Computers and Electronics in Agriculture 207 (2023) 107762

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

A novel pollination robot for kiwifruit flower based on preferential flowers selection and precisely target

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ARTICLE INFO

Keywords:
Pollination robot
Kiwifruit flowers
Vision perception
Suitable flower selection
Air-liquid spray

ABSTRACT

Manual pollination of kiwifruit flowers is a labor-intensive work that is highly desired to be replaced by mechanical/robotic operations. In this application note, a pollination robot was developed for achieving precision pollination of kiwifruit flowers in orchard. The pollination robot consists of five systems include vision system, air–liquid spray system, mechanical arm, crawler-type chassis, and control system, which could select suitable flowers and then target to their pistil for precision pollination. Field experiments were conducted in a commercial kiwifruit orchard to evaluate its feasibility and performance, which achieved an average pollination success rate of 99.3% with an average fruit set rate of 88.5%. Furthermore, compared to artificial assisted pollination methods, it could improve utilization rate of kiwifruit pollen with an average consumption of 0.15 g in 60 flowers. The validations demonstrated that this pollination robot could achieve efficient pollination for kiwifruit flowers and save pollen.

1. Introduction

Sufficient pollination for kiwifruit flowers is critical to acquire satisfying kiwifruit production and quality. As a typical cross-pollinated plant, kiwifruit does not have ability to achieve autonomous self-pollination (Arcerito et al., 2021; Castro et al., 2021). For most commercial kiwifruit orchards, there are usually not enough non-fruiting male kiwifruit plants available for pollination considering practical planting densities and final yield profit (Broussard et al., 2021). Artificial assisted pollination method, such as hand pollination, hand-held pollen blowers and pollen dusters are common pollination methods in commercial kiwifruit orchards (Williams et al., 2020). However, these assisted pollination methods are not sustainable as precise pollination cannot be achieved. Furthermore, rising labor costs and pollen prices have brought challenges to kiwifruit pollination cost control (Sakamoto et al., 2016). In this case, robotic kiwifruit pollination has been proposed for saving people from heavy labor and reducing pollen losses by imprecise pollination in orchards.

Selecting suitable flowers for pollination is the key to kiwifruit pollination robot for high-quality and precise operations. As flowering period of kiwifruit is not synchronized, not all flowers are blooming and able to receive pollen at the same time (Tacconi et al., 2016; Li et al., 2022a). In a previous study, Gianni et al. (2018) divided blooming flowers of kiwifruit into multiple flowering periods according to their phenological features, which pointed out that different pollination methods (dry pollination and liquid pollination) are suitable for different flowering periods. In addition, flower selective pollination could determine growth distribution of kiwifruits in the canopy in advance to maximize nutrient usage, which can also reduce additional labor requirements caused by flowers and fruits thinning (Li et al., 2022b).

Pollination approach is another essential consideration for kiwifruit pollination robots to achieve precise operations. According to different methods of pollen transmission, there are two pollination approaches for kiwifruit include dry pollination and liquid pollination (Tacconi et al., 2016). Due to the weight of kiwifruit pollen being very slight and easily blown by wind, the dry pollination approach is mostly used in hand pollination and hand-held pollen duster, which needs to pollinate

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https://doi.org/10.1016/j.compag.2023.107762
Received 11 January 2023; Received in revised form 5 March 2023; Accepted 6 March 2023
Available online 13 March 2023
0168-1699/

Fig. 1. Kiwifruit pollination robot operation scene during a field experiment. (1) Air-liquid spray nozzle; (2) Air pump; (3) Imaging module; (4) Crawler-type chassis; (5) Mechanical arm; (6) Control unit; (7) Electric pollen fluid tank.

flowers with a very close distance. Comparatively, the liquid pollination approach could achieve quantified pollination by controlling spraying time of prepared pollen liquid, which provides an easier medium for rapid delivery of controlled polled doses (Williams et al., 2021). Especially air assistance with liquid has effectively reduce the spray droplets size of liquid (Musiu et al., 2019), which could enhance pollen deposition and improve utilization rate of kiwifruit pollen significantly.

Many studies have researched automatic pollination for kiwifruit flowers to solve the problems of low fruit sets by natural pollination and high labor intensity by artificial pollination. Williams et al. (2020) constructed a robotic pollinator with single class flower detection, which could achieve quantitative pollination for individual flowers with a self-designed air-assist spray system. Li et al. (2022c) presented an approach for detecting the operational position and orientation of kiwifruit flowers for robotic pollination, which could achieve precise targeted pollination with a robotic arm according to detected positions and orientations of flowers. However, there is a certain waste of pollen in these studies, as kiwifruit flowering periods are not synchronized and not all flowers in the canopy are suitable for pollination.

In this study, a novel pollination robot based on preferential flowers selection and air assisted liquid pollination approach was designed and built for kiwifruit flowers. For this pollination robot, a vision system, an air–liquid spray system, a mechanical arm, a crawler-type chassis, and a control system were designed and adopted for achieving suitable flower selection and precisely target pollination. A field experiment verified the feasibility of this pollination robot and provided its performance compared with common artificial assisted approaches.

2. Materials and methods

2.1. Composition of the pollination robot

The kiwifruit pollination robot was mainly composed of five systems with seven parts, which could select suitable flowers and then target to their pistil for achieving precision pollination. Cost of the current developed robot with five systems is $4,418.00 (all components were purchased from China in 2022). A field experiment scene of this robot with detailed composition information was shown in Fig. 1. A special vision system was designed of an imaging module with kiwifruit flower detection and location methods for suitable flower selection combined with agronomy. Furthermore, an air–liquid spray system composed of a liquid path and an air path was designed for targeting selected flowers

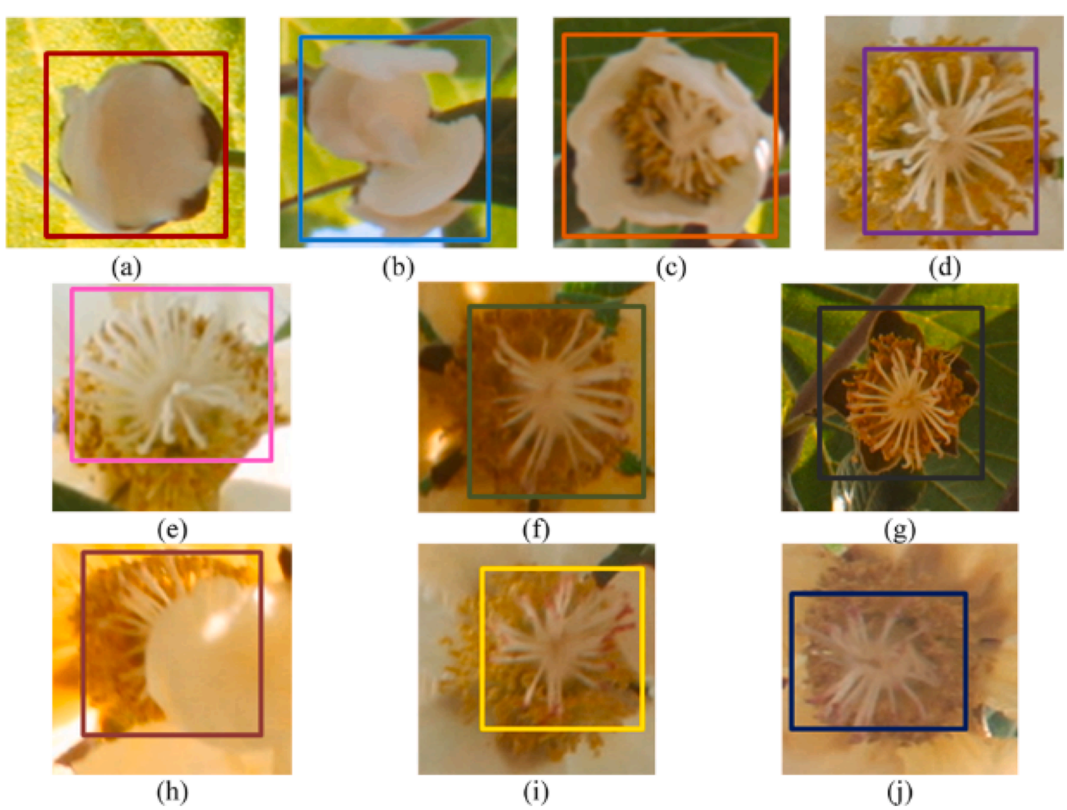

Fig. 2. Labeling examples of multi-class kiwifruit flowers with different colors. (a) Bud (BD); (b) Early open (EO); (c) Half-open (HO); (d) Fresh pistil (FP); (e) Early ocher pistil (EOP); (f) Ocher pistil (OP); (g) and Petal fall (PF); (h) Occluded pistil of flower (OF); (i) Bright pollen (BP); (j) Dark pollen (DP).

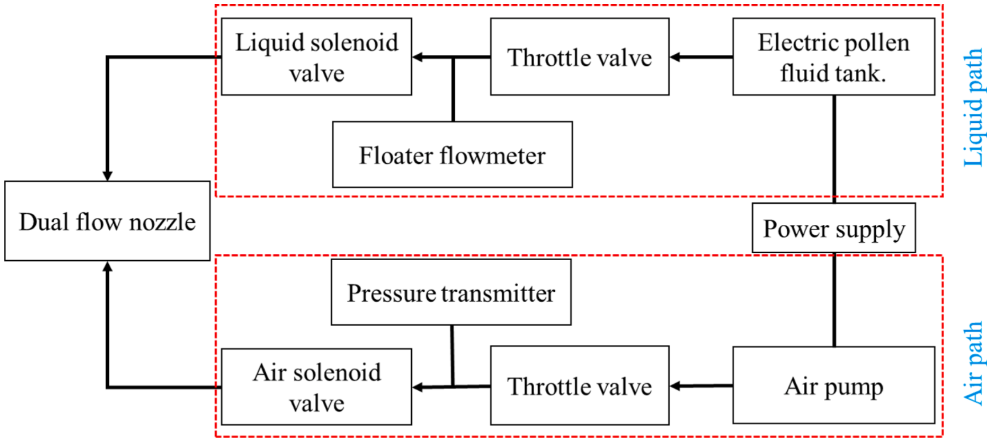

Fig. 3. The air–liquid spray system functional block diagram.

and quantitative pollination by cooperating with a mechanical arm. More design detail about this robot is as follows.

2.2. Vision system

The vision system includes an RGB-D (Red, Green, Blue -Depth) camera (RealSense D435, Intel, USA) for kiwifruit canopy image acquisition and image processing methods for suitable flower detection and location. Frame rate of images acquired by the camera is 30 frames per second. Due to flowering period of kiwifruit is not synchronized, a multi-class flower detection method (shown in Fig. 2) based on You Only Look Once version 5 large (YOLOv5l) was employed for detecting and determining which flowers of the canopy were in the best pollination periods. After that, a further selection strategy based on Euclidean distance matching method was applied to obtain its distribution in the canopy for suitable flowers selection, which combing the agronomic characteristics of kiwifruit growth for optimal nutrients partition with quality and yield assurance. The specific implementation of selective pollination strategy applied in this study has been described detailly in the previous study of Li et al. (2022b).

To achieve precisely target pollination, spatial locating of selected suitable kiwifruit flowers is required for the pollination robot, which can be obtained from color images and aligned depth maps by the assembled RGB-D camera. First, the corresponding depth information of detected and selected kiwifruit flowers in the depth map were obtained. Second, camera coordinate is calculated from camera internal parameters including focal length (f_x, f_y) and principal point (c_x, c_y), as shown in Eq. (1), Eq. (2), and Eq. (3). Where u of Eq. (2) and v of Eq. (3) combination represents pixel coordinates of a single point on the kiwifruit flower.

$$z = depth \tag{1}$$

$$x = \frac{(u - c_x)\cdot z}{f_x} \tag{2}$$

$$y = \frac{(v - c_y)\cdot z}{f_y} \tag{3}$$

Then corresponding coordinates of all pixels in the detection rectangle of selected suitable kiwifruit flowers were obtained according to Eq. (1), Eq. (2), and Eq. (3). And the mean value was calculated as camera coordinates of kiwifruit flowers. After that, on the basis of location relationship between the camera and mechanical arm, external parameters of camera can be determined, and the world coordinates of kiwifruit flowers can be obtained. Finally, obtained coordinates were

Table 1
Parameters and performance of air–liquid spray system instrument.

Instrument	Type	Power supply	Parameter	Numerical value	Appearance package
Air-liquid nozzle	Taper	–	Aperture Screw thread aperture	1 mm M8	
Liquid solenoid valve	N2W	20.4 ~ 26.4 V	Pressure range Flow aperture	0 ~ 0.5 MPa 2.5 mm	
Air solenoid valve	VT 307	20.4 ~ 26.4 V	Pressure range Response time	0 ~ 0.6 MPa ≤ 20 ms	
Floater flowmeter	DFG-6T	–	Accuracy Measurement range	± 4% 25–250 mL/min	
Pressure transmitter	HC-P30	12 ~ 30 V	Accuracy class Measurement range	0.5% FS 0 ~ 0.4 MPa	
Electric pollen fluid tank	6L	12 ~ 26 V	Rated power Flow	24 W 2.5 LPM	
Air pump	750W-30L	220 V	Air displacement Rated pressure	60 L/min 0.7 MPa	

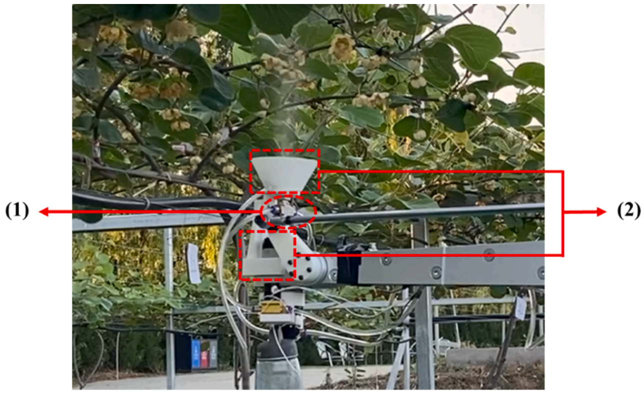

Fig. 4. Field experiment scene of pollination spray effect and construction of air–liquid dual flow spray end-effector. (1) Air-liquid nozzle; (2) Nozzle mounting brackets.

sent to the control system, which was utilized for the mechanical arm to target selected suitable flowers.

2.3. Air-liquid spray system

The air–liquid spray system in this pollination robot is composed of an air–liquid nozzle, air path and liquid path modules. An overall structure of designed air–liquid spray system was shown in Fig. 3. For this system, the liquid path module was composed of a liquid solenoid valve (N2W, CHNT, China), a throttle valve (SA-8, ZhuoJi, China), and an electric pollen fluid tank (6L, KeNeng, China). And the air path module was composed of an air solenoid valve (VT307, SMC, Japan), a throttle valve (SA-8, ZhuoJi, China), and an air pump (750 W-30L, Outstanding, China). In addition, a floater flowmeter (DFG-6 T, Darhor, USA) and a pressure transmitter (HC-P30, Nstrument, Germany) were adopted to measure rate of flow and air pressure, respectively. The performance and appearance of air–liquid spray system instrument were listed in Table 1.

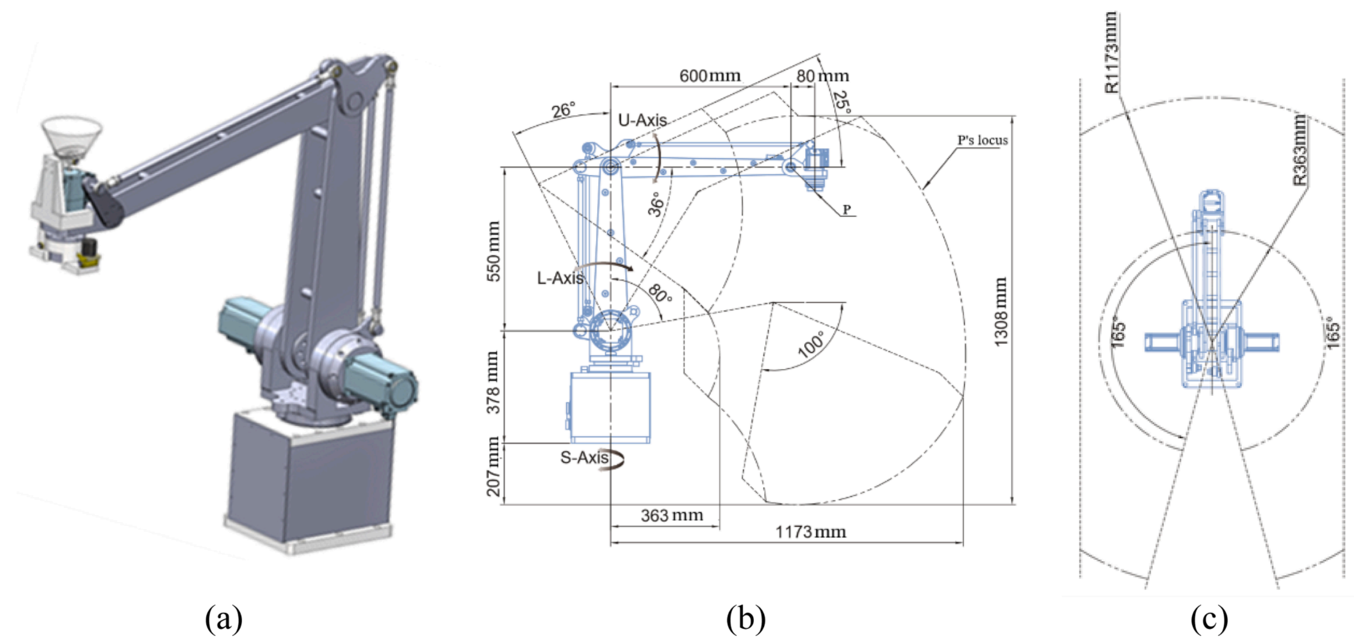

Fig. 5. 3D diagram and working space diagram of mechanical arm. (a) 3D mechanical drawing. (b) Side view of mechanical arm workspace and dimensions. (c) Top view of mechanical arm workspace.

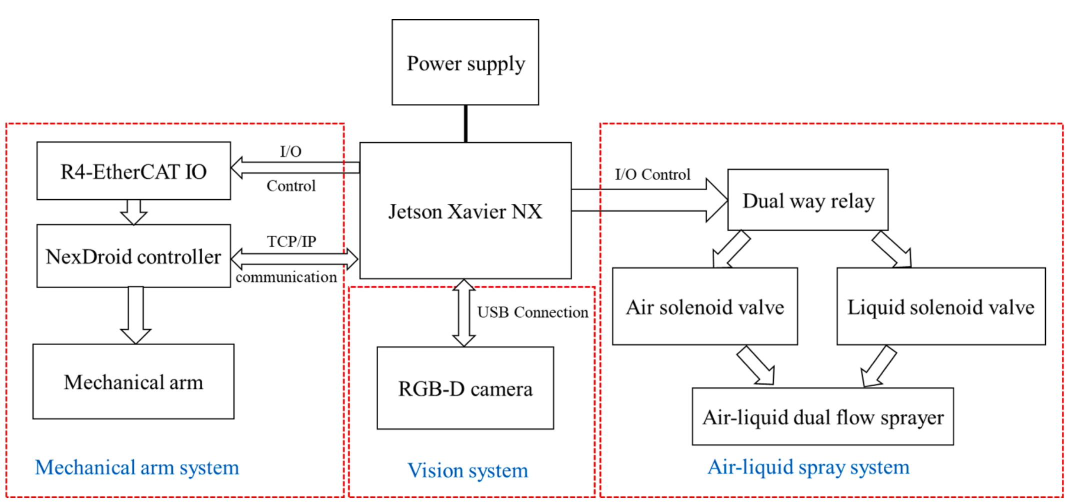

Fig. 6. The designed control system functional block diagram.

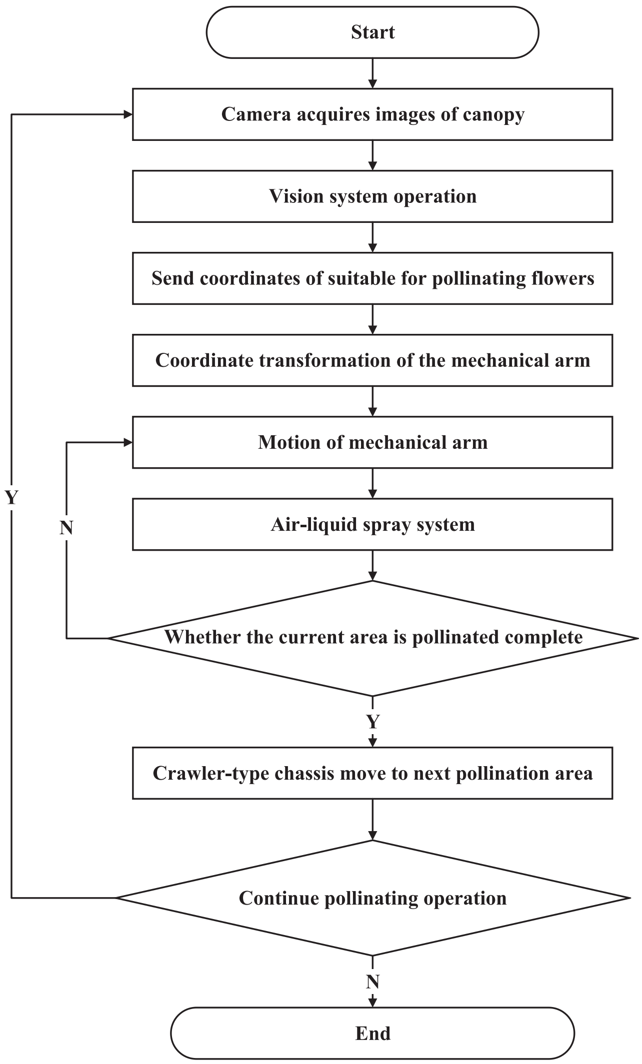

Fig. 7. Workflow of robotic pollination for kiwifruit flower.

For this spray system, a conical air–liquid nozzle with aperture of 1 mm was applied with set air pressure and liquid flow for generating suitable droplet size of prepared pollen liquid for kiwifruit flower pollination. Comprehensive consideration of flower size and effective pollination area, a pre-experiment was carried out for pollination parameters optimization and selection, which determined parameters of distance between nozzle and selected flower was 25 cm, air pressure was 56 kPa, and liquid flow was 45 mL/min, respectively. A field experiment scene of pollination spay effect was shown in Fig. 4, which also presented a detailed construction of designed air–liquid spray end-effector.

2.4. Mechanical arm and mobile platform

The mechanical arm (ECR5-120, Never, China) utilized for this pollination robot to target selected suitable flowers was a parallel four-link mechanism with three degrees of freedom, which can meet the needs of pollination. It has three servo motors (SV-X2MH075A-B2LA, HCFA, China) equipped with three harmonic reduction gears (LSS-32, Laifual Drive, China), which is simple in structure and easy to control. Three-dimensional diagram and working space diagram of the mechanical arm are shown in Fig. 5.

Apart from achieving precise pollination, the pollination robot also requires a mobile platform to carry and autonomously move it through the orchard. A crawler-type chassis (Safari-880T, GuoXing, China) has been adopted as the mobile platform, which is capable of moving it through an orchard.

2.5. Control system design and operating process

For this pollination robot, a control system was designed and constructed to receive kiwifruit canopy information by an RGB-D camera and coordinated control of air–liquid spray system and mechanical arm for targeting selected flowers precisely. Fig. 6 showed the overall structure of the control system. And the type of programming enabled in the current system is Python. The main controller utilized for the control system is a Jetson Xavier NX module (NVIDIA, USA), which connected with the RGB-D cameral by USB interface for canopy images acquisition and communicated NexDroid controller by Transmission Control Protocol/Internet Protocol (TCP/IP) for selected suitable flowers coordinate information sending. The action signal of the mechanical arm is generated by the main controller, which is sent to R4-EtherCAT for motion control of the mechanical arm. Besides, a dual way relay was adopted for air–liquid system to realize the on–off control of air solenoid valve and liquid solenoid valve.

The workflow of this pollination robot is illustrated in Fig. 7. When pollination robot moves to desired pollination zone, its camera acquires image of canopy in real time. After vision system detects and selects suitable flowers for pollination, three-dimensional coordinates of selected flowers are sent to the control system, which is transformed into a coordinate of mechanical arm. Then the air–liquid spray system receives signals to spray, while the motion of mechanical arm is accomplished. If the current area is pollinated completely, the crawler-type chassis will move to next pollination zone.

3. Experimental results and discussions

3.1. Performance validation of the developed pollination robot

The pollination robot was tested in International Kiwifruit Innovation Orchard, Yangling, Shaanxi Province, China (34°17′ N, 108°2′ E, approximately 504 m in altitude) and evaluated its feasibility. For this orchard, a standard trellis planting mode was adopted for kiwifruits, as described by Li et al. (2022b), which can provide a simple and structured workspace for robotic pollination.

The experimental pollination zones were randomly divided from the kiwifruit orchard, and each zone took one kiwifruit plant as the pollination experiment subject with area of 3 × 3 m^2. Besides, artificial assisted pollination including manual dry pollination approach, electric sprayer with liquid pollination approach, and hand-held sprayer with liquid pollination approach were applied in different zones of the same orchard at the same time to verify performance of this pollination robot.

For this pollination robot, a selective strategy based on multi-class kiwifruit flower detection and its distribution identification was applied to select suitable flowers for pollination. An example of canopy flowers selection in field experiments was shown in Fig. 8. Results of multi-class flowers detection was shown in Fig. 8a. In addition, flowers that are not suitable for pollination were excluded, as shown in Fig. 8b, including flowers that are not in the optimal pollination periods and flowers with insufficient nutrition at the base of branches. A normal pollination sequence of flower cluster/single flower was left to right and far to near, which was labeled in canopy image, as shown in Fig. 8b.

Performance of robotic pollination is assessed by flower detection success rate and effective pollination rate in field experiments. The flower detection success rate is described as the performance of the detection model after removing false detections and missed detections. Besides, the effective pollination rate is described as proportion of flowers whose pistil are hit by sprayed out pollen droplets among all selected flowers. Statistics of robotic pollination performance in field experiments for different selected pollination zones were summarized in Fig. 9. Mean of flower detection success rate and effective pollination rate were 98.1% and 99.3% in different pollination zones, respectively.

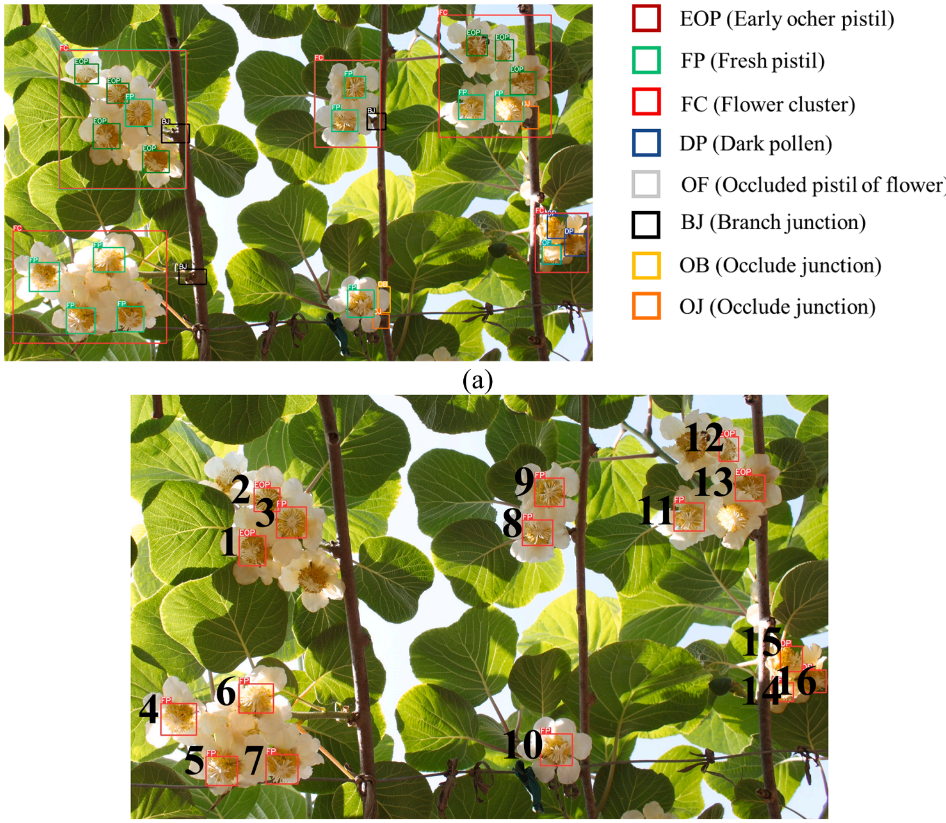

Fig. 8. Example of suitable flower selection for pollination. (a) Results of multi-class kiwifruit flowers detection with rectangles marked in different colors; (b) Suitable kiwifruit flowers for pollination based on selection of flowering periods and distributions with red rectangle marks and their pollination sequence with number marks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

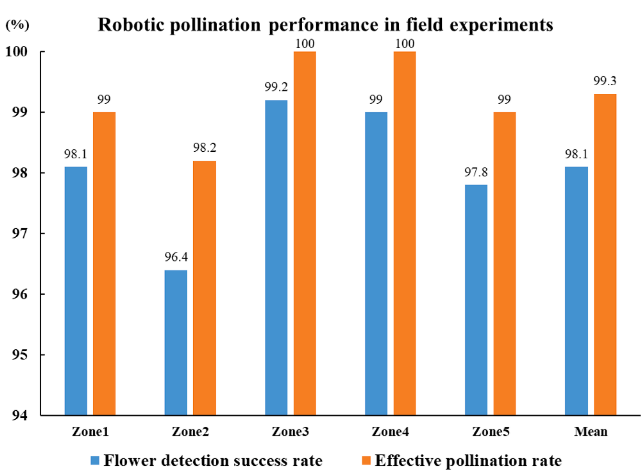

Fig. 9. Statistics of robotic pollination performance in field experiments.

According to experimental records during field experiments, strong winds of fields could make sprayed pollen droplets to drift, which was the main reason for the failure of effective pollination.

3.2. Evaluation of the robotic pollination effects

Results from field experiments show that the robot has a promising pollination effect and high operating efficiency. Specific effects of robotic pollination and other three artificial assisted pollination approaches are shown in Table 2. Fruit set rate of robotic pollination is

Table 2
Comparison of different pollination methods.

Pollination approach	Performance		
	Fruit set rate (%)	Average pollination time for a single flower (s)	Average pollen consumption of 60 flowers (g)
Robotic pollination	88.5	2.0	0.15
Manual dry pollination	91.7	1.0	0.20
Electric sprayer	73.3	0.5	0.60
Hand-held sprayer	81.8	1.5	0.40

88.5%, which is superior to electric sprayer approach and hand-held sprayer approach and second only to manual dry pollination approach. While ensuring a good fruit setting rate, the robotic pollination method consumed the least amount of pollen with an acceptable operation speed of 2.0 s for a single flower. Average pollen consumption of 60 flowers is 0.15 g for robotic pollination, compared with average pollen consumption of 0.20 g, 0.60 g, and 0.40 g for 60 flowers, by manual dry pollination, electric sprayer, and hand-held sprayer, respectively, which could improve utilization rate of pollen significantly.

A more detailed comparison was made between previous studies of robotic kiwifruit flower pollination and our robot. Li et al. (2022c) obtained flower detection success rate of 94.13% with average pollination time of 6 s for a single flower, where the detection success rate was

3.97% lower and the pollination time was 4 s slower than this study. Williams et al. (2020) developed a pollination system, which is capable of targeting and pollinating 79.5% of flowers at 3.5 km/h with fruit set rate of 71.6%. Although its average pollination rate was better, the effective pollination rate and fruit set rate were 22.7% and 16.9% lower than this study, respectively. In addition, neither of the above two studies has the ability to select suitable flowers for pollination. From the above results, the constructed pollination robot attained satisfactory performance.

4. Conclusions

In this application note, a novel kiwifruit pollination robot was developed for saving people from heavy labor and reducing pollen losses by precise pollination in orchards. For this pollination robot, strategy of selecting suitable flowers and targeting to their pistil for achieving precision pollination was designed and adopted to ensure suitable kiwifruit flowers selection and precise targeting. Field experiments shown that flower detection success rate and effective pollination rate reached 98.1% and 99.3%, respectively, which implies that selecting suitable flower for robotically precision pollination is promising. However, strong winds in fields may cause the sprayed pollen liquid droplets to drift in trajectory, which could lead to insufficient pollination. Future improvements for this pollination robot will seek to design a device for preventing wind disturbance while multiple nozzles and multi-arm cooperation to improve the velocity of pollination is also expected.

CRediT authorship contribution statement

Changqing Gao: Data curation, Investigation, Methodology, Writing – original draft. **Leilei He:** Data curation, Investigation, Methodology, Writing – original draft. **Wentai Fang:** Conceptualization, Methodology, Writing – review & editing. **Zhenchao Wu:** Methodology, Supervision, Writing – review & editing. **Hanhui Jiang:** Conceptualization, Methodology, Writing – review & editing. **Rui Li:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Longsheng Fu:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was partially supported by the Key R&D Program of Zhejiang (2022C02055); National Natural Science Foundation of China (32171897); Youth Science and Technology Nova Program in Shaanxi Province of China (2021KJXX-94); National Foreign Expert Project, Ministry of Science and Technology, China (DL2022172003L, QN2022172006L).

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