Development of an Automatic Rolling System for Rice Seedlings

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The objective of this study was to develop an automatic rolling system for rice seedlings, which can roll up the seedling mat from a 30 by 60 cm tray into a cylindrical shape of 18 cm diameter and combine three rolls in one tray ready for transportation. The system employs a pneumatic mechanism for movement, with a programming logic controller for processing the procedure. Experimental results showed that the mechanism worked satisfactorily at 362 trays an hour, at which speed more than 95% of the seedling mats were rolled successfully and more than 90% of the three rolled mats were successfully combined in one tray. Since there was no significant difference in seedling quality for the machine-rolled mats compared to the manually rolled mats, this system should be favourably accepted by farmers.

1. Introduction

Rice is a staple crop in Taiwan. The traditional cultivation involves transplanting rice seedlings to the paddy field using a transplanter. Producing seedlings is a valuable stage in the rice production process. Taiwan produces two crops of rice per year. Each requires 200–240 boxes of seedlings per hectare for transplanting (Chiu and Chang, 1987). Seedlings are provided by more than 600 nursery centres around the island.

The work involved in the nursery operations is seasonal, labour-intensive and time-consuming. Lack of farm labour has increased the cost of this work and has necessitated the mechanization of the process. As the seedling production in the rice nursery centre is seasonal and either younger or older seedlings will result in poor quality and less quantity of grain production, the entire process must be carefully scheduled. Chiu et al. (1999) developed a linear programming model to analyse the production schedule for rice seedlings grown in a nursery.

The procedures in a seedling nursery can be divided into four parts: sowing, input operations, seedling growth, and output operations. The sowing operation can be broken down into supplying boxes, soil filling, water spraying sowing, pesticide spraying and soil covering (Chiu et al., 1998).

The seeded trays are stacked in a conditioning room for 2 or 3 days to speed up sprouting and then moved to the field for acclimatization and further growth, thus completing the ‘input operations’. The grown seedlings eventually form a dense root mat in the tray and can be rolled into a cylindrical shape for transportation and later transplanting.

The ‘output operations’ include rolling the seedling mats, collecting the rolled mats from trays, conveying and stacking on the truck for transportation. The seedling mat rolling is a popular method used for distant transportation in Taiwan. Many workers are required to complete this job within a few hours in the early morning (Fig. 1). It is often difficult to hire so many people at the same time and the use of machines would alleviate this problem.

The objective of this study was to develop an automatic rolling system for rice seedlings grown in a soil bed within 30 by 60 cm trays. This required a system which could roll up the seedling mat from a 30 by 60 cm tray into a cylindrical shape of 18 cm diameter and place three rolled mats in one tray ready for further transportation.
2. Materials and methods

2.1. Mechanism Design

The automatic rolling system for rice seedlings can be divided into two working units: rolling and relocating. The rolling unit is a device that rolls up the seedling mat to a cylindrical shape; while the relocating unit groups three of the rolled mats into one tray ready for transportation. The system employs a pneumatic mechanism for movement, with a programmable logic controller (PLC) to process the sequential control. Figure 2 depicts the concept of the rolling process.

2.1.1. Rolling unit

When rolling a seedling mat manually, the mat is firstly released from one end of the tray by gripping the seedlings and lifting the mat slightly. The mat is then rolled towards the opposite side of the tray to form a neat cylindrical shape. The motion of rolling should have two functions: pulling and rolling. The schematic motion flow of the rolling unit is shown in Fig. 3.

2.1.1.1. Seedling-mat pulling. The seedling mat must be separated first at one end of the tray before rolling. Therefore, a seedling-mat pulling plate (SP plate) was designed as a breaker to raise the mat. The SP plate, driven down by an air cylinder, exerts a pushing force directly on the upper part of seedlings toward the end as it moves (Fig. 3). The seedlings are then bent sideways accompanied by lifting the mat slightly, which creates room for the seedling-mat rolling plate to descend and reach the bottom of the mat.

2.1.1.2. Seedling-mat rolling. The rolling action is accomplished by a pair of French curve plates, the seedling-mat rolling plate (SR plate) and the seedling-mat forming plate (SF plate). Following the SP plate which breaks the seedling mat at one end, the SR plate descends to its lowest position and starts to plough the seedling mat by pushing it both laterally and upwards. Simultaneously, the SF plate swings down to the position against
the other end of the seedling mat and helps in forming the mat roll. To facilitate smooth feeding of mat to the SR plate, an auxiliary feed wheel was installed with protruding spikes on its outer surface (Fig. 4). The mechanism is self-driven through a gear walking along a rack located on one side of the frame. As the SR plate moves forward, the auxiliary wheel is rotated by the drive gear.

The radius of curvature of the SR plate, however, becomes a key factor that affects the success of rolling and determines the diameter of the roll formed as well. The optimum radius is 100 mm, with an arc length of 150 mm along its surface. The SF plate acts as a stopper at the end of the tray but is shaped in a reverse curve to that for the forming action. It is pneumatically driven to achieve two positions, one in work and the other to allow the seedling mat to pass freely underneath (Fig. 5). The SF plate also provides a support for the finished roll and prevents it from dropping at the end of the working stroke.

2.1.2. Relocating unit

The purpose of the relocating unit is to place three seedling rolls at a time into an empty tray. The flowchart for the relocating operation is shown in Fig. 6 and the schematic diagram of the relocating operation is shown in Appendix A.

There are two sets of grippers that can temporarily hold seedling rolls. At the beginning, the first set holds the first finished roll from the rolling unit, and then the second holds another. After both are loaded, the two sets of grippers are in sequence waiting above the relocating unit until the third roll finished. The grippers lower the first and second seedling rolls onto the tray that contains the third roll. Finally, three seedling rolls are placed in one tray. The gripper set is driven by two pneumatic cylinders, one moves the gripper vertically and the other controls the jaws of the gripper. The design of the gripper set is shown in Fig. 7.

2.2. Controlling System

A pneumatic mechanism with a programmable logic controller (PLC) was applied to process the sequential events, with 34 channels for input and 18 for output. Both rolling and relocating units are arranged in line but can work independently. The rate of operation is dependent upon the slower unit. As one cycle of the rolling operation takes about 9 s and the relocating operation takes about 5 s (Fig. 8), the theoretical system rate is 9 s/tray. In other words, the system throughput may reach 400 trays/h.

There are a total of 14 double-acting cylinders in the system with a working pressure of 0.45 MPa. Their specifications are shown in Table 1. As a double-acting cylinder has different acting areas on both the pull and the push strokes, its corresponding acting forces can be calculated as follows:

\[ F_1 = \eta A_1 P \]  
\[ F_2 = \eta A_2 P \]

where \( F_1 \) and \( F_2 \) are the forces in kN acting on the push and pull strokes, respectively, \( A_1 \) and \( A_2 \) are the cross-sectional areas in mm\(^2\) of the push and pull side of cylinder; \( P \) is the operating pressure in MPa, and \( \eta \) is the loading rate. In estimating the loading rate, the SMC technical note (SMC, 1997) suggested that the value for \( \eta \) is 0.5 for dynamic action and 0.7 for static action. Except at position one, the operation of each cylinder requires dynamic action. Due to differently designed
functions, some of the cylinders work with a pulling action; and others with a pushing action. The relevant forces acting on the cylinders are listed in Table 1.

Since it is difficult to measure the force for rolling, a pressure sensor (range between 0 and 10 bar with an output of 4–20 mA) was employed to detect the difference between the loading and unloading conditions. If the two pressures differed significantly in measurement, then more pressure was required for the cylinder. The pressure was recorded by a data logger (Campbell CR-10X), under a scanning rate of 0.25 s.

In this system, the transfer cylinder for seedling-mat rolling requires the largest stroke of all the various operations (Table 1). Figure 9 illustrates the pressure variations under loading and unloading operations at the system inlet and at the transfer cylinder for seedling-mat rolling, as measured over one production cycle to complete a three-roll tray. The pressure during the loading and unloading operations has no significant difference in both cases. In fact, the transfer cylinder for seedling-mat rolling performed perfectly at a system pressure of 0.45 MPa.

Calculation of the air consumption in the pneumatic system was essential to select the capacity of air compressor. The system consumption includes the cylinder capacity $Q_{cc}$ and the pipe capacity $Q_{cp}$ in l/min, which can be calculated as follows:

$$Q_{cc} = (A_1 + A_2) \ln \frac{P + 0.1013}{0.1013} \times 10^{-6}$$

$$Q_{cp} = 2aSn \frac{P}{0.1013} \times 10^{-16}$$

$$Q_c = Q_{cc} + Q_{cp}$$

where: $Q_c$ is the total system consumption in l/min, $L$ is the cylinder stroke in mm, $n$ is the acting frequency of cylinder in frequency/min, $a$ is the inner sectional area of pipe in mm$^2$ and $S$ is the pipe length in mm.

Table 1 also shows the corresponding air consumption. The total system air required will be 317.1 l/min. With a safety factor of 1.2, suggested by Leu and Hwang (1992) for possible leakage, the system may be rated as 380.5 l/min.

### 2.3. Experiment Procedures

A prototype of the automatic rolling system is shown in Fig. 10. The whole system, 550 by 80 by 150 cm, is made of stainless steel. The source of compressed air is supplied by a two-cylinder compressor with a power requirement of 2.2 kW at a rated displacement of 480 l/min. The system was tested in I-Lan county, Taiwan. A variety of Taikan 8 of Japonica paddy,
Fig. 8. The flowchart of acting sequence for an automatic rolling system

Table 1
Technical data of cylinders in the system

<table>
<thead>
<tr>
<th>Name of cylinder</th>
<th>Inner diameter of cylinder, mm</th>
<th>Plunger diameter of cylinder, mm</th>
<th>Cylinder stroke, mm</th>
<th>Acting force, kN</th>
<th>Acting frequency of cylinder, frequency/min</th>
<th>Pipe length, mm</th>
<th>Air consumption, l/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dividing position cylinder</td>
<td>32</td>
<td>12</td>
<td>50</td>
<td>253.8</td>
<td>10</td>
<td>1000</td>
<td>0.44</td>
</tr>
<tr>
<td>Front stopper</td>
<td>32</td>
<td>12</td>
<td>50</td>
<td>253.8</td>
<td>6</td>
<td>2200</td>
<td>0.59</td>
</tr>
<tr>
<td>Rear stopper</td>
<td>32</td>
<td>12</td>
<td>50</td>
<td>253.8</td>
<td>6</td>
<td>1600</td>
<td>0.43</td>
</tr>
<tr>
<td>Lift cylinder for seedling-mat pulling plate</td>
<td>63</td>
<td>20</td>
<td>250</td>
<td>701.7</td>
<td>6</td>
<td>2350</td>
<td>0.63</td>
</tr>
<tr>
<td>Lift cylinder for seedling-mat rolling plate</td>
<td>63</td>
<td>20</td>
<td>250</td>
<td>701.7</td>
<td>6</td>
<td>2400</td>
<td>0.64</td>
</tr>
<tr>
<td>Transfer cylinder for seedling-mat rolling</td>
<td>63</td>
<td>20</td>
<td>700</td>
<td>631.1</td>
<td>6</td>
<td>850</td>
<td>0.23</td>
</tr>
<tr>
<td>Transfer cylinder for seedling-mat forming</td>
<td>50</td>
<td>20</td>
<td>150</td>
<td>371.4</td>
<td>6</td>
<td>1600</td>
<td>0.43</td>
</tr>
<tr>
<td>Position cylinder for the first tray</td>
<td>32</td>
<td>12</td>
<td>50</td>
<td>253.8</td>
<td>1.5</td>
<td>3900</td>
<td>0.26</td>
</tr>
<tr>
<td>Lift cylinder for the first gripper</td>
<td>63</td>
<td>20</td>
<td>250</td>
<td>701.7</td>
<td>3</td>
<td>3400</td>
<td>0.45</td>
</tr>
<tr>
<td>Grip cylinder for the first gripper</td>
<td>32</td>
<td>12</td>
<td>100</td>
<td>181.3</td>
<td>3</td>
<td>3400</td>
<td>0.45</td>
</tr>
<tr>
<td>Position cylinder for the second tray</td>
<td>32</td>
<td>12</td>
<td>50</td>
<td>253.8</td>
<td>1.5</td>
<td>3700</td>
<td>0.25</td>
</tr>
<tr>
<td>Lift cylinder for the second gripper</td>
<td>63</td>
<td>20</td>
<td>250</td>
<td>701.7</td>
<td>3</td>
<td>2900</td>
<td>0.39</td>
</tr>
<tr>
<td>Grip cylinder for second gripper</td>
<td>32</td>
<td>12</td>
<td>100</td>
<td>181.3</td>
<td>3</td>
<td>3400</td>
<td>0.45</td>
</tr>
<tr>
<td>Position cylinder for the third tray</td>
<td>32</td>
<td>12</td>
<td>50</td>
<td>253.8</td>
<td>1.5</td>
<td>3500</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Total system air consumption, l/min 317.1

popularly planted in Taiwan, was sorted to prepare the seedling trays for the experiment. In operation, the worker stands in front of the machine to upload the seedling trays onto the conveyor. The system first senses the approaching trays and arranges them in a queue for the rolling operation. The finished
Fig. 9. The pressure variations in loading and unloading operations at the system inlet and at the transfer cylinder for seedling-mat rolling: system inlet (unloading); seedling-mat rolling cylinder (unloading); system inlet (loading); seedling-mat rolling cylinder (loading)

rolls are completed tray by tray, and are then stacked up for further use.

This study tests the mat-rolling performance of seedlings at three stages of growth, with 21 trays each. Ten trays of seedlings are randomly selected to check the moisture loss of seedlings due to drainage during the rolling operation. Weighing was by means of an electric balance.

3. Analysis and discussion

3.1. Analysis of Seedling-Mat Pulling

In the rolling process, the SP plate must bend and turn the seedling mat far enough before the SR plate can start to work properly. Adjustment of the clearance between the tip of the SP plate and the seedling mat is essential for smooth operation. If the SP plate is too far from the mat, the mat will not bend well. A small clearance, however, may induce a greater resistance between the plate and the seedlings and eventually damage the seedling mat. In addition, the SP plate stroke also has a side effect on the insertion space for the SR plate. It was observed that a smaller insertion clearance and a longer stroke were likely to jam the mechanism in operation. The best condition is when the insertion clearance is larger than the distance

\[ y = \sqrt{4a^2 \sin^2 \frac{\theta}{2} - l^2} \]  

where \( a \) is the curvature radius, \( l \) is the height of the tray; \( \theta \) is the curvature angle with chord \( l \) and curvature radius \( a \). The value of \( \theta \) can be derived as follows:

\[ \theta = \alpha \frac{l}{2a \sin \alpha/2} \]  

where \( \alpha \) is the curvature angle of SR plate.

The curvature radius \( a \) and arc length (\( \alpha \alpha \)) of the SR plate are 100 and 150 mm, respectively, and the height of tray \( l \) is about 20 mm. Accordingly, \( \alpha \) is 86° and \( \alpha/2 \) 9.1 mm. In other words, the SR plate can be smoothly inserted into the tray to process the rolling work as long
as the SP plate can drag the seedling mat upwards to an insertion clearance greater than 9.1 mm.

It is difficult to mathematically relate the insertion clearance to the clearance and stroke of SP plate. In this study, the transfer stroke of the SP plate at 1 cm of insertion clearance was tested under different clearance of SP plate from 1 to 5 cm with increments of 1 cm. There were five replications for each experiment. The tests failed for the clearances greater than 5 cm, because the resistance was not large enough. Figure 12 shows a regression equation, $z = 1.38x + 5.156$ with a coefficient of determination $R^2$ of 0.963, in which $z$ in cm is the transfer stroke required for the SP plate and $x$ cm is the clearance of the SP plate above the tray.

3.2. Result of Rolling Operation

In the experiment, it was found that the seedling mat must be wetted before feeding the machine, otherwise it would not bend well during rolling as the soil was too dry and hard. In addition, the squeezing action during roll forming could cause much weight loss, with the water contained in the mat draining away. The results show that the total weight per tray was $7206.3 \pm 532.1$ g before rolling, of which $6025 \pm 443.2$ g was for the seedling mat and $816.7 \pm 37.3$ g for the empty tray after rolling. There was about $364.6$ g of water drained during rolling.

The success rate for rolling and relocating was recorded and shown in Table 2. For the large and medium seedlings, the success rate for rolling reached 100%, in comparison with 95.2% for the small ones. The reason is that when the roots of the small seedlings are insufficiently developed, the seedling mats are likely to be broken during the rolling process. For the relocating unit, the success rate with the rolls of the medium and small seedlings was also 100%, but only 90.5% was obtained for the rolls of the large seedlings. The reason is that the larger seedlings are likely to result in larger rolls, which turn loose more readily during relocating.

As the medium seedlings are mostly supplied from the nursery centre, the rolling machine will handle most of the product without failure. In fact, there was no significant difference on the diameter of rolls between the manually handled, and machine handled, product. For the system throughput, it took about 209 s to process 21

<table>
<thead>
<tr>
<th>Seedling size</th>
<th>Large</th>
<th>Medium</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seedling variety</td>
<td>Taikan 8</td>
<td>Taikan 8</td>
<td>Taikan 8</td>
</tr>
<tr>
<td>Seedling age, d</td>
<td>18</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Seedling length, cm</td>
<td>$16.9 \pm 2.6$</td>
<td>$14.5 \pm 4.4$</td>
<td>$12 \pm 2.3$</td>
</tr>
<tr>
<td>Success rate for rolling, %</td>
<td>100</td>
<td>100</td>
<td>95.2</td>
</tr>
<tr>
<td>Success rate for relocating, %</td>
<td>90.5</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Diameter of seedling roll made by machine, cm</td>
<td>$18.7 \pm 0.39$</td>
<td>$18.5 \pm 0.53$</td>
<td>$18.1 \pm 0.63$</td>
</tr>
<tr>
<td>Diameter of seedling roll made manually, cm</td>
<td>$18.4 \pm 0.48$</td>
<td>$18.1 \pm 0.47$</td>
<td>$17.8 \pm 0.76$</td>
</tr>
</tbody>
</table>
trays of seedlings, i.e. 362 trays/h, only 38 trays less than the theoretical one.

However, it is still far less than that done by hand. Usually, it takes 4–5 workers to handle a similar job at 2000 trays/h (Chiu & Fon, 1998). Therefore, further improvement on the machine operation rate is necessary. At present in Taiwan, the lack of farm labour may increase the market interest in this type of machine. In addition, by linking this prototype to a parallel development of a machine that can automatically load trays for conveying to and from fields for acclimatization (Fon & Chiu, 1997), this seedling-mat rolling machine would be a part of the whole system.

4. Conclusion

An automatic rolling system for rice seedlings has been successfully developed for rolling up the seedling mat in the field from a typical 30 by 60 cm tray into a cylindrical shape of 18 cm diameter and combining three rolls in one tray ready for transportation. The whole system can be divided into two working units: rolling and relocating. A pneumatic mechanism was designed with a programmable logic controller to process the sequential actions.

The experimental results have shown that the system throughput could reach 362 trays/h. The success rate for rolling was 100% for the large and medium seedlings, and 95.2% for small ones. For the relocating unit, it was 100% for medium and small seedlings and 90.5% for large ones. Large seedlings generate larger rolls which are more likely to turn loose during relocating. There was no significant difference between the diameters of the finished rolls produced by hand and by machine. In terms of performance, however, the machine reached 362 trays/h, which is slightly lower than that for manual production.

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References


Chiu Y C; Fon D S; Chen L H (1999). Predicting the production schedule of paddy-rice nursery. Transactions of the ASAE, 42(2), 505–511


Fon D S; Chiu Y C (1997). Automation on seedling production for rice nursery centres. Taipei: Project Report. Department of Agricultural Machinery Engineering, National Taiwan University


SMC (1997). SMC Best Pneumatics. SMC Inc., Tokyo

Appendix A—The schematic actions of the relocating unit