Structural Environment Suited to the Operation of a Strawberry-harvesting Robot Mounted on a Travelling Platform

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Abstract

To establish a structural environment suited to the operation of a strawberry-harvesting robot, a rolling-type hanging bench and travelling platform were developed. The rolling-type hanging bench, consisting a bench frame, a driving shaft, a DC motor, a pinion-rack and a rolling plate, moved left and right along the beam of the greenhouse and could change the width of the path. The travelling platform, consisting of a main frame and a table, was a gantry structure that enabled a robot to move both in the path direction and sideways. No severe mechanical vibration during stepwise path travel at speed of 182 mm s⁻¹ was observed, although negative slippage occurred. It was verified that the travelling platform performs stable travelling.

[Keywords] path travel, rolling-type hanging bench, travelling platform, traverse motion, strawberry

I Introduction

The area of greenhouses in Japan, including polytunnels, was 52,209 ha in 2005. The top three crops, in descending order, were tomatoes, spinach and strawberries (JGHA, 2008). In spite of the area for strawberry cultivation showing a decreasing tendency (5,256 ha in 2005) yields have remained at around 200,000 t. This is because the yield per unit area has increased due to the breeding of new cultivars and the adoption of elevated substrate culture. However, there are concerns that the aging of farmers combined with the shortage of younger people willing to take over the industry will speed up the shrinkage of the area used for growing strawberries. Innovation in farming techniques, such as year-round production using new ever-bearing cultivars, cropping season expansion using environmental control, and so on, will be needed to guarantee a stable supply. Improvements in or mechanization of labour-intensive work such as crop management, harvesting and packing will be required.

Strawberry harvesting is a labour-intensive process, since as human workers have the ability to handling fruits with the necessary finesse. Moreover, the workers select and pick only the mature red fruits during the early morning hours when the atmospheric temperature is still reasonably low; as the day progresses, the harvested fruit loses its firmness. One way to apply mechanization of the harvesting process would be to apply robotic technology (RT), which involves determining the 3D position, assessment of maturity, and careful handling of the fruits. Extensive research on strawberry-harvesting robots has been conducted (Cui et al., 2007; Kondo et al., 2001; Yamamoto et al., 2009) and machine vision algorithms and end-effectors specialized to the harvesting task of strawberries have been developed. Our two types of strawberry-harvesting robot, a cylindrical-type robot (Hayashi et al., 2010) and an articulated-type robot (Nakao et al., 2009a; 2009b), have performed autonomous harvesting while moving back and forth along a set of rails. Besides strawberry harvesting, several attempts to use robots for selective harvesting in a field have been reported (Hayashi et al., 2003; Van Henten et al., 2003; Tanigaki et al., 2008); however, as a travelling method, they have carried out only forward and backward movement on a set of rails, without traversing to neighbouring paths.

For practical use, harvesting robots need a mechanism for traversing to neighbouring paths to accomplish harvesting tasks over the 2D area of a greenhouse. A former study on a cucumber-harvesting robot proposes a design for a docking system to traverse it (Van Henten et al., 2002). Another noteworthy method is to employ a gantry mechanism (e.g., West Park History Contributors, 2009). A gantry mechanism can provide precise and stable travel on fixed tracks, and

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carry out several tasks while straddling the planted area (Yamashita et al., 2002). These technical aspects provide advantages for robotic harvesting. In the light of such technical considerations, in this study a gantry-structured travelling platform, which makes it possible to lift the harvesting robot and move it to neighbouring paths, was developed. The travelling platform runs on an infrastructure of hanging benches for strawberries; it travels under the benches so as to efficiently utilize the greenhouse space. One feature of the travelling platform is its independent structure: the platform and harvesting robot can be developed independently and be assembled in the field. It also acts as a multipurpose device, since it can carry not only harvesting robots, but other machines such as sprayers and carrying carts. Another challenge when operating a harvesting robot in the field is the variability of the peripheral environment. In general, the environment in a greenhouse is unstructured, due to the various locations and maturity levels of fruits, variation in solar radiation, and seasonal changes in canopy form. To establish a structural environment suited to robotic harvesting, a rolling mechanism for the hanging benches to the left and right was designed, making it possible to change the width of the path to correspond to plant growth and maintain a constant distance between the robot and the fruits. Integration and an interface protocol between these peripheral devices and the strawberry-harvesting robot are also crucial for moving around a greenhouse. The experimental greenhouse was built in Matsuyama City in Japan.

The objectives of this study were: (1) to develop rolling-type hanging benches for strawberries and install them in an experimental greenhouse; (2) to develop and evaluate a travelling platform for a strawberry-harvesting robot; and (3) to establish a structural environment suited to the robot

II Materials and Methods

1. Experimental greenhouse

An experimental greenhouse measuring 48 m long and 6 m wide was built adjacent to a farmer’s existing greenhouse (Fig. 1). Six hanging benches were installed in it; three benches were the fixed type and the other three were rolling type. The length of each bench was 42.75 m to ensure headland spaces of 3.75 m and 1.50 m at both sides of the greenhouse. A travelling platform then was fabricated to enable a harvesting robot to traverse as well as to travel in the path direction.

A block diagram of the devices is shown in Fig. 2; the PLC in the control box sends commands to the rolling benches and the travelling platform to operate the harvesting robot. Communication between the harvesting robot and the travelling platform is done through digital I/O signals.

Fig. 1 Schematic diagram of experimental greenhouse

2. Rolling-type hanging bench

In elevated substrate cultivation for strawberries, there are two types of bench structure: upright and hanging benches. The upright bench system is common in small polytunnels due to its low cost. The hanging bench system, on the other hand, needs the strong beams of a greenhouse from which to hang the benches, and can provide utilizable space under them for a travelling platform, which is described in the following section. In this study, a rolling mechanism for a hanging bench, which moves right and left, was designed in reference to previous studies (e.g., Giacomelli et al., 1983). The rolling bench system has two features: one is high-density planting to increase productivity per unit area, and the other is adjustability of the distance between the harvesting robot and fruits, since the canopy of strawberries changes shape during the cropping season. By adjusting the distance to be almost constant, an appropriate environment could be established for robotic harvesting.

The rolling-type hanging bench measures 42.75 m long and chiefly comprises a bench frame, a driving shaft, a 34-W DC motor, a pinion-rack, and a rolling plate with casters, as shown in Fig. 3. The DC motor rotates the driving shaft and its power is transmitted to the rolling plate through a rack-and-pinion arrangement. As the rolling plate moves at a
speed of 16 mm s\(^{-1}\) along the beam with thickness of 45 mm, the path can be set to be narrow (about 50 cm) at equal spaces if there are no personnel or no robots working, and it can be widened (to about 90 cm) if workers or robots pass through (Fig. 4). Since not all tasks can be automated, many manual tasks remain. For this reason, the rolling benches have manual switches to drive them left or right.

Fig. 3 Rolling-type hanging bench: (a) schematic diagram and (b) close-up of driving mechanism

A previous study of a strawberry-harvesting robot found the need for a mechanism to traverse to the next path to accomplish harvesting tasks in the two-dimensional area of a greenhouse (Hayashi et al., 2010). To allow the harvesting robot to make traverse movements, the travelling platform, which has a gantry structure, was developed by utilizing the space under the hanging benches (Fig. 4). The specifications are shown in Table 1. Both sides of the main frame have a 120-W motor along the rails that moves in the path direction in step motion using an open-loop control on a set of three rails placed at intervals of 2,770 mm. The center rail is for the non-driving auxiliary wheels. The table moves in the traverse direction, powered by a 120-W motor along the main frame. The table measures 1,200 × 600 mm, and its height from the ground level is approximately 250 mm. The travelling platform can carry a harvesting robot on the table (Fig. 4), communicate with a robot through a digital I/O interface (see Fig. 2), and supply 100 V AC electric power to the robot.

Table 1 Specifications of travelling platform

<table>
<thead>
<tr>
<th>Size, mass</th>
<th>5,700 × 1,200 × 1,200 mm, 260 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main frame (path direction)</td>
<td>Travelling method Step travel (209 mm)</td>
</tr>
<tr>
<td>Material</td>
<td>Aluminium</td>
</tr>
<tr>
<td>DC motor</td>
<td>120 W (×1), gear ratio: 1/30</td>
</tr>
<tr>
<td>Wheel</td>
<td>Diameter: 50 mm</td>
</tr>
<tr>
<td>Speed</td>
<td>Max: 261.8 mm s(^{-1}) (set value: 182 mm s(^{-1}))</td>
</tr>
<tr>
<td>Table (traverse direction)</td>
<td>Size 600 × 1,200 mm</td>
</tr>
<tr>
<td>Height from GL</td>
<td>250 mm</td>
</tr>
<tr>
<td>DC motor</td>
<td>120 W (×1), gear ratio: 1/30</td>
</tr>
<tr>
<td>Speed</td>
<td>Max: 261.8 mm s(^{-1}) (set value: 140 mm s(^{-1}))</td>
</tr>
<tr>
<td>Maximum carrying mass</td>
<td>350 kg</td>
</tr>
<tr>
<td>Control unit</td>
<td>PLC KV-1000 (Keyence)</td>
</tr>
<tr>
<td>Communication with robot</td>
<td>Digital I/O (input: 15, output: 15)</td>
</tr>
<tr>
<td>Communication with panel</td>
<td>Wireless digital I/O</td>
</tr>
<tr>
<td>Power source</td>
<td>100 V AC</td>
</tr>
<tr>
<td>Rail</td>
<td>Material Square pipe (50 × 50 × 2.3 mm)</td>
</tr>
<tr>
<td>Number of rails</td>
<td>3 (interval: 2,770 mm)</td>
</tr>
<tr>
<td>Length</td>
<td>46.5 m (headland space: 3 m)</td>
</tr>
</tbody>
</table>

(2) Bending of travelling platform and installation of auxiliary wheel

The main frame bends when the harvesting robot is loaded on the table due to its long span structure of 5,700 mm. To investigate its basic characteristics, the bending of the main frame without a auxiliary wheel was investigated by applying increasing force from 0 N to 2,600 N. Fig. 5 shows the relationship between the load and the deflection at five entry points on the table: (0, −2200), (0, −1100), (0,0), (0, 1100) and (0, 2200). The deflection increased in close proportion to the load, and was approximately 24 mm at a load of 2,600 N when the table was located at the centre. It is clear that the

3. Travelling platform for strawberry-harvesting robot

(1) System components
closer the load to the centre, the greater the deflection.

Under conditions where the platform has no auxiliary wheel, it was observed that longitudinal vibration occurred when the platform constantly stopped and started. Thus, two auxiliary wheels, each one with two springs with a spring constant of 37.4 N mm\(^{-1}\), were installed at the centre of the main frame in such way that the four springs were compressed by 2 mm, resulting in an upward force of 299.2 N.

Fig. 5 Relationship between load and deflection at different positions of the table

(3) Interface between travelling platform and strawberry-harvesting robot

The travelling platform communicates with a PLC in the control unit by means of wireless signals (see Fig. 2). An autonomous motion linked to a travelling task with a picking task requires a simple and easily operated interface between the travelling platform and the robot components. In this study, the interface protocol was established with digital I/O signals to communicate the travelling platform with the robot components. It consists of 11 input signals: a periodic pulse signal, 6 status signals of the robot and 4 command signals from the robot, and 15 output signals: a periodic signal, 12 status signals of the robot and 4 command signals to communicate the travelling platform with the robot. This step movement includes signal communication of about 1 s. On reaching the end of the path (position of LSW-E in Fig. 1), it starts travelling backward and returns the home position. After this round trip, the platform repeats similar movements for the selected paths [2], [3], [4], or [5]. Additionally, in case of travelling on paths [3], [4], or [5], the rolling benches move to open the path.

Fig. 6 Flowchart of movement of travelling platform in experimental greenhouse

(4) Movement of travelling platform in experimental greenhouse

The travelling platform carries out the path travel and traversing movement controlled by signals exchanged with the robot loaded on the table. Fig. 6 shows a flowchart for the movement of the platform in the experimental greenhouse. As illustrated in Fig. 1, the table of the platform starts traversing from the home position, enters the path [1] (position of LSW-1 in Fig. 4), and moves to the start point of the bed (position of LSW-S in Fig. 1). It then travels forward along the path [1] in stepwise movement while communicating with the robot. This step movement includes signal communication of about 1 s. On reaching the end of the path (position of LSW-E in Fig. 1), it starts travelling backward and returns the home position. After this round trip, the platform repeats similar movements for the selected paths [2], [3], [4], or [5]. Additionally, in case of travelling on paths [3], [4], or [5], the rolling benches move to open the path.

The stable path travel was obtained at speed of 182 mm s\(^{-1}\), after it was adjusted. Therefore, an autonomous travelling test of the platform was carried out to investigate for slippage at a path travel speed of 182 mm s\(^{-1}\); the platform moved without carrying any robot components. The actual travelling distances per step movement were measured with the platform carrying a weight of 0, 102 or 204 kg, and moved a distance of 40 m. The entry points of the table in the traverse direction were set as (0, –2200), (0, –1100), (0, 0), (0, 1100) and (0, 2200), since the origin is located on the central rail as described in Fig. 4. The slippages in path travel were calculated using Equation (1):

$$S = \frac{L - L_0}{L_0} \times 100 \quad (1)$$

where $S$ is the slippage ratio (%), $L_0$ is the theoretical travelling distance per step movement (mm), and $L$ is the
The travelling platform needed 189 to 192 steps to travel a distance of 35.5 m. The operational time for each path is shown in Table 2. The variability of the entry process and return process were caused by the distance between the home position and the entry point; there were no major differences in other operational times, resulting in 5,282 s in total. For path travel, the platform needed about 500 s to move a distance of 35.5 m; however, backward travel tended to take longer than forward travel. This is likely to be caused by the smaller negative slippage ratio than backward travel.

This slippage tests were conducted under dry rail conditions; however, the rail may become wet from nutrient solutions, chemical spray or dew condensation. In preliminary observations, the travelling platform showed greater negative slippage when the rail was wet, but smooth operation was observed.

### III Results and Discussion

#### 1. Slippage ratio during path travel

The travelling platform needed 189 to 192 steps to travel a distance of 40 m. Fig. 7 shows the slippage ratios of the travelling platform in the forward and backward directions. The slippage occurred under all conditions and varied from −0.67 % to −2.38 %. This negative slippage means that the actual travelling distance was greater than the theoretical travelling distance \( L_0 \); i.e., the platform moved by an influence of inertia after the wheels had stopped. Fig. 7 also indicates that the heavier the load on the table, the greater the negative slippage ratio of travelling. Moreover, slippage tended to increase negatively as the table entered positions further from the centre, and forward travel showed greater negative slippage than backward travel.

#### 2. Acceleration level at table during path and traverse travel

During path travel, the accelerations were −3.1 to 2.0 m s\(^{-2}\) for x-axis, −1.0 to 1.6 m s\(^{-2}\) for y-axis, and −3.1 to 2.4 m s\(^{-2}\) for z-axis, respectively. During traverse motion, they were −1.8 to 1.6 m s\(^{-2}\) for x-axis, −1.6 to 2.2 m s\(^{-2}\) for y-axis, and −2.9 to 2.4 m s\(^{-2}\) for z-axis, respectively. Maximum acceleration for z-axis (vertical direction) was equal to the one for x-axis. No severe mechanical vibration at the set speeds was observed, and it was verified that the robot can capture images without a waiting time after it stops.

#### 3. Operational time for each path

The operational time for each path is shown in Table 2. The variability of the entry process and return process were caused by the distance between the home position and the entry point; there were no major differences in other operational times, resulting in 5,282 s in total. For path travel, the platform needed about 500 s to move a distance of 35.5 m; however, backward travel tended to take longer than forward travel. This is likely to be caused by the smaller negative
slippage in backward travel.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Operational time for each path travel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry process</td>
<td>1.2</td>
</tr>
<tr>
<td>Path travel to bed start</td>
<td>12.0</td>
</tr>
<tr>
<td>Forward travel</td>
<td>494.0</td>
</tr>
<tr>
<td>Backward travel</td>
<td>500.0</td>
</tr>
<tr>
<td>Path travel to traverse point</td>
<td>12.6</td>
</tr>
<tr>
<td>Return process</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td>1021.1</td>
</tr>
</tbody>
</table>

Unit: s

Since the operational time included actual travelling time, communicating time and waiting time for suppressing mechanical vibration, there is potential for shortening the communicating time and waiting time by optimizing the communication program.

4. Electric energy for each path

The electric power used during path travel and traverse motion were 107.8 W and 103.4 W, respectively, neglecting the electric power consumed by the robot components. Based on operational time, the electrical energy used for path travel in [1] to [5] was estimated at 30.6 Wh, 31.4 Wh, 31.8 Wh, 32.1 Wh, and 32.2 Wh, respectively, resulting in a total electrical consumption of 158.1 Wh.

5. Structural environment

To operate an advanced mechatronics system such as a harvesting robot, the structural environment is important. In this study, although the rolling-type bench enabled adjustment of the distance between the robot and the fruit, the position of setting fruit varies in height depending on the season. For example, the height of the fruit becomes lower in the spring due to the strong vigor of the plants. This measure requires a long vertical stroke by the robot; i.e., it would be possible to capture the fruit in the center of the image by adjusting the camera height as occasion requires.

Moreover, the travelling platform realized stable path travel and traverse motion. Although the platform was designed for the robot to harvest during forward and backward travel, it can return at high speed to the home position, resulting in efficient work, if another device such as a chemical sprayer or a robot with an ambidextrous picking function were used. Further studies on validation of performance combining a harvesting robot and the peripheral technologies developed in this study are needed in the future.

IV Conclusions

To establish a structural environment suited to the robotic harvesting of strawberries, a rolling-type hanging bench and a travelling platform were developed and tested in an experimental greenhouse. The rolling-type hanging bench, consisting chiefly of a bench frame, a driving shaft, a DC motor, a pinion-rack and a rolling plate with casters, moved left and right along the beam of the greenhouse, allowing the width of the path to be changed in response to the extent of plant growth. The travelling platform, consisting of a main frame and a table (5.7 m by 1.2 m), was a gantry structure that enabled the robot to move in both the path direction of 35.3 m and in traverse motion along a set of three rails placed at intervals of 2,770 mm. The center rail was for the non-driving auxiliary wheels.

A travelling test of the platform when operated autonomously showed a negative slippage of –0.67 to –2.38 % at path travel speed of 182 mm s\(^{-1}\) when a weight of 0 kg to 204 kg was loaded on it; i.e. the platform moved after the wheels stopped. It was also shown that the heavier the load on the table, the greater was the negative slippage ratio of travelling.

Furthermore, an integrated program was developed to communicate between the platform and the robot components, and a performance test in interlocked operation with the robot components of 245 kg was conducted. The absolute maximum acceleration in path travel was 3.1 m s\(^{-2}\) along the x-axis (path direction) and the z-axis (vertical direction), and that in traverse motion was 2.9 m s\(^{-2}\) along the y-axis (vertical direction). Since no severe mechanical vibration was observed, the travelling platform realized stable path travel and traverse motion at the set speeds.

On this condition, the total operational time of the platform from path [1] to [5] was 5,282 s. It took about 500 s to travel in the path direction of 35.5 m; however, backward travel tended to take longer than forward travel. The electric power consumed during path travel and traverse motion were 107.8 W and 103.4 W, respectively, ignoring the electric power consumed by the robot components. Based on an operational time of 5,282 s in total, the electric energy from path [1] to [5] was estimated at 158.1 Wh.

References


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