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Study of an Autonomous Fruit Picking Robot System in Greenhouses*

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Abstract

The objective of this research was to develop an autonomous picking robot system for greenhouse-grown tomatoes, which consists of four major components: the end-effector, machine vision, robot carrier, and control system. The graphical programming language LabVIEW ver. 7.1 was employed to develop the image processing and control system. The experimental results showed the success rates of the integrated picking were 94.83 %, 91.83 %, and 89.63 %, respectively. The average picking time needs about 35.96 s/sample, with a throughput of 100.1 samples/h. Consequently, an autonomous picking robot system was successfully developed and it needs to be further tested for real tomato picking operations in greenhouses in the future.

[Keywords] automation, end-effectors, harvest, robot, gripper

I Introduction

Greenhouse-grown fruits and vegetables are mostly harvested manually, and the process in Taiwan is labor-intensive. Japan, Korea, the United States, and some European countries are developing agricultural operational robots, among which, the agricultural product picking robot is an important project. According to the development, the technology of applying robots to agricultural production has become mature.

Jimenez *et al*. (2000) reviewed previous studies to automate the location of fruit on trees using computer vision methods, paying special attention to the sensors and accessories utilized for capturing tree images, the image processing strategy used to detect the fruit, and the results obtained in terms of the correct/false detection rates and the ability to detect fruit independent of its maturity stage. Most of these works use CCD (Charge-Coupled Device) cameras to capture the images and use local or shape-based analysis to detect the fruit.

The research on agricultural harvesting robots has achieved practical effects. For example, Van Henten *et al*. (2002) designed an autonomous robot for harvesting cucumbers in greenhouses, which included the autonomous vehicle, manipulator, end-effector, the two computer vision systems for detection and 3D imaging of the fruit and the environment, and a control scheme that generates collision free motions for the manipulator during harvesting. Van Henten *et al*. (2003) also developed a cucumber-picking robot that can pick cucumbers inside the greenhouse automatically. It uses a mobile CCD to capture images, and requires 124 s for searching and picking the cucumber, achieving a success rate of 74.4 %.

Ling *et al*. (2004) developed a tomato-picking robot, using a machine vision system to detect and analyze the fruit. The end-effector device consists of four claw fingers, and a robot arm picking and releasing fruit. The success rate of detecting tomatoes is 95 %, and the picking success rate is 85 %. Kim *et al*. (2008) developed a strawberry-picking robot, using two CCD's and a laser distance meter to identify the position of a strawberry, and an end-effector to cut off the strawberry. The average time for picking a strawberry is 7 s. Bulanon *et al*. (2004) developed a real-time machine vision system to guide a harvesting robotic manipulator for red Fuji apples. The machine vision system was composed of a color CCD video camera to acquire Fuji apple images at the orchard and a PC to process the acquired images.

Kondo *et al*. (2008) developed a cluster tomato-picking robot, which end-effector has two fingers. A double-CCD vision system is used for identifying the position of a cluster tomato. This study aimed to develop an autonomous picking robot system for greenhouse-grown tomatoes, including the end-effector, the machine vision, the robot carrier, and the control system.

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II Materials and Methods

The autonomous picking robot system for greenhouse-grown tomatoes proposed by this study consists of four major components: the end-effector, the machine vision, the robot carrier, and the control system. The control system contains three units, namely the robot arm and end-effector control unit, the robot carrier control unit, and the central control unit. Fig. 1 shows the structure of the autonomous picking robot system. The detailed design of the autonomous picking robot system is described as follows.

1. Design of the autonomous picking robot system

(1) Design of the end-effector

The robot arm used in this study is a Mitsubishi RV-M1. It is a vertical joint robot arm with five degrees of freedom, which are the waist (J1, 300°), shoulder (J2, 130°), elbow (J3, 110°), wrist tibia (J4, 90°) and wrist (J5, 180°). The robot arm consists of the upper arm, forearm, and wrist pitch, in length of 250 mm, 160 mm and 72 mm respectively. The total length is 482 mm. Each axis has its maximum operating angle, so the applicable workspace to the robot arm must be defined for future test planning. The maximum clamping weight is 11.76 N, and the maximum path velocity is 1000 mm/ s.

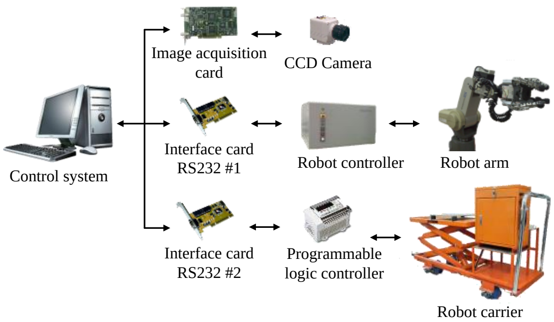

Fig. 1 Structure of the picking robot system

The end-effector of this study is fixed to the front end of the robot arm, positioning, picking and placing by means of the robot arm. The control signals of the end-effector are transmitted from the computer or controlled by the robot arm control unit through the RS-232 adapter card. Fig. 2 is the schematic diagram of the end-effector, drawn by CAD (Computer-Aided Design) application software Solid Works 2007. The end-effector is designed as four fingers, which are mounted on a left-right open-close board. The claw is opened and closed using the left-right open-close device at the front end of the robot arm. The maximum open size of the claw is 89.62 mm. Each finger has three joints, which can bend by spring leaves. Each finger is mounted with foam-like soft coating material to reduce the fruit and vegetable injuries during picking. In addition, the end-effector is equipped with a photoelectric proximity switch, two limit switches and four solenoid actuators, to detect whether the tomato is in the clamping claw, detect the open-close range of the claw, and drive the claw fingers to bend.

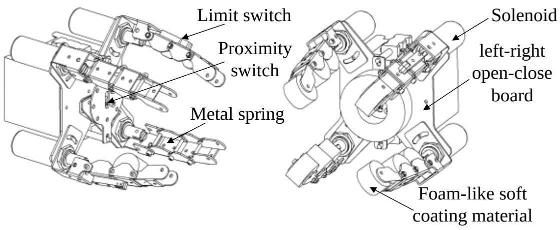

Fig. 2 Schematic diagram of the end-effector

(2) Design of the machine vision system

The machine vision system consists of an image capture adapter card (NI PCI-1411), a CCD camera (SENTECH STC-630), and a lens (AVENIR CCTV LENS 8 mm). The ultimate resolution of the CCD camera is 768 pixel (Horizontal) × 494 pixel (Vertical), the sensor chip is 1/3", the chip size is 4.8 mm (Horizontal) × 3.6 mm (Vertical). The lens focus is 8 mm, and the aperture range is F1.3~F16. The captured visual field is determined by the working distance. The camera transfers the captured image signals to the computer by an image capture adapter card for further processing, and the images are displayed on the screen. A stereo vision system is applied to capture the image with a single camera constructed in a mobile platform for establishing binocular vision. The stereo vision system obtains an actual three-dimensional position of each tomato feature for the end-effector path planning.

(3) Design of the robot carrier

The robot carrier carries some hardware units, such as the robot arm, lifting platform controller, robot arm controller, PC, and carrier driving motor. The robot carrier has positioning control in two axes, including forward and backward of the robot carrier (X-axis) and the ascent and descent of the robot carrier (Y-axis), so the robot system can carry out picking operation in the facilities.

(4) Control system

This study used the LabVIEW ver. 7.1 image controlled program language of NI as the control software. The Vision Assistant 7.1 was used as front end image processing software, and the image processing program generated by the Vision Assistant was built on LabVIEW for integrated application. The control system consists of four units including the robot arm and end-effector control, image processing, robot carrier control and central control unit, as shown in Fig. 3. The details of the control system are as follows.

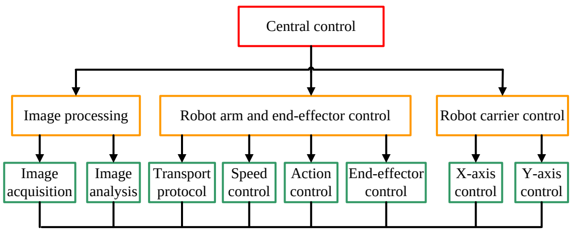

Fig. 3 Robot system program structure end-effector

a Robot carrier control

Fig. 4 shows the schematic diagram of the control hardware structure of the robot carrier. The computer transfers control instructions to the PLC (Programmable Logic Controller, Delta DVP-32EH with 16 inputs and 16 outputs). The PLC is in charge of the positioning control in XY directions of the robot carrier. The RS-232 is used as the transmission interface for the computer and PLC, the communication parameters between computer and PLC are set using Serial Port Init in the development environment of LabVIEW. The instruction read/write for robot carrier control also uses the VISA (Virtual Instrument Software Architecture) module of LabVIEW for serial communication, to control the robot carrier to move horizontally and vertically. The four wheels of the robot carrier move on the rail of the carrier in the X-direction, which drives by a 30:1 reduction motor of 3φ 220 V 90 W. A rotary encoder with 400 pulses per revolution (Hontko, HTR-MW) is employed to count the pulses to calculate the moving distance of the carrier wheels. The platform moves up and down in the Y-direction driven by a hydraulic device with a stroke of 1200 mm. A linear encoder with 0.5 mm per pulse is applied to calculate the displacement of the platform.

Fig. 5 shows the control action flow of the robot carrier. First, the command from the operator is read to judge whether the robot carrier should move forward or vertically. If it moves forward, the robot carrier will execute forward action and judge whether it is in the set position; if not, it will keep moving forward. This action flow is finished if it has reached the position. If it moves vertically, the set parameter will be read to judge whether the running system should ascend or descend. If it ascends, the robot carrier will execute the lifting movement and judge whether it is in the set position; if not, it will keep ascending. This action flow will be finished if it has reached the position. If it descends, the running system will execute a lowering movement and judge whether it is in the set position; if not, it will keep descending. This action flow will be finished if it has reached the position.

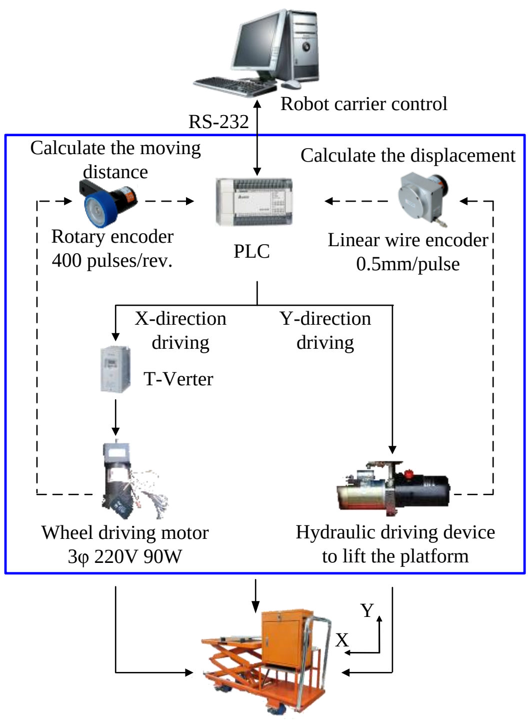

Fig. 4 Schematic diagram of the control hardware structure of the robot carrier

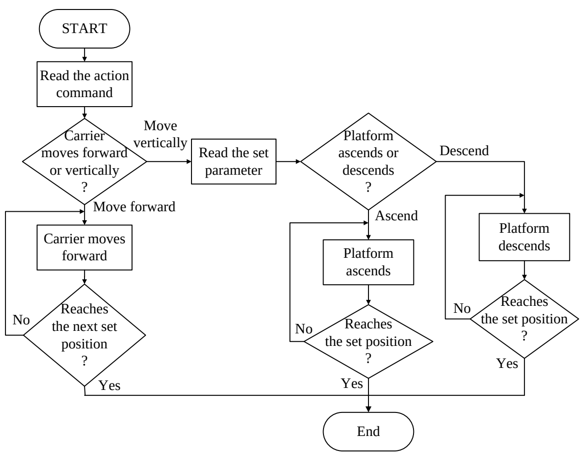

Fig. 5 Control action flow of the robot carrier

b Image processing

LabVIEW was used as the development environment, and the cameras were controlled through an image capture card using the IMAQ (IMage AcQuisition) module that was the image process tool kit of LabVIEW. The image-processing program from Vision Assistant 7.1 was developed on LabVIEW for integrated application. At first, the camera gets good exposure image and conducts white balance adjustment to obtain a good image no matter how the light condition was changed. The program utilized the hue index from the HIS (Hue, Saturation, Intensity) color system to perform tomato grading, then searched the tomato position individually and the external characteristics on two-dimensional coordinates. It also calculated the information of the pedicle, center, and bottom of the tomato. In addition, the program could also use image-processing methods to find the center of the tomato if the situation of overlapping tomatoes occurred. In summary, the developed image processing and analysis could successfully capture good images and calculate the tomato's three-dimensional coordinates of the external characteristics. For details of the algorithm of the image processing and analysis, please refer to Li's thesis (2009).

c Robot arm and end-effector control

The robot arm control unit communicates with the computer via RS-232. The communication parameters for the computer and robot arm control unit are set using Serial Port Init in the development environment of LabVIEW. The communication parameters are set as flow control enable, serial port number (COM1: 0 or COM2: 1); baud rate is 9,600, the data bit is 7-bit, the stop bit is 2-bit, and the parity check is even parity. The instruction read/write of the robot arm mainly uses Icon, such as the VISA module for instruction transmission, to control the robot arm.

Fig. 6 shows the control action flow of the robot arm system. First, the claw of the robot arm is fixed right in front of the target tomato, and stretches in this direction and drives the solenoid to bend the claw fingers. The robot arm then retracts in the same direction. The proximity switch detects whether there is a target tomato; if not, the fingers will be released by resetting the solenoid and this action flow will be finished. If there is a target tomato, the claw will be driven to clamp and hold it, meanwhile, the limit switch signal will be detected to judge whether the limit switch is triggered, meaning whether the fingers bend into the set position. If it is not triggered, whether the clamping of the claw has reached the limit will be judged; if not, the clamping will continue; if it has reached the limit, the claw will rotate to remove the tomato from stem. The robot arm will then be driven to place the removed tomato into the basket. This action flow will be finished.

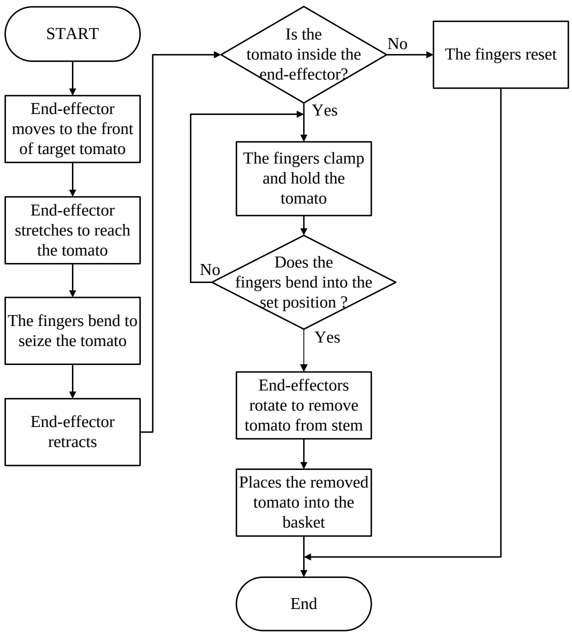

Fig. 6 Control action flow of the end-effector system

d Central control unit

The control action flow of the picking robot system has three stages, as shown in Fig. 7. Stage 1 is initialization where the power is switched on and the executive program is started, the control system will communicate with the robot arm and the robot carrier, and then calibrate the origin. Stage 2 searches for ripened tomatoes to pick. The robot arm will move to the set point position for the camera to take photos. The camera begins to capture and process images, and analyze whether there is any ripened tomato in the frame for picking. It determines whether all the harvest work is completed if there is no ripened tomato; if not, the picking action will continue, returning to the robot carrier movement control action. The operation will end if all the harvest work is completed. If there is any ripened tomato inside the captured image frame, it will move to the third stage. Stage 3 is to pick all the ripened tomatoes. The target tomatoes are sequenced, and the robot arm and end-effector control actions are carried out according to the sequence number. When control actions are carried out for all the targets, whether the picking is completed will be judged; if not, the picking action will continue, returning to the robot carrier movement control action. The operation will be stopped if the picking is completed.

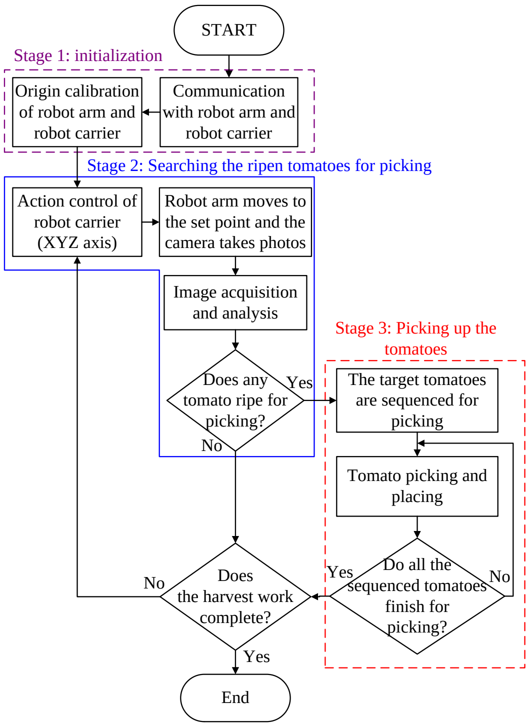

Fig. 7 Control action flow of the picking robot system

2. Picking test

(1) Joint picking test of end-effector and vision system

Section numbers and marks are attached to the captions in the text and used as a rule in the following order.

The working distance of the camera is 660 mm, and the visual field is 396 × 297 mm. The end-effector can pick targets within a range from 184 mm to 336 mm, accounting for 52.57 % of the visual field area. This range is the block derived from analyzing the barycentric coordinates of the target. In other words, if the barycentric coordinates of a target in image analysis are in this range, the target can be picked by the end-effector. This test is carried out for analysis to determine the image space, and the picking success rate of the end-effector in the limited range. The computing mode for the picking success rate is shown in Eq. (1).

$$\text{Picking success rate} = \frac{\text{Success picking samples}}{\text{Total test samples}} \times 100\ (\%) \quad (1)$$

Three polystyrene balls with diameters of 60 mm, 70 mm and 80 mm are used for the picking success rate test, and the balls are hung on a picking test stand. Within the picking limit range, if the test balls are not adjacent and the claw does not touch other balls when picking a ball, the base mark program is derived from the self-composed random numbers. Three testing point coordinates hanging test balls are generated each time to simulate picking. This is repeated 30 times, thus summing to 90 balls, to calculate the picking success rate. The picking operation time is tested and analyzed, from image capture identification to picking completion. Thus, three test balls are placed in the picking range for picking, fifteen groups are recorded, and 45 balls are analyzed, so as to calculate the average picking operation time.

(2) Integration test of the autonomous picking system

The integration autonomous picking system test contains carrier movement, platform up and down, image acquisition and analysis, and picking. To simulate the practical picking operations of greenhouse-grown tomatoes, this test uses random number programs to generate fruit coordinate positions within a range of 1008 × 925 mm. Three types of polystyrene test balls with diameters of 60 mm, 70 mm and 80 mm were hung. Thus, there were 45 balls of each type that were tested three times to calculate the picking success rate and the average picking operation time. Fig. 8 is a schematic diagram of the workflow of the integration test. The robot carrier control contains 15 actions, from the initial point to O point. The amount of forward and vertical movements is set according to the image space, and the end-effector picking range.

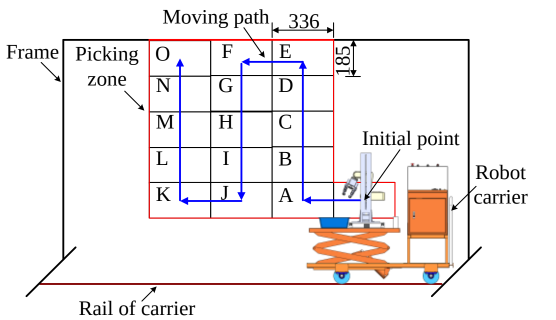

Fig. 8 Schematic diagram of the workflow integration test

III Results and Discussion

1. Prototype of the autonomous picking robot system

The dimensions of the greenhouse grown tomato picking robot system are 1650 × 700 × 1350 mm, and the total weight is around 2190 N. The prototype system of

Table 1 Integrated test result of the autonomous picking robot system

Test ball diameter (mm)	Test #1		Test #2		Test #3		Avg. ± Std.	
	Picking success rate (%)	Operation time (s)	Picking success rate (%)	Operation time (s)	Picking success rate (%)	Operation time (s)	Picking success rate (%)	Operation time (s)
60	91.1	1432	95.6	1497	97.8	1636	94.83 ± 3.42	1522 ± 104
70	91.1	1631	91.1	1657	93.3	1560	91.83 ± 1.27	1616 ± 50
80	86.7	1558	91.1	1510	91.1	1436	89.63 ± 2.54	1501 ± 62

the greenhouse grown tomato-picking robot is shown in Fig. 9. The robot arm and end-effector are automatically controlled. The robot carrier and its platform can move horizontally and vertically, respectively, on the rails for automatic positioning control, and capture and analyze images automatically, to identify fruit. The operating interfaces of the control system are four tabs written by LabVIEW ver. 7.1, which are the program main menu, image capture setting menu, robot arm setting menu, and robot carrier setting menu.

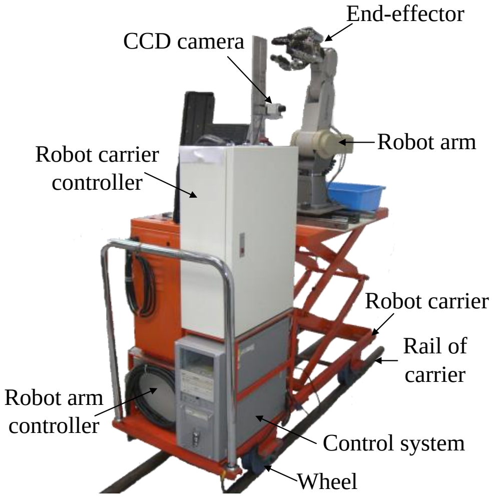

Fig. 9 Prototype of tomato picking robot system

2. Test result of joint picking of end-effector and vision system

According to the test results of the jointed picking works of the end-effector and vision system, the picking success rates of the test balls of different sizes are above 92.8 %. The picking success rates of test balls with diameters of 60 mm, 70 mm, and 80 mm are 97.3 %, 96.4 % and 92.8 %, respectively. The failed picking was due to image analysis coordinate errors and end-effector positioning errors. It was found balls with larger diameters were more likely to not be picked. As for the operation time, the robot picking system spends an average of 30.88 s on each fruit harvest from image capture, identification to picking completion. The standard deviation is 1.30 s. The maximum value is 33.74 s, and the minimum value is 28 s. A robot arm with higher control speed and a communication interface with a higher transmission rate will shorten the picking operation time.

3. Result of the integrated picking test

The integration test uses test balls with diameters of 60 mm, 70 mm, and 80 mm. There are 45 balls of each type, tested three times. There were 405 balls tested, and 387 test balls used in the picking procedure; of which, 373 balls were picked and placed in the basket successfully, while 14 balls were picked but not put into the basket, and 18 balls were not picked. Table 1 shows the integration test result of the autonomous picking robot system. As seen, the overall picking success rate is more than 89.63 %. The average picking success rates of the test balls with diameters of 60 mm, 70 mm and 80 mm were 94.83 %, 91.83 % and 89.63 %, respectively. The average time for picking a ball was 35.96 s, so the picking operation capacity per hour is 100.1 balls.

IV Conclusions

This study developed a greenhouse grown tomato autonomous picking robot system. The picking robot system consists of a robot arm, an end-effector, machine vision, and a robot carrier. The control system consists of four units including a robot arm and end-effector control, image acquisition and analysis, robot carrier control, and central control unit. The LabVIEW ver. 7.1 graphical program language was used for constructing the control program. If the field range is 396 × 297 mm, the range within which the end-effector can pick targets is 336 × 184 mm, accounting for 52.57 % of the visual field area. According to the picking success rate of the end-effector integrated with machine vision, since the end-effector size is fixed, a higher accuracy is required for picking large fruit. Therefore, fruit size influences the picking success rate. This study developed the software and hardware for a greenhouse grown tomato picking robot system, and the expected functional requirement was met. The practical greenhouse grown tomato picking operation test will be enhanced in the future, so the system will be more practical and applicable.

Acknowledgements

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