Unmanned Rice-Transplanting Operation Using a GPS-Guided Rice Transplanter with Long Mat-Type Hydroponic Seedlings

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ABSTRACT

A low-cost guidance system was developed for a global positioning system (GPS)-guided automated rice transplanter. In 2005, the already available GPS-guided automated rice transplanter was modified to carry long mat-type hydroponic rice seedlings and attached an herbicide-dripping machine. The use of long mat-type hydroponic rice seedlings allows rice-transplanting operations to be carried out on a 0.3 ha standard-size Japanese field without the need to supply additional seedlings. Fully automated rice transplantation was achieved with the modified transplanter. To reduce the costs of the transplanter, the expensive fiber-optic posture sensor was replaced by a low-cost posture sensor, developed at Hokkaido University, for measuring the heading angle and inclination. The processing program of this posture sensor was modified to adapt it to rice-transplanting operation. Instead of establishing a reference station, a real-time, kinematic GPS was used. The modified rice transplanter, when tested in planting a farmer's paddy field took about one hour between entering and leaving the field. The trial was almost successful, with a few minor problems.

Keywords: Automated operation, GPS, long mat type hydroponic rice seedlings, paddy field, rice transplanter

1. INTRODUCTION

The objective of this study is to develop an automated operating system for paddy fields. The goal of this research is to permit one operator to control a number of machines, making the operation highly efficient. In Japan, although the average area operated by a single farmer is increasing, there is insufficient consolidation, and fields remain dispersed. It is therefore necessary to develop technologies for automatic operation that will permit a single operator to control a number of machines in several scattered fields. This becomes possible if operators use automated control systems.

An automated rice transplanter was previously developed and tested (Nagasaka et al., 2002). A real-time kinematic global-positioning system (RTKGPS) was used to identify the location of the transplanter, and fiber-optic gyro (FOG) sensors were used to measure its heading angle and inclination. In 2002, all data processing and actuator control was performed on one main controller attached to several interface boards. The automated rice transplanter was then modified to improve its operating precision (Nagasaka et al., 2004). The RTKGPS and FOG sensors were retained, but the vehicle control system was replaced and a programmable logic controller (PLC) was used for precise control of the actuators.

Until 2004, conventional-type rice seedlings were used in the automated rice transplanter. With these conventional-type rice seedlings and the rice transplanter, farmers require 20 seedling mats to plant an area of 10 acres. A six-row rice transplanter can carry 12 seedling mats at one time. Previously, it was necessary to supply seedlings during operation of the transplanter, and this was a problem for a fully automated rice-transplanting operation. Tasaka et al. (1998) developed long mat-type hydroponic rice seedlings, which are now used by several dozens of farmers (Kitagawa et al., 2004). When farmers use long mat-type hydroponic rice seedlings, they do not need to supply additional seedlings during the operation of the transplanter. Therefore, an operating attachment of the automated rice transplanter was modified to carry these long-mat seedlings.

In this study, the aim was to develop a system that has a lower cost than those of the previous systems. First, the expensive FOG sensors used to measure the heading angle and inclination of the vehicle were replaced by a low-cost posture sensor, consisted of two inclinometers and three rate gyro sensors, developed at Hokkaido University (Mizushima et al., 2004). A network-based RTKGPS (Rizos, 2002) was also used instead of a reference station. In Japan, the Geographical Survey Institute has established about 1200 GPS-based control stations throughout the country, and their real-time data can be used as GPS reference data.

Within this paper, the design of the modified rice transplanter and a trial of its fully automated operation in a farmer's paddy field are reported.

2. MATERIALS AND METHODS

A six-row rice transplanter, manufactured by ISEKI & CO., LTD. (Japan), was modified by attaching sensors, actuators, and controllers to permit automated operation. An herbicide-dripping machine and special parts for long mat-type hydroponic seedlings were attached to the transplanting implement. Figure 1 shows the modified rice transplanter. Figure 2 is a schematic for the automated rice-transplanting system.

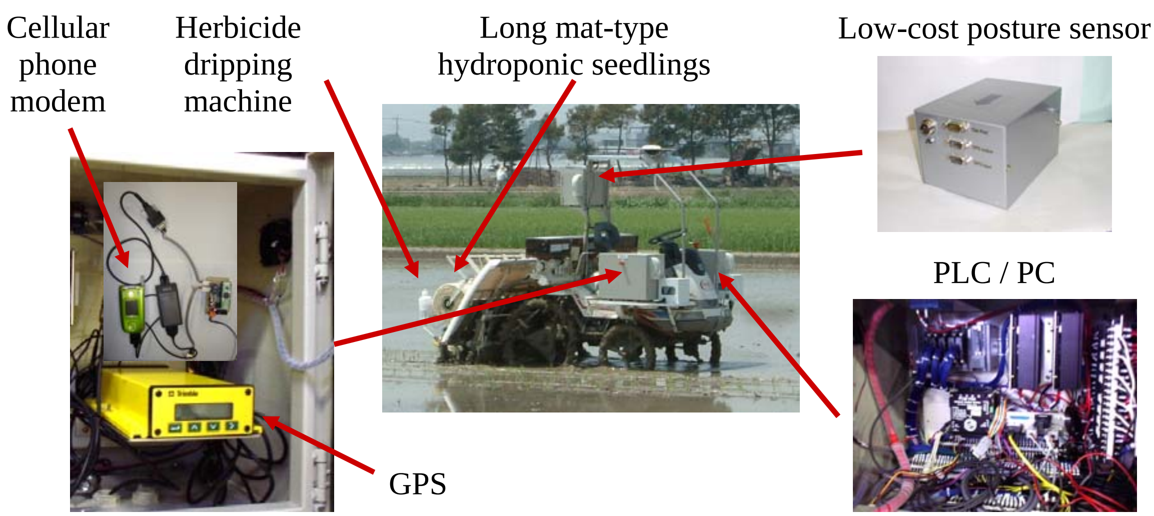


Figure 1. Automated rice transplanter.

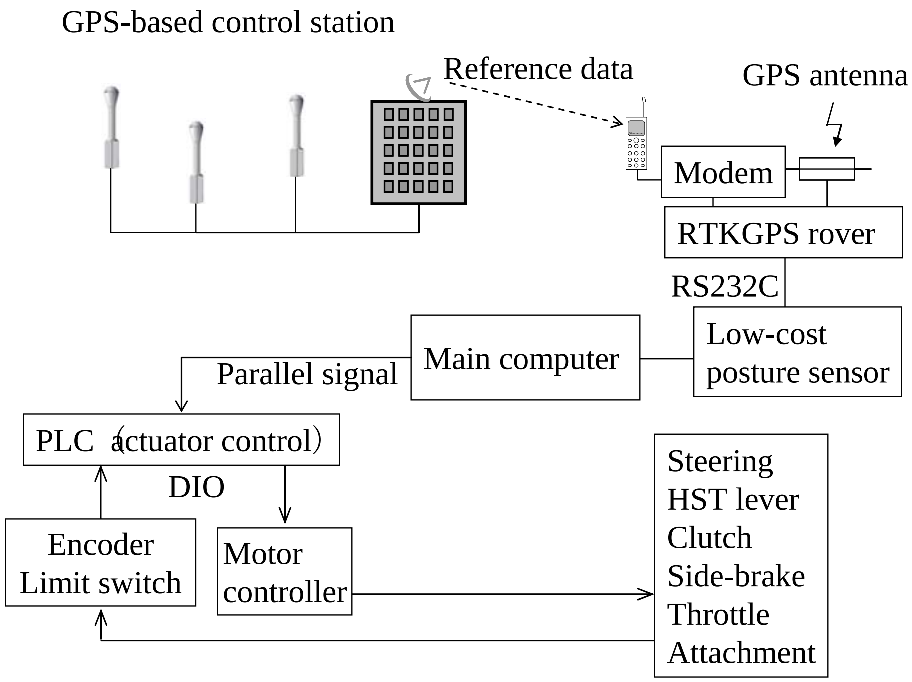


Figure 2. Schematic for an automated rice-transplanting system.

2.1 Sensors, Actuators, and Controllers

2.1.1 Network RTKGPS

A MS750 GPS receiver, manufactured by Trimble Navigation Ltd. (Sunnyvale, CA), was used. The GPS position data output cycle was 5 Hz, and the data were transferred to a low-cost posture sensor through an RS232C serial interface. The data output baud rate was set to 19,200 bps. Previously, an individual reference station for real-time kinematic positioning was used, but in this study, a network-based reference station was used.

The GPS Earth Observation Network System (GEONET) of the Japanese Geographical Survey Institute (GSI) consists of about 1200 GPS-based control stations and is used to study the daily movements of land in Japan for studies of earthquakes and volcanic activity. In 2004, the GSI began to permit GPS-based control stations to use real-time data from GEONET. Some companies process these data and deliver the reference data in RTCM format through packet communication or through a circuit-switching system using a cellular phone and a modem.

When these reference data are used, there is no need to establish an individual reference station and the number of expensive GPS receivers required can be reduced. A modem manufactured by JENOBA Co., LTD. (Japan) was used for communication between the reference station network and the rover station: the baud rate for modem communication was set to 38,400 bps.

2.1.2 Low-Cost Posture Sensor

In paddy fields, the GPS position data needs to be corrected for the effect of the inclination of the vehicle. A low-cost posture sensor developed at Hokkaido University was used to measure the heading angle and inclination of the vehicle. This sensor consists of two inclinometers manufactured by OMRON Co., Ltd. (Japan), three piezoelectric vibrating gyroscopes manufactured by Murata Manufacturing Company, Ltd. (Japan), and three 16-bit micro-controllers (H8S2612) manufactured by Renesas Technology Co., Ltd. (Japan). The cost of this system is about one tenth that of posture-measuring apparatus consisting of fiber optic gyro sensors. When the new sensor receives GPS position data in the NMEA-0183 GGA data format, the micro-controllers process them together with data from the inclinometers and gyroscopes then transfers data on the inclination-corrected position and the heading angle to the main computer. Although a piezoelectric vibrating gyroscope has larger drift than FOG, it is canceled according to GPS data.

This sensor was originally developed for tractors operating at a speed of more than 1 m/s. The operating speed of our rice transplanter is slower than that of a tractor and is less than 1 m/s; it is even slower when the vehicle is turning. The turning radius at the end of each row is around 2 m, and this is also smaller than that of a tractor. The data-processing software for the sensor was modified to adapt it to rice-transplanting operation. The data-output cycle was 5 Hz and the baud rate was set to 19,200 bps.

Previously, the inclination correction and gyro-sensor drift correction were processed by the main computer. The new sensor eliminates the need to process these corrections on the main computer. The sensor can also be reset by a command from the main computer.

2.1.3 Controllers

An embedded PC-104 computer with a 486-compatible 66-MHz central processing unit was used as the main computer. The operating system was PC-DOS 2000, and the control program was written in Turbo-C 4.0J. A main computer receives data on the position and heading angle from a low-cost posture sensor. It then calculates the control parameters and sends them to a KZ-350 PLC (programmable logic controller) manufactured by Keyence Co., Ltd. (Japan) through a parallel output port. The PLC receives control parameters from the main computer at 5 Hz and then controls the actuators. The PLC control program does not rely on timer interrupts, but is sequence controlled. The PLC control-loop timing was about 2 to 3 milliseconds.

2.1.4 Actuators

All actuators were connected to relays to permit the direction of movement and the speed to be controlled from the pulse width from the PLC. The steering angle was controlled by an 80-W DC geared motor and sensed by an absolute rotary encoder. The positions of the clutch and pedals were controlled by electrical linear cylinders and sensed by magnetic proximity sensors. The control lever of the transplanting instruments, the engine throttle lever, and HST control lever were controlled by electrical linear cylinders and their positions were measured by absolute rotary encoders

2.2 Long Mat-Type Hydroponic Seedlings

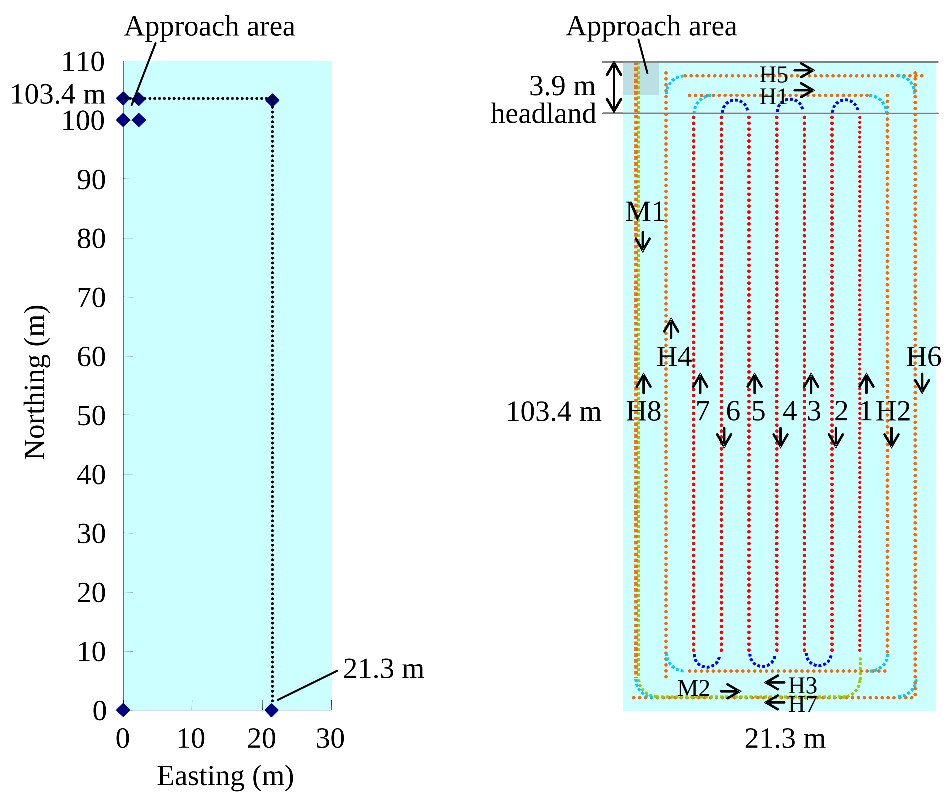
The size of a conventional rice seedling mat is about 60 cm long by 30 cm wide. The weight of one seedling mat is about 7 kg. When farmers operate with conventional-type rice seedling mats and a rice transplanter, they require 20 seedling mats for an area of 10 acres. Long mat-type hydroponic seedling mats are about 6 m long and 30 cm wide. Because they are cultured on 6 m long trays without soil, the weight of one 6 m length of seedling mat is 14 kg. When the seedling mat is set in a rice transplanter, it is rolled up and positioned in a holder on the rice-transplanting attachment.

2.3 Control Method

2.3.1 Path Planning

The desired traveling path was planned before the operation began. The traveling path was previously planned automatically by using four corner points of the square field measured by RTKGPS. Paddy fields, however, usually have an approach area on the inside. The size of this approach area is different for each field. The four corner points of the square field and the shape of the approach area were measured and the traveling path then was planned manually.

The paddy field in the trial was nearly rectangular in shape and it measured 103.4 m long by 21.3 m wide. The size of approach area was 2.6 m long and 2.1 m wide (fig. 3a).



a) Measured points b) Planned path

Figure 3. Measurements of the field and path planning.

The transplanting operation was performed along the longer side of the field. As the sowing width of the six-row rice transplanter was 1.8 m, 11 traverses along the longer side of the field were required. The width of the headland was set to 3.9 m, so this required two traverses. The rice transplanter moved through the approach area into the paddy field to reach the start point, where it began operating. The transplanter made seven straight passes and turns and finally traveled around the operating area twice and exited the field (fig. 3b).

2.3.2 Straight Control

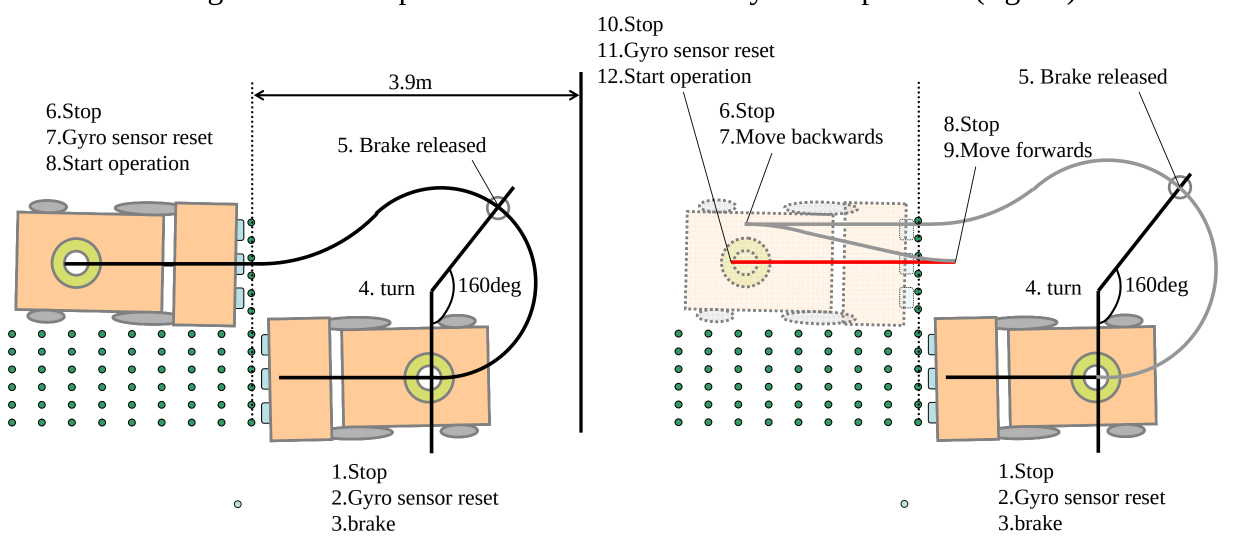
The rice transplanter must be driven along the planned path by controlling the steering to remain close to the desired path. If the deviation from the target line is d and the heading angle error is ψ, the aiming steering angle δ_{aim} is given by the equation

$$\delta_{aim} = \mathrm{Kp1}d + \mathrm{Kp}\psi \qquad (1)$$

where the values of K_{p1}, K_{p2} are decided by the speed of the vehicle.

2.3.3 U-Turn Control

At the headland, the rice transplanter has to turn to enter the next operating path. When it turned under muddy conditions, the turning radius was not constant, even if the steering angle and speed remained the same. Figure 4 shows the direction of turns made at the headland. When the rice transplanter reaches the edge of the field, it stops and the posture sensor is reset. While the rice transplanter is turning, the rice transplanter obtains only yaw-angle data from the gyro sensor. Because the turning radius is so small, the use of drift-corrected yaw angle data according to GPS data is not effective, and it is sufficiently short to permit the use of non-drift-corrected yaw-angle data during the 30 s or so required to make a turn. Until the yaw angle is more than 160°, the steering angle is kept at 40° and one side brake is applied. When the yaw angle becomes more than 160°, the rice transplanter is controlled to get back close to the next desired path. When a rice transplanter reaches a point 3.9 m from the edge of the field, it stops and the posture sensor is reset again. The transplanter then starts its next cycle of operation (fig. 4a).



a) U-turn without forward and backward motion b) U-turn with forward and backward motion

Figure 4. Turning control.

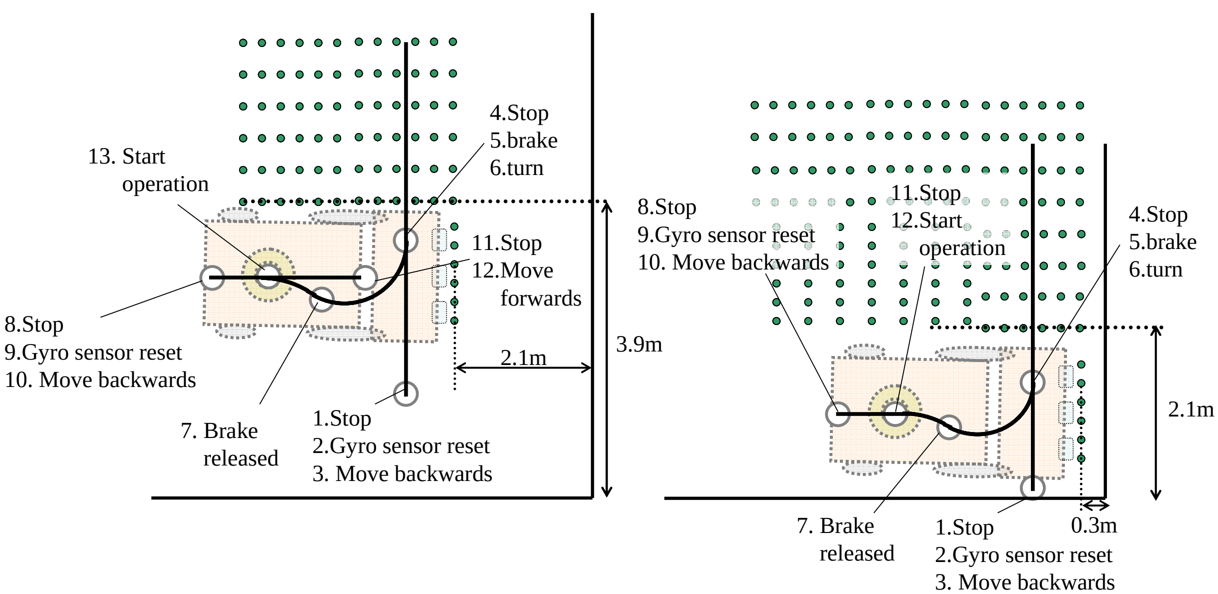
If the rice transplanter is not sufficiently close to the new desired path when it reaches the point 3.9 m point after turning, it moves backwards and the steering is controlled to get close to the desired path (fig. 4b).

2.3.4 Headland Control

After traveling seven times along the longer sides of the field, the automated rice transplanter operates in the headland. In the headland, the straight-control method is based on equation (1). Turning control at the corners was different to the usual U-turn control method described above.

In the traverse, when the automated rice transplanter reaches a point 3.9 m from the edge of the field, it stops and the posture sensor is reset. As the next desired path is too close to turn, the transplanter moves backwards 1 m before it starts to turn. Until the heading angle is over 80°, the steering angle is maintained at 40° and one side brake is applied. When the heading angle becomes more than 80°, the rice transplanter is controlled to get back close to the next desired path. It stops at a point 4.5 m from the edge of the field and the posture sensor is reset. The transplanter then moves backwards, stops when it reaches the edge of the field, and then moves forwards again; it starts transplanting operations when it reaches a point 2.1 m from the edge of the field. (fig. 5a).

In the second traverse, when the transplanter reaches the edge of the field, it stops and the posture sensor is reset. As there remains only a small space in which to turn, the transplanter moves backwards 1.2 m and then starts turning. The method for the right-angle turn is as same as the first path in the headland. After the right-angle turn, the transplanter stops 3 m from the edge of the field and the posture sensor is reset. The transplanter then moves backwards, stops when it reaches the edge of the field, and starts transplanting operation. (fig 5b).



a) First path b) Second path

Figure 5. Headland control.

2.4 Preparation of the Field

The experiment was conducted three days after paddling by using a 37.3 kW output tractor. The depth of the paddy was about 15 cm.

3. RESULTS

This automated rice transplanter was set near the approach area of the paddy field. When the program was started, it entered the field, transplanted the field and the entire headland, and then left the field.

Figure 6 shows the entire recorded path of the rice transplanter. These data are corrected for the effects of the vehicle inclination. Fully automated rice transplanting was successfully performed. The operating speed was 0.6 m/s and the machine took about 45 min to complete planting the entire field. The network RTKGPS operated well during the operation. At the path H6, highlighted by a blue circle, the path was distorted by 1.4 m to the right. Near this point, the data output from the posture sensor was abnormal. It was observable, that the automated rice transplanter set the steering angle according to the position data from the posture sensor, but the main computer sensed, that the data were abnormal and sent a reset signal. The data from the sensor then became normal and the transplanter traveled along the planned path. A U-turn without moving forwards and backwards was made only between the 3rd and 4th paths, and the transplanter took 35 s in turning: this is highlighted by a red circle. All the other U-turns required forward and backward movements, and each took more than 1 min.

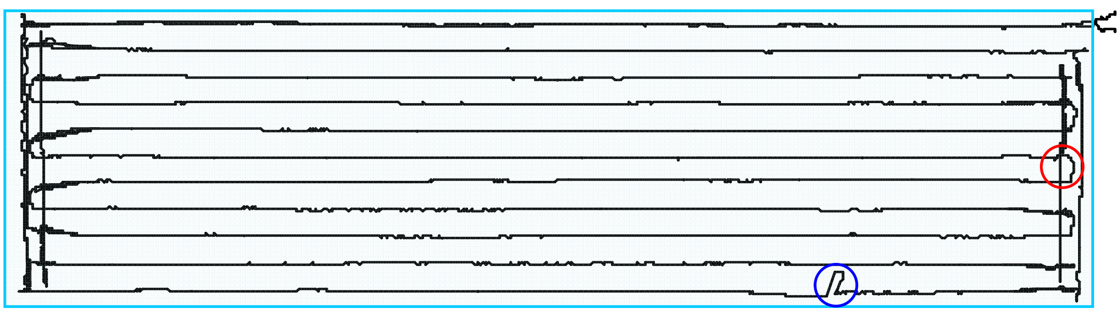


Figure 6. Recorded path of the automatic operation.

Table 1 shows a summary of the control achieved in terms of the parameters described by Yukumoto et al. (1998). M1 and M2 are the moving-only paths, 1 to 7 are the usual straight paths, and H1 to H8 are the paths in the headland.

The RMS deviation from the planned path was smallest (0.05 m) for the sixth path in the experiment. The maximum deviation was 0.11 m and the minimum was –0.09 cm. The mean deviation from the planned path was 0.03 m. The mean deviation from the planned path was less than –0.1 m in both the third and sixth paths. The headland paths H1, H3, H5, and H7 are along the short sides of the field. All except H6 showed RMS deviations that were larger than those along the long sides. The reasons for this are discussed below.

Table 1. Summary of the control.

Path number	M1	M2	1	2	3	4	5	6	7
Path width [m]	0.44	0.12	0.26	0.21	0.29	0.29	0.21	0.20	0.38
Deviation from the planned path, RMS [m]	0.09	0.03	0.08	0.06	0.13	0.15	0.06	0.05	0.09
Deviation from the planned path, mean [m]	-0.05	0.0	0.06	-0.03	-0.14	-0.12	0.04	0.03	0.01
Heading error [°]	0.13	0.49	0.87	0.87	0.59	0.62	0.37	0.73	0.54

Path number	H1	H2	H3	H4	H5	H6	H7	H8
Path width [m]	0.23	0.22	0.17	0.29	0.71	1.85	0.61	0.36
Deviation from the planned path, RMS [m]	0.07	0.06	0.10	0.06	0.17	0.20	0.14	0.08
Deviation from the planned path, mean [m]	0.04	0.04	-0.09	-0.01	-0.02	-0.05	-0.03	0.00
Heading error [°]	0.85	0.93	0.49	1.06	0.02	0.75	-0.03	0.59

4. DISCUSSION

A fully automated rice-transplanting operation was successfully conducted, but some problems still remain.

The first problem is related to straight control. In second, fifth, and sixth paths, the automated rice transplanter was controlled well in this experiment, but in the third and fourth paths, the mean deviations were more than –0.1 m and the automated rice transplanter was not controlled sufficiently well to travel along the path. This could be, because the 37.3 kW tractor had produced wheel tracks on the soft ground during the paddling operation. The tread width of the tractor and that of the rice transplanter are different, so the rice transplanter followed the wheel tracks of the tractor and could not get back to the planned path. Even when the deviation was more than 15 cm and the steering angle was set to 5°, it was hard to get the transplanter out of the wheel tracks of the tractor. Although the automated rice transplanter was well controlled in the second, fifth, and sixth paths, more precision is needed to obtain a path width of less than 0.1 cm RMS and a mean deviation of less than 0.05 m. There is a need to develop additional control methods.

The second problem is related to the control of the U-turns. The turning radius depends on the soil conditions. In this experiment, most of U-turns required forward and backward movements to be made. The automated rice transplanter makes wheel tracks on the ground as it moves. When it moved to backward, it moved along its own wheel tracks and it could not escape them. Control methods need to be developed, which are able to prevent traveling along wheel tracks.

The third problem is related to headland control. The paths H1, H3, H5, and H7 along the short sides of the field have a short distance. To improve the precision of operation over these short paths, turning control is important. When the heading angle and vehicle position are near the planned path, the precision of the operation could be improved.

The fourth problem is the stability of the posture sensor. When the output from the posture sensor was abnormal, the inclination data were also abnormal. This could be caused by data processing problems in the posture sensor, but it is difficult to diagnose what triggered the abnormal output. This sensor is cost effective for automated equipment. It needed each sensor diagnosis output and vehicle controller had to obtain it.

5. CONCLUSIONS

Several conclusions can be drawn from the trials of the automated rice transplanter. At first, fully automated rice-transplanting operation was achieved. The operator only needed to push a start button. Before operation, the travel path was planned from the shape of the field and the approach area. Secondly, as long mat-type hydroponic seedlings were used, there was no need to supply additional seedlings during the operation of the transplanter. And finally, the costs of the sensors were more than halved through the use of network RTKGPS and a low-cost posture sensor that worked well.

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