diameter of about 50 mm and a 1520 cm long fruit stalk.

A. *The paper bag area*

The paper bag area has an L-shaped hook that allows one side of the bag to be secured. By contrast, the other side naturally opens due to a specially designed U-shaped cut on the edge, as shown in Fig. 8. Two springs are placed behind the paper bags to push them forward, increasing the extent of the bag opening. At the entrance of the young fruit, a bag-opening hook continues to widen the bag opening. The young fruit can be packed into the paper bag by moving the overall mechanism upward.

B. *The strapping area*

The strapping area is divided into the gripper section and the tie section. The gripper section is formed by two C-shaped jaws and is driven by a DC motor with a dual lead screw to perform bidirectional motion. Its primary function is to tighten the bag opening. As shown in Fig. 10, above each C-shaped jaw, there is a V-shaped constraint to prevent the paper bag from getting outside the gripper when the jaws are closing, which could later interfere with the transportation of the twist tie. Inside each C-shaped jaw, a tunnel guides the twist tie along the circular path formed by two C-shaped jaws around the paper bag. The twist tie is propelled by a servo motor-driven roller, which first passes through one hole of the rotating piece, then encircles around the paper bag, and once again passes through the other hole of the rotating part. After that, the twist tie is cut by servo motor-driven scissors. Subsequently, a DC motor drives the rotating piece, causing the twist tie ends to entwine each other and tighten the bag opening.

C. *The control system*

The robotic fruit detection and pick-and-place system leverages the advanced mechanical arm system and mechanism design integrated with the STM32F446RE microcontroller board. Compared to other development boards, STM32F446RE offers distinct advantages in terms of enhanced processing power, a wide range of input-output capabilities, and efficient control algorithms. These features make it the ideal choice for this study, allowing for complex control tasks and real-time data processing. The core objective of the system is to automate the process of fruit bagging using a mechanical arm. The arm has five motors for actuation and relay control to achieve bidirectional rotation.

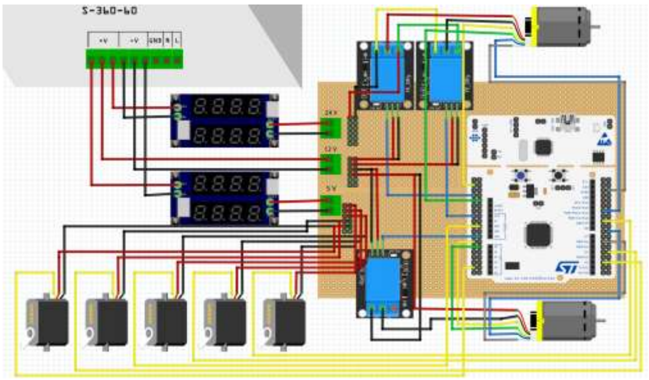


Fig. 11. The wiring diagram of the mechatronic system of the robot

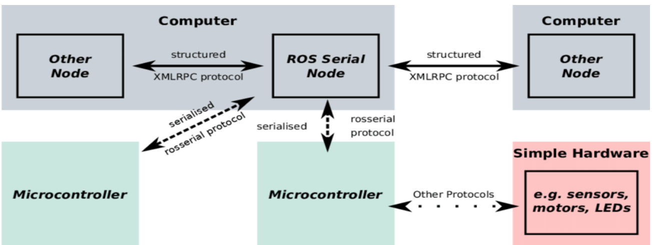


Fig. 12. The communication between PC and STM32 through Rosserial

Relays are utilized to achieve forward and reverse rotation to achieve precise control over the C-shaped jaw's movements. To facilitate smooth movement and avoid interference, limits on the rotational angles of each arm axis have been established to avoid potential collisions with the surrounding mechanisms. Additionally, the lightweight design adheres to a maximum arm load capacity of 4 kilograms. This ensures the arm's ability to handle fruits while maintaining optimal performance. To control the robot arm, the trajectory planning and efficient pick-and-place operations in ROS MoveIt ensures smooth rotation and precise location. This mechanism allows precise control over arm's movements, ensuring smooth and efficient pick-and-place operations. By carefully controlling joint rotations, accurate positioning of the arm for fruit detection and bagging can be achieved without any collision. Heat dissipation concerns have been addressed by incorporating small fans and heat sinks into the electromechanical design. These components are strategically placed to facilitate efficient cooling and prevent overheating, which could negatively impact the system's performance. The fans promote airflow, dissipating the heat generated during the system's operation, while the heat sinks absorb and dissipate heat away from critical components. This ensures that the system remains within optimal temperature ranges, maintaining its reliability and longevity.

A high-power version of the 12-to-5-volt regulator is included to overcome previous driving issues. This regulator ensures a stable power supply, eliminating potential disruptions caused by voltage fluctuations. The high-power version can handle the system's power demands and provide consistent voltage output to all components. This stability ensures smooth and uninterrupted operation, mitigating potential driving issues arising from power-related fluctuations. The robotic fruit detection system operates optimally and reliably by addressing heat dissipation and implementing a stable power supply. The integration of small fans, heat sinks, and a high-power voltage regulator ensures efficient cooling and a steady power supply. These improvements enhance the system's overall performance, reliability, and durability. Integrating heat dissipation mechanisms and a stable power supply is crucial in optimizing the performance and reliability of this robotic fruit detection and pick-and-place system. The system operates smoothly by carefully managing heat generation and power fluctuations, ensuring accurate fruit detection, efficient pick-and-place operations, and improved overall productivity. Future advancements could further enhance the heat dissipation technique and power management to accommodate larger-scale fruit bagging operations.

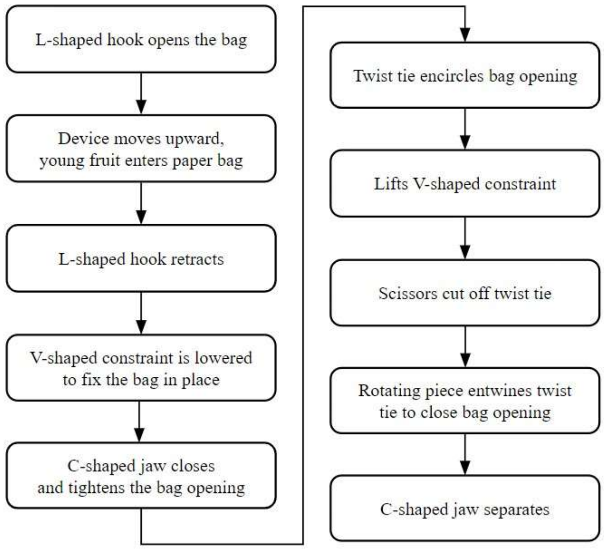


Fig. 13. The operation process of the bagging mechanism

D. *The operation process*

As shown in Fig. 13, the clamp initially attaches to the mechanism cover to open the bag mouth, allowing the young fruit to enter the bag through the indicated arrow in Fig. 6 by approximately 10 cm. The V-shaped constraint then works together with the C-shaped jaws to secure and tighten the paper bag. Subsequently, the twist tie wraps around the paper bag along with the C-shaped jaws. Once the bagging is complete, the twist tie is cut, and its ends are twisted together. Lastly, the C-shaped jaws return to their original position, completing the bagging process.

VI. EXPERIMENTAL RESULTS

A. *The fruit recognition*

Fig. 14 shows the training model's results with the depth camera D435i for recognition. The training results are shown in Fig. 15. With a remarkable precision rate of 93.0%, the model ensures reliable and efficient fruit detection and classification.

B. *The bagging mechanism*

The bagging process and results are shown in Fig. 16 and Fig. 17. The average bagging cycle was approximately 40 seconds. Based on actual field tests, the average efficiency of manual

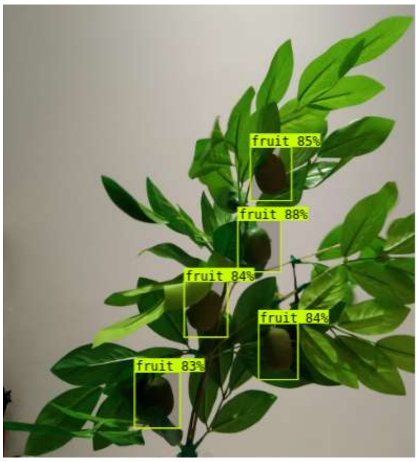


Fig. 14. Fruit detection using the depth camera D435i

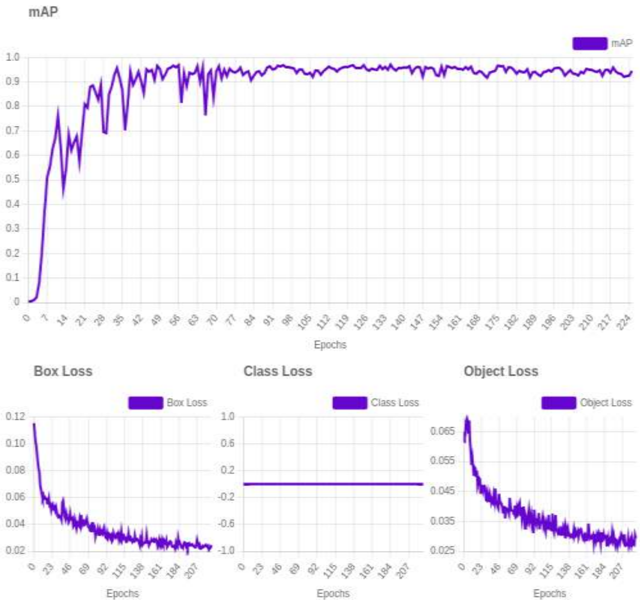
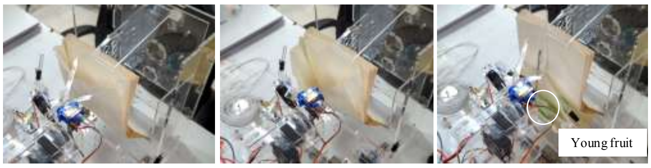
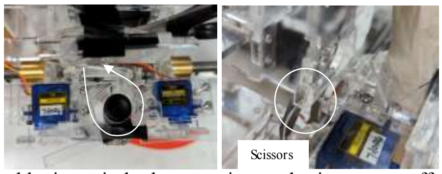


Fig.15. Results of the fruit recognition training

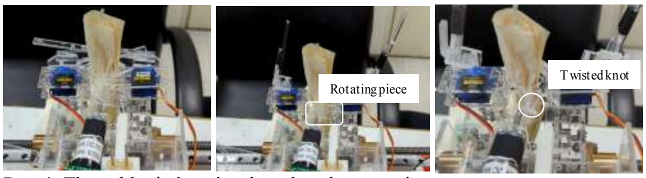


Part 1: The L-shaped hook opens the bag, and then the young fruit enters paper bag

Part 2: The V-shaped constraints fix bag in place, and then the C-shaped jaws tighten bag opening



Part 3: The cable tie encircles bag opening, and scissors cuts off the twist tie



Part 4: The cable tie is twisted to close bag opening

Part 5: The C-shaped jaw separates and frees the bagged fruit

Fig. 16. The snapshots of the bagging process

fruit bagging was approximately 200–250 fruits per hour. This study did not conduct field tests; however, based on these results, the automated bagging machine still needs to be faster than manual labor. However, the advantage of the bagging machine developed in this study is that it is less affected by working temperature and time, allowing for longer working hours.

VII. Conclusion

This project has developed an agricultural bagging robot that utilizes visual recognition to locate young fruits. It incorporates a mechanical arm and innovative mechanisms, including binding jaws, twist tie conveyance, cutting, and tightening designs. These components work together to complete the tasks of bagging fruits and represent an advancement in agricultural automation.

This study has developed a relatively efficient and accurate system for automating fruit bagging operations by integrating advanced electromechanical components, precise control algorithms, and state-of-the-art computer vision techniques. Utilizing the STM32F4 microcontroller board and integrating ROS and the YOLOv8 model ensures seamless communication, precise control, and reliable object recognition. The simulation and digital twin approaches further contribute to the system's development, allowing for thorough evaluation and optimization. With the potential to revolutionize the agricultural industry, this system offers increased productivity, reduced labor costs, and improved fruit quality. It is a testament to the

Fig. 17. The fruit after bagging

power of robotics and automation in addressing real-world challenges and driving sustainable advancements in agriculture. Further research and improvement are required in the force control of the robot, the efficiency of the bagging process, and the lightweight design of the mechanism to make it more competitive than manual labor in the future.

MULTIMEDIA

A video of the bagging process is available at https://youtu.be/CkRURIqKsvs.

ACKNOWLEDGMENT

This work is supported by the National Science and Technology Council (NSTC), Taiwan, under contract MOST110-2634-F-007-027-and MOST 111-2634-F-007-010-. The authors would like to thank the Bio-inspired Robotics Lab, the Autonomous and Soft Robotics Lab, and the Robotics Practice Lab for their assistance.

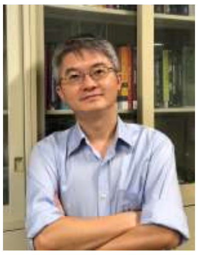
REFERENCES

[1] R. R. Sharma, S. V. R. Reddy & M. J. Jhalegar, "Pre-harvest fruit bagging: a useful approach for plant protection and improved post-harvest fruit quality – a review," *The Journal of Horticultural Science and Biotechnology*, Vol. 89:2, 2014, pp. 101-113.
[2] Peter J Hofman, Lyn G Smith, Daryl C Joyce, Greg I Johnson, Geraldine F Meiburg, "Bagging of mango (Mangifera indica cv. `Keitt') fruit influences fruit quality and mineral composition," *Postharvest Biology and Technology*, Vol. 12, Issue 1, 1997, pp. 83–91.
[3] Shu-Wen Chen, Chun-Wen Chen, "The development of hand carried bagging machine for mango on the tree," *Research Bulletin of Kaohsiung District Agricultural Research and Extension Station*, Vol.13:2, 2002, pp. 26–35.
[4] Wang Yingxi, Zhang Yuhe, Pu Yi, Zhang Jintang, Wang Fangchao, "Design of a new fruit tree bagging machine." *IOP Conference Series: Materials Science and Engineering*, 2018.
[5] M. Monta, N. Kondo and Y. Shibano, "Agricultural robot in grape production system," *Proceedings of 1995 IEEE International Conference on Robotics and Automation*, Nagoya, Japan, vol.3, 1995, pp. 2504–2509.
[6] Jian-Fa Liang, R.O.C. Patent 197143, Taipei, U Gear Automatic Machinery Co., Ltd. December 21, 1992.
[7] Xinxing Zhang, Yi Xun, Yaohui Chen, "Automated identification of citrus diseases in orchards using deep learning," *Biosystems Engineering*, vol. 223, Part A, 2022, pp. 249-258.
[8] Guichao Lin, Yunchao Tang, Xiangjun Zou, Jinhui Li, Juntao Xiong, "In-field citrus detection and localisation based on RGB-D image analysis," *Biosystems Engineering*, vol. 186, 2019, pp. 34–44,
[9] Abdelaziz, Bassem, Walid, "A deep learning-based approach for detecting plant organs from digitized herbarium specimen images," *Ecological Informatics*, vol. 69, 2022, 101590.
[10] S. E. Serafino, L. B. Cicerchia, G. Pérez, S. Adorno and A. Balmer, "Detection and Counting of Lemons using Artificial Vision and Tracking Techniques for Real Time Harvest Estimation," *2020 XLVI Latin American Computing Conference (CLEI)*, Loja, Ecuador, 2020, pp. 496–502.
[11] DadrasJavan, F., Samadzadegan, F., Seyed Pourazar, S.H. et al. "UAV-based multispectral imagery for fast Citrus Greening detection," *J Plant Dis Prot,* vol. 126, 2019, pp. 307–318.

Tsai-Hsu Wu received the B.S. in mechanical engineering from the National Taiwan University (NTU), Taipei, Taiwan, in 2023. Her current research interests and publications are in mechanism design and robotics.

Ya-Ting Hsu received the B.S. in mechanical engineering from the National Taiwan University (NTU), Taipei, Taiwan, in 2023. Her current research interests and publications are motion planning, robot dynamics and control, and bio-inspired robotics.

You-Ling Liang received the B.S. in mechanical engineering from the National Taiwan University (NTU), Taipei, Taiwan, in 2023. Her current research interests and publications are in mechanical design and kinematics analysis.



Pei-Chun Lin received the B.S. and M.S. degrees in mechanical engineering from National Taiwan University, Taipei, Taiwan, in 1996 and 1998, respectively, and the M.S. degree in electrical engineering and computer science and the Ph.D. degree in mechanical engineering from the University of Michigan, Ann Arbor, MI, USA in 2005. He was a Postdoctoral Research Fellow with the Department of Materials Science and Engineering, University of Pennsylvania, Philadelphia, PA, USA, from 2005 to 2007. He is currently a Distinguished Professor with the Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan.

His research interests include bio-inspired robotics, mechanism design, mechatronics, control, dynamic locomotion, and compliant composites.