An Autonomous Rice Transplanter Guided by Global Positioning System and Inertial Measurement Unit

Yoshisada Nagasaka, Hidefumi Saito, Katsuhiko Tamaki, Masahiro Seki, Kyo Kobayashi, and Ken Taniwaki
Research Team for Farm Machinery and Systems
National Agricultural Research Center
Kannondai, Tsukuba
Ibaraki 3058666
Japan
e-mail: zentei@affrc.go.jp

Received 26 July 2008; accepted 22 January 2009

This paper reports the development of an automated rice transplanter guided by a global positioning system and an inertia measurement unit using the controller area network bus. The actuator control command and data communication protocols comply with the ISO 11783. The project aims to develop an autonomous agricultural system for operation in the paddy field. The automated rice transplanter presented in this paper is the first stage in achieving the project objective. This paper focuses on the development of sensor and main computer connections to the operating autonomous unit and the use of common control protocols for each of the automated machines. A simple steering control algorithm was used for straight traveling. The automated rice transplanter made a turn at the headland of the paddy field and moved to the next desired path. After 12 straight operations, the rms lateral deviation was observed to be less than 0.04 m and the rms heading angle error was less than 3.6 deg.

1. INTRODUCTION

With the increase in the average area operated by a single farmer in Japan, it is difficult to consolidate the fields. As a result, the fields remain dispersed. It is therefore necessary to develop an automated system that will permit a single operator to control a number of machines in several scattered fields. This is possible if automated control systems are utilized. In the DARPA Grand Challenge (Thrun et al., 2006) and the Urban Challenge (Urmson et al., 2008), autonomous vehicles were controlled with many sensors and multiple systems, but in agricultural robotics, studies have focused on farmland operation and used simple systems.

An automated rice transplanter was previously developed and tested (Nagasaka, Otani, Shigeta, & Taniwaki, 1999). The base vehicle was a PV14 six-row rice transplanter manufactured by Yanmar Corporation (Osaka, Japan). A real-time kinematic global positioning system (RTKGPS) was used to identify the location of the transplanter, and fiber-optic gyroscopic (FOG) sensors were used to measure its heading angle and inclination. As the wheelbase of the PV14 was longer than that of the usual rice transplanter, the turning radius was large, and it took more time to turn at the edge of the field. In 2002, the base vehicle was changed to a PH6 six-row rice transplanter manufactured by Iseki Corporation (Matsuyama, Japan) (Nagasaka, Taniwaki, Otani, & Shigeta, 2002). It had a shorter wheelbase than usual. One computer processed all data and controlled all actuators. In 2004, the PH6 was modified to improve its operating precision (Nagasaka, Umeda, Kanetai, Taniwaki, & Sasaki, 2004). The RTKGPS and FOG sensors were retained, but the vehicle control system was replaced with a programmable logic controller (PLC) for the precise control of the actuators. Until 2004, conventional rice seedlings were used in the automated rice transplanter, where 20 seedling mats were required to plant an area of 1,000 m^2. A six-row rice transplanter can carry 12 seedling mats at one time. Previously, seedlings had to be supplied during the transplanting operation, and this was a problem for a fully automated rice-transplanting operation. Long mat-type hydroponic rice seedlings were developed, which would eliminate the need to supply additional seedlings during the transplanting operation (Tasaka, 1998). The automated rice transplanter was therefore modified to add an appendage in order to carry these long-mat seedlings.

In 2005, a fully automated operation in a paddy field with an area of 0.3 ha (100 × 30 m) was carried out (Nagasaka et al., 2007), focused on rice-transplanting operations. Transplanting is just one farm operation involved in rice production. It is necessary to develop autonomous systems for paddy fields to increase the task efficiency of not only the rice-transplanting operation but also tillage, spraying, and harvesting. Several studies reported on tractors and combined harvester guidance systems. A tilling robot guided by a laser range finder (Matsuo, Yamamoto, & Yukumoto, 2002; Yukumoto & Matsuo, 1995), GPS-guided tractor (Bell, 2000; Gan-Mor, Clark, & Upchurch, 2007), laser sensor–guided tractor (Sutiarso et al., 2002; Takigawa, Sutiarso, Koike, Kurosaki, & Hasegawa, 2002), vision-guided tractor (Billingsley & Schoenfisch, 1997), stereo vision–guided tractor (Kise, Zhang, & Rovira-Más, 2005; Rovira-Más, Zhang, & Reid, 2004, 2008), vision and laser radar–guided tractor (Subramanian, Burks, & Arroyo, 2006), 2D scanner–guided tractor between orchard trees (Barawid, Mizushima, Ishii, & Noguchi, 2007), vision-guided combine harvester (Benson, Reid, & Zhang, 2003), GPS-guided combine harvester (Coen, Vanrenterghem, Saeys, & De Baerdemaeker, 2008), and GPS-guided combine harvester (Iida & Yamada, 2006) were developed. There are studies about tractor implement control (Leemans & Destain, 2007; Tellaechea, BurgosArtizzub, Pajaresc, Ribeirob, & Fernández-Quintanillad, 2008; Tian, Reid, & Hummel, 1999).

Relatively few studies have been carried out on rice-transplanting operations (Chen, Tojo, & Watanabe, 2003; Kaizu & Imou, 2008).

In Japan, agricultural machinery such as rice transplanters, combine harvesters, and tractors are operated for only a short period in a year. When sensors, computers, and actuators communicate by the same protocol, each machine can share the sensors and computers with the other machines and the total system cost can be reduced.

In summary, the goal of our project is to develop an autonomous rice production system in paddy fields. In this study, an automated rice transplanter using the controller area network (CAN) bus for sensor and actuator communication was developed according to the ISO 11783 (SAE J1939) protocols (SAE, 2001). There was a study about autonomous tractor control using the CAN bus (Darr, Strombaugh, & Shearer, 2005). A new rice transplanter was modified to test the common control protocol. The design of the automated rice transplanter and its experimental result are reported in this paper.

2. HARDWARE

2.1. An Automated Rice Transplanter

The base unit of the rice transplanter was a SPU650 six-row rice transplanter, manufactured by Kubota Corporation (Osaka, Japan). It was equipped with an 11-kW, a 0.4-L engine, hydrostatic transmission (HST), a rugged rubber tire suitable for paddy terrain, and a transplanting instrument for the long-mat–type hydroponic seedlings. Transplanting instrument control was automated through a microprocessor unit onboard the vehicle.

Modifications were made to the rice transplanter for the automation task (Figure 1). A geared servomotor that output 36-Nm torque was attached to the steering system of the front wheels. The motor output was fed through a 1:2 speedup gear because rotation speed was too low for the steering control, thereby producing an 18-Nm torque on the steering rack. An absolute rotary encoder was connected to the steering axle to sense the steering angle (Figure 2). Another servomotor was installed in the engine bay and

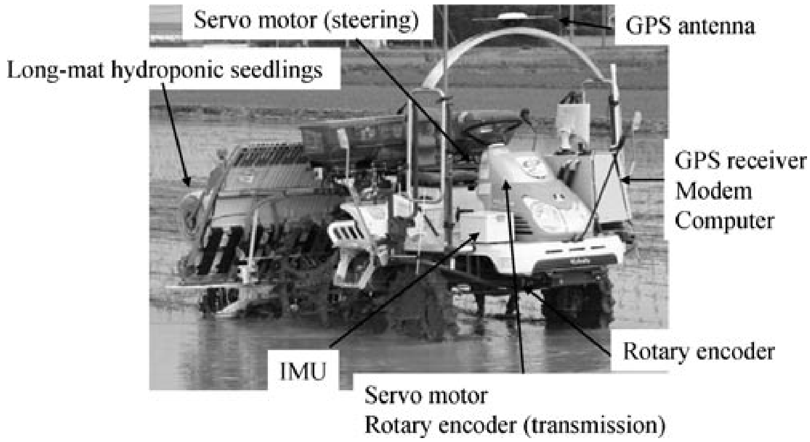

Figure 1. The automated rice transplanter.

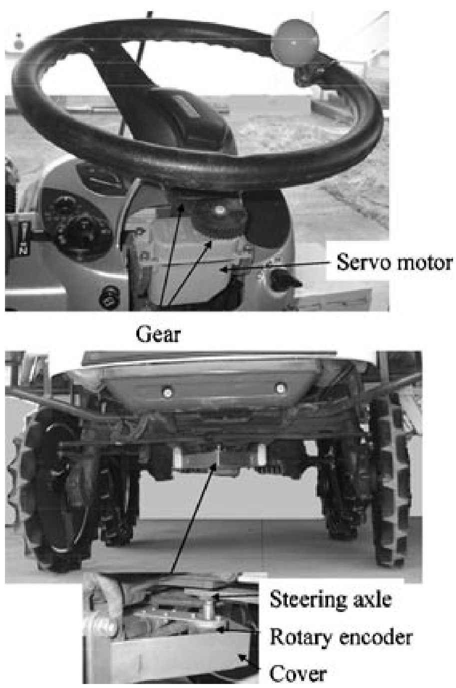

Figure 2. Steering servo and rotary encoder.

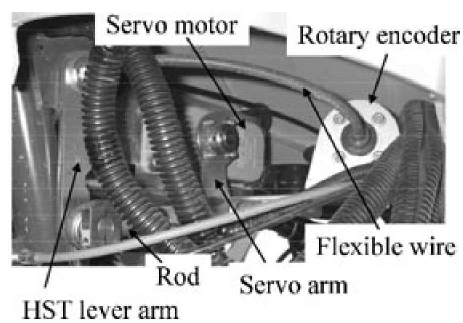

Figure 3. Transmission servo and rotary encoder.

attached to the transmission to actuate the HST lever. The motor output was fed to the rod link, thereby producing a 45-N force on the HST lever. An absolute rotary encoder was connected to the HST lever axle to measure the HST lever position (Figure 3). All of the servos were directed by the microcontrollers, which communicated with a main computer via the CAN bus. The transplanting depth and horizontal level were controlled by a vehicle microprocessor, which controls the lifting-up and down switch to start or stop the transplanting operation, respectively.

2.2. Electrical Power System

The SPU650 was equipped with a generator and two charged 12-V vehicle batteries during operation. Power for the actuators, sensors, computer, and microcontrollers was provided by vehicle batteries. Excluding that for the actuators, the power was conditioned by dc–dc converters and provided 5, 12, and 24 V dc, as shown in Figure 4.

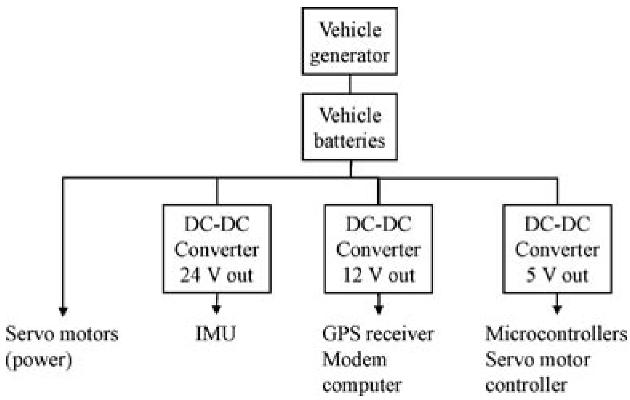

Figure 4. Electrical power system.

2.3. Electronics

Figure 5 shows the schematic of the automated rice-transplanting system. The sensors, actuators, controllers, and the main computer are connected to the CAN bus. The sensors and the main computer were designed so that they could easily be disconnected. The ISO 11783 protocol was used for communicating among the nodes.

2.4. Sensors

An MS750 GPS receiver, manufactured by Trimble Navigation, Ltd. (Sunnyvale, California), was used to locate the vehicle position (Figure 6, right). The measuring accuracy is 0.02 m. The GPS antenna was set over the front axle. The antenna was 2 m high from the ground surface when the rice transplanter was put on the level ground. The GPS position data output cycle was 10 Hz, and the data were transferred to the CAN bus. This GPS receiver had a CAN interface based on the SAE J1939 standard. However, it did not have a GPS-quality indication output through the CAN interface. A GPS node equipment control

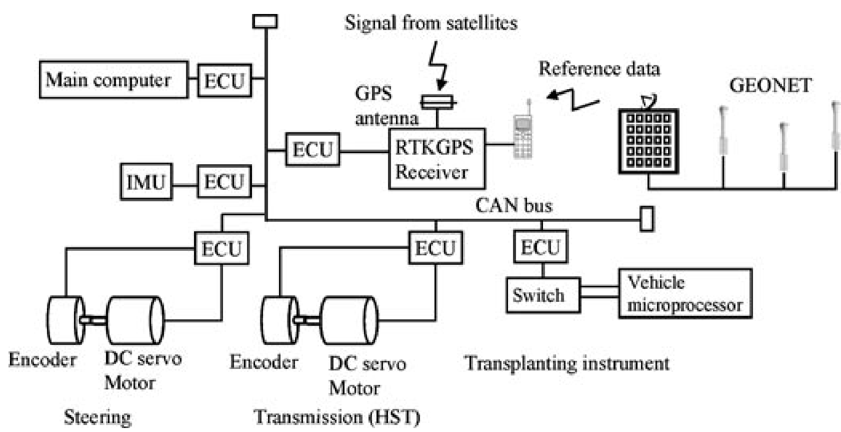

Figure 5. Schematic of the automated rice-transplanting system.

Figure 6. The GPS receiver (right) and modem (left).

unit (ECU) converted the RS232 NMEA0183 format to the CAN protocol RS232C; the serial baud rate was set to 19,200 bits per second (bps), and the CAN bus baud rate was set to 250 kbps.

A GPS receiver mounted on the automated rice transplanter received reference data from a network-based reference station. The Japanese Geographical Survey Institute (GSI) permits GPS-based control stations to use real-time data from the GPS Earth Observation Network system (GEONET). Jenoba Co., Ltd. (Tokyo, Japan), processed the data of GEONET and delivered the reference data every second in the RTCM format through packet communication. The GPS reference data were received using a CPTrans-ST/J modem manufactured by the Hitachi Industrial Equipment Systems Co., Ltd. (Tokyo, Japan) (Figure 6, left). The baud rate for modem communication was set to 38,400 bps.

The GPS position data need to be verified to determine the inclination of the vehicle in paddy fields. JCS-7401A, an inertial measurement unit (IMU) manufactured by Japan Aviation Electronics Ind., Ltd. (Tokyo, Japan), was used to measure the roll, pitch, and heading angle (Figure 7). This sensor has analog and RS232C serial data outputs. Therefore, a microcontroller board was used to convert the RS232 binary format to the CAN protocol RS232C; the serial baud rate was set to 19,200 bps.

Figure 7. The IMU.

2.5. The Main Computer and the Microcontroller Unit

A ULV Celeron 400-MHz central processing unit with CAN interface, manufactured by Interface Corporation (Hiroshima, Japan), 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 microcontroller board was developed as an ECU to transfer the sensor data to the CAN bus and to receive the commands from the main computer to control actuators. Figure 8 shows the microcontroller board. The main processor was the PIC18F458, produced by Microchip Technology, Inc. (Chandler, Arizona). It had a CAN, serial, 10-bit A/D, digital I/O interface. Microcontroller boards were programmed on a CCS-C compiler.

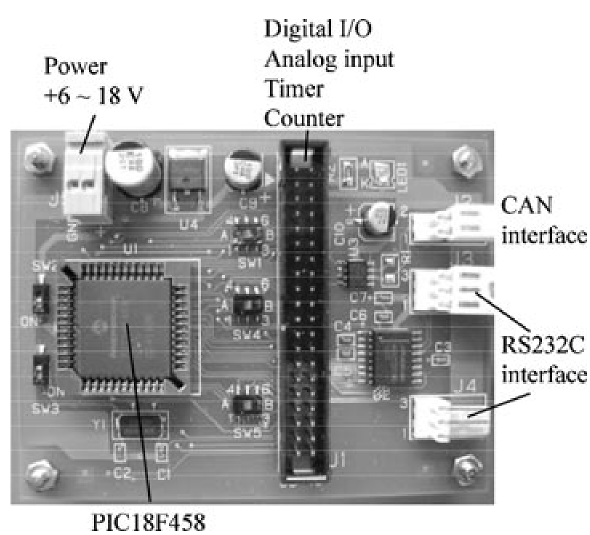

Figure 8. The microcontroller board developed for the automated rice transplanter.

The main computer received data from the GPS and IMU nodes. It then calculated the control parameters based on the given reference trajectory. It also recorded GPS position data, GPS speed data, IMU data, and inclination-corrected position data to the internal solid-state disk. The resulting actuator commands were then sent to the actuator node through the CAN bus at 10-Hz frequency. Each actuator node received the control parameters from the main computer at 10 Hz and then controlled the actuators at 10 Hz.

3. SOFTWARE

3.1. Experimental Field and Path Planning

The desired traveling path was planned before the operation began. The field was located in the Furukawa agricultural experiment station. The paddy field used in the trial was almost rectangular in shape, with a length of 108.4 m and width of 25.3 m. The soil puddling was made 2 days before the transplanting operation.

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, it traverses the longer side of the field 14 times. In this experiment, it was planned to create two sets of six straight paths, as shown in Figure 9.

The four corners A, B, C and D in the field were measured with RTKGPS in advance of the experiment. The latitude and longitude of each corner point were stored in the main computer of the rice transplanter. Then the first operating path, line segment $P_{11}P_{12}$, was planned. Line segment $P_{11}P_{21}$ and line segment AB were parallel at intervals of 2.7 m. Point P_{11} was on line segment AD, and P_{21} was on line segment BC. From the second to sixth operating path, line segment $P_{1i}P_{2i}$ and line segment $P_{1i-1}P_{2i-1}$ were parallel at intervals of 1.8 m. Start point P_{s1} and end point P_{e1} were set at 4-m extensions of line segment $P_{11}P_{21}$ and $P_{16}P_{26}$. Points P_{1i}, P_{2i}, P_{sj}, and P_{ej} were computed from points A, B, C, and D.

3.2. Control Methods

The function of the control program includes the navigation and control of the automated rice transplanter

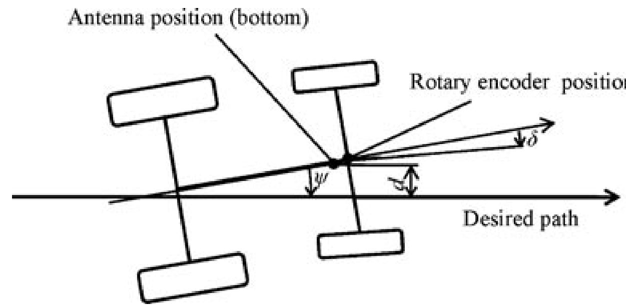

Figure 10. The deviation from the desired path (d) and the heading angle error (ψ).

to accomplish the following:

- move into the paddy field
- carry out the straight-line traverse operation
- carry out turns
- perform the repetition of straight operations and turns
- move out of the paddy field

3.2.1. Steering Control (Straight)

The rice transplanter was guided along the planned path by controlling its steering. By denoting the deviation from the desired path as d and the heading angle error as ψ, as shown in Figure 10, the steering angle δ_{aim} is given by the following equation:

$$\delta_{\mathrm{aim}} = K_{p1}d + K_{p2}\psi. \tag{1}$$

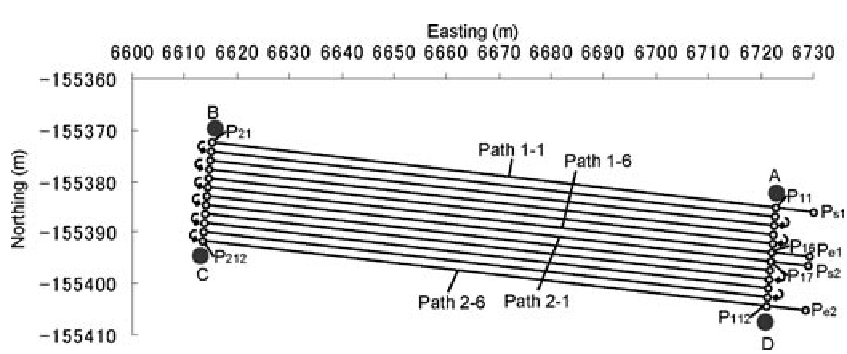

Figure 9. Planned operating path.

In this study, the steering control parameters were obtained experimentally. The values of K_{p1} and K_{p2} were determined as follows:

in case of $|d| < 0.06$, then $K_1 = 0.07$, $K_2 = 0.4$
in case of $0.06 \leq |d| < 0.12$, then $K_1 = 0.10$, $K_2 = 0.3$
in case of $|d| \geq 0.12$, then $K_1 = 0.29$, $K_2 = 0.1$

3.2.2. Speed Control

The traveling speed of the rice transplanter was controlled according to the position of the transplanting finger. Figure 11 shows the speed-control strategy of the automated rice transplanter in a paddy field. When the distance between the transplanting finger and the edge of the field, L_f, exceeded 8 m in a high-speed area, the HST lever was set to a speed of 0.7 m/s. When L_f was between 4.2 and 8 m (a low-speed area), the HST lever was set to a speed of 0.3 m/s. When L_f reached 4.2 m, the operation was stopped.

When the measured value of the encoder was T_{enc} radian and the encoder value of desired position was T_{des} radian, the servomotor was controlled as follows:

in case of $T_{enc} < T_{des} - 0.009$,
  if $T_{des} - T_{enc}$, <0.017, then servomotor pulse width modulation (PWM) duty was 100%,
  else servomotor PWM duty was 70%

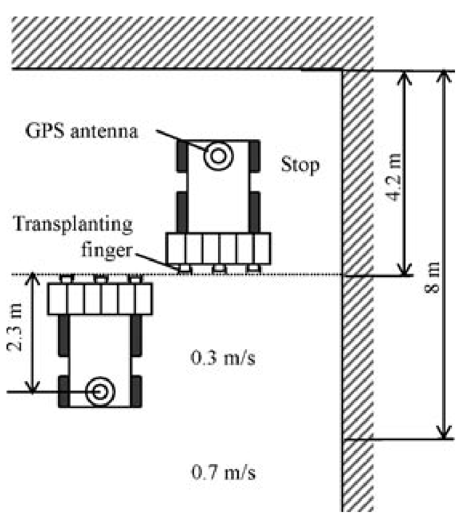

Figure 11. Speed according to position.

in case of $T_{des} - 0.009 \leq T_{enc} \leq T_{des} + 0.009$, then servomotor was stopped
in case of $T_{enc} > T_{des} + 0.009$,
  if $T_{enc} - T_{des}$, >0.034, then servomotor PWM duty was 100%,
  else servomotor PWM duty was 70%

In this study, PWM duty and threshold value were determined experimentally.

3.2.3. Turn Control

The rice transplanter had to turn at the headland to enter the subsequent traverse path. When it turned under muddy conditions, the turning radius was not constant, even when the steering angle and speed remained constant. Figure 12 shows the direction of the turns made at the headland. The rice transplanter stopped on reaching the edge of the field, and the IMU heading angle was set to 0 deg. While the rice transplanter was turning, the main computer obtained only the heading angle data from the IMU. Whereas the yaw angle is less than 170 deg, the steering angle was maintained at 40 deg. When the yaw angle exceeded 170 deg, the rice transplanter was set to stop and move backward. While moving backward, the steering was controlled to achieve and maintain a heading angle of 180 deg. When the transplanting fingers reached the edge of the field, it stopped and the main computer added 180 deg to the heading angle. Then it moved to the starting point of the new traverse path.

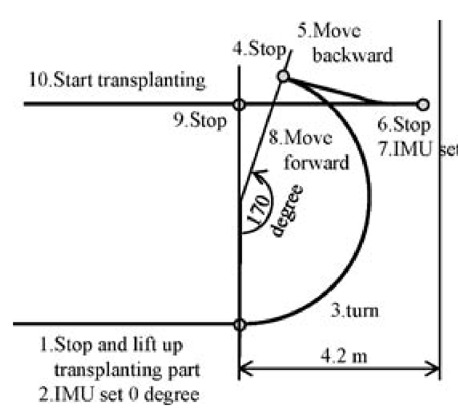

Figure 12. The turn control strategy.

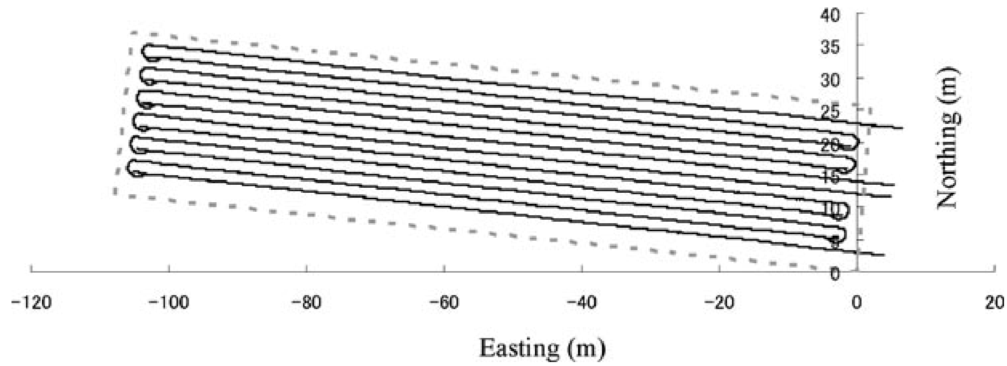

Figure 13. The recorded path of the automated rice-transplanting operation.

4. RESULTS AND DISCUSSION

4.1. Results

Figure 13 shows the entire recorded path of the rice transplanter. In this figure, the southeast corner of the rice paddy field was set as a local origin.

Table I shows the summary of the tracking performance of the automated operation. The rms lateral deviation from the desired operating path was observed to be less than 0.04 m, and the heading angle rms error was 3.6 deg or less. The mean lateral deviation from the planned path was found to be no larger than 0.03 m, and the mean heading angle error was no larger than 3.4 deg.

Figure 14 shows the frequency distribution of the lateral deviation. In Table II, more than 90% of the measured points on the traveled path were located within 0.06 m of the desired path. Table III shows the lateral deviation from the planned path at the starting positions. The lateral deviations at the starting points of paths 1–5, 1–6, 2–2, and 2–4 were more than 0.06 m. Others were 0.06 m or less.

Figure 15 shows the speed control results for each path. It was measured with GPS. The operating speed was between 0.68 and 0.78 m/s in the high-speed operation area and between 0.28 and 0.35 m/s in the low-speed area at the beginning of each operation; however, the speed was between 0.48 and 0.55 m/s at the end of each operation.

4.2. Discussion

From Table I, the absolute value of lateral deviation from the desired operating path was less than 0.1 m.

Table I. Summary of the automated operation.

	Lateral deviation (m)					Heading angle error (deg)				
Path no.	Max	Min	Mean	rms	Std	Max	Min	Mean	rms	Std
1–1	0.07	−0.08	−0.01	0.03	0.02	0.6	−2.7	−1.2	1.3	0.6
1–2	0.10	−0.03	0.03	0.04	0.02	2.7	−1.2	0.8	1.1	0.6
1–3	0.07	−0.07	0.01	0.03	0.02	3.0	−1.4	0.6	1.0	0.5
1–4	0.04	−0.07	−0.02	0.03	0.02	4.5	0.5	2.7	2.9	0.7
1–5	0.08	−0.09	0.02	0.03	0.02	4.6	−1.4	1.9	2.1	0.8
1–6	0.11	−0.10	−0.01	0.03	0.03	5.3	−1.5	2.2	2.5	0.9
2–1	0.07	−0.08	−0.02	0.03	0.02	5.9	0.6	3.1	3.2	0.7
2–2	0.09	−0.08	0.00	0.04	0.03	5.6	0.0	2.7	2.9	0.9
2–3	0.07	−0.10	0.01	0.04	0.03	4.3	−1.6	1.4	1.7	0.8
2–4	0.09	−0.08	−0.01	0.03	0.03	4.1	−1.2	1.5	1.9	0.9
2–5	0.08	−0.10	−0.01	0.04	0.03	6.8	0.3	3.0	3.2	0.9
2–6	0.08	−0.07	0.00	0.03	0.03	6.0	0.4	3.4	3.6	1.0

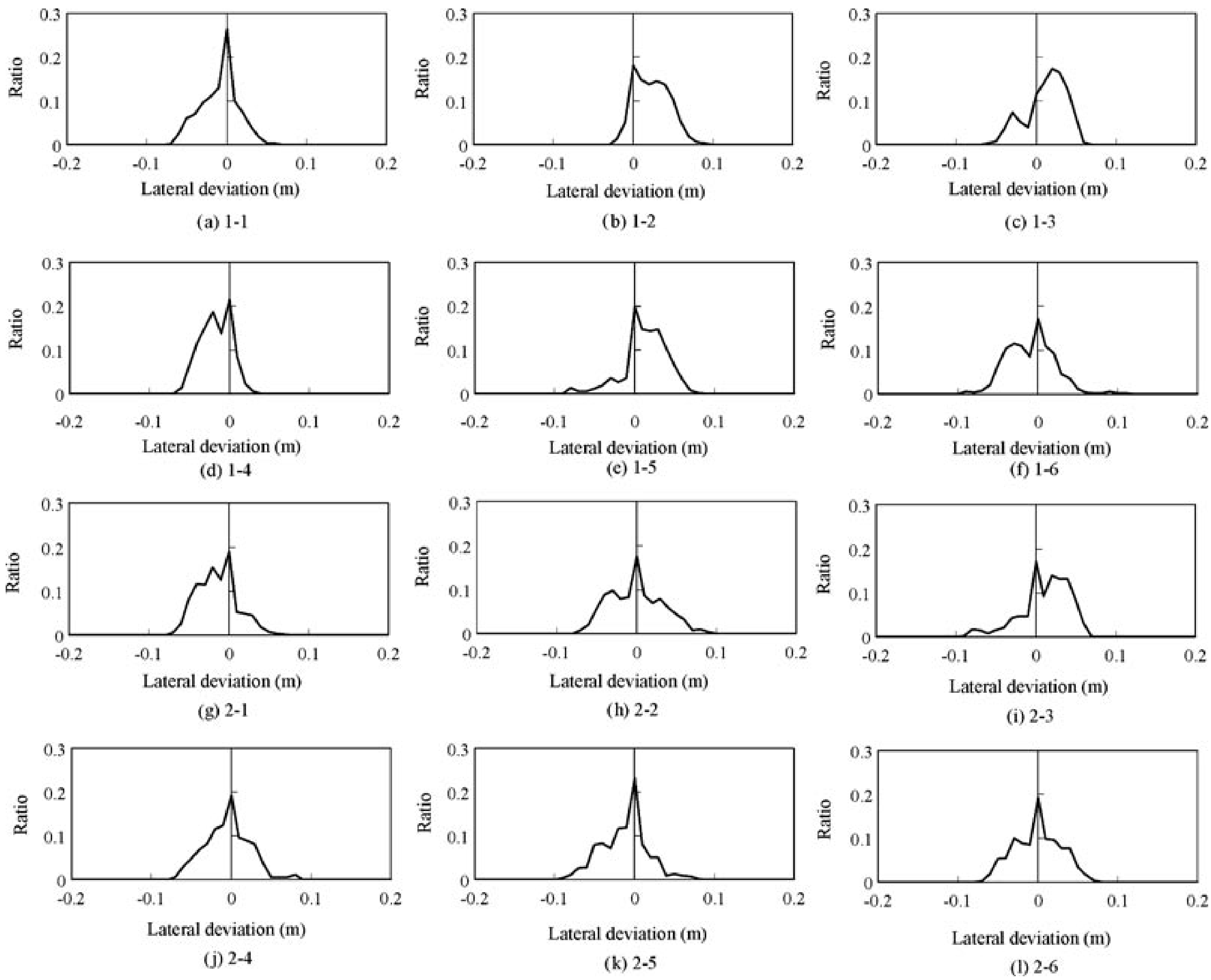

Figure 14. The frequency distribution of the lateral deviation in each path.

As common row spacing of rice plants is 0.3 m in Japan, it was observed that the plant rows did not cross each other in this operation. Thus, the performance of this automated rice transplanter could be good enough for a transplanting operation.

Figure 16 shows the performance of a skilled operator (Nagasaka, 2008). In this test, the skilled operator drove the rice transplanter manually and recorded the operating path. A skilled operator was found to operate the rice transplanter with an rms lateral deviation of 0.03 m or less, maintaining the difference between the maximum and minimum at no greater than 0.12 m. In this experiment, the results observed from paths 1 to 4 were comparable to that of a skilled operator. The rms lateral deviation was found to be 0.03 m, and the difference between the maximum and minimum was 0.11 m. The rms lateral deviations of other paths were 0.03 or 0.04 m, and the difference between the maximum and minimum was observed to be between 0.13 and 0.21 m.

As shown in Table II, the ratio of deviation less than 0.06 m from the desired path was observed to be no less than 96% on paths 1–1, 1–3, 1–4, 2–1, and 2–6. In Table III, the lateral deviations from the desired path at the operation starting positions in the above-mentioned paths were no greater than 0.06 m.

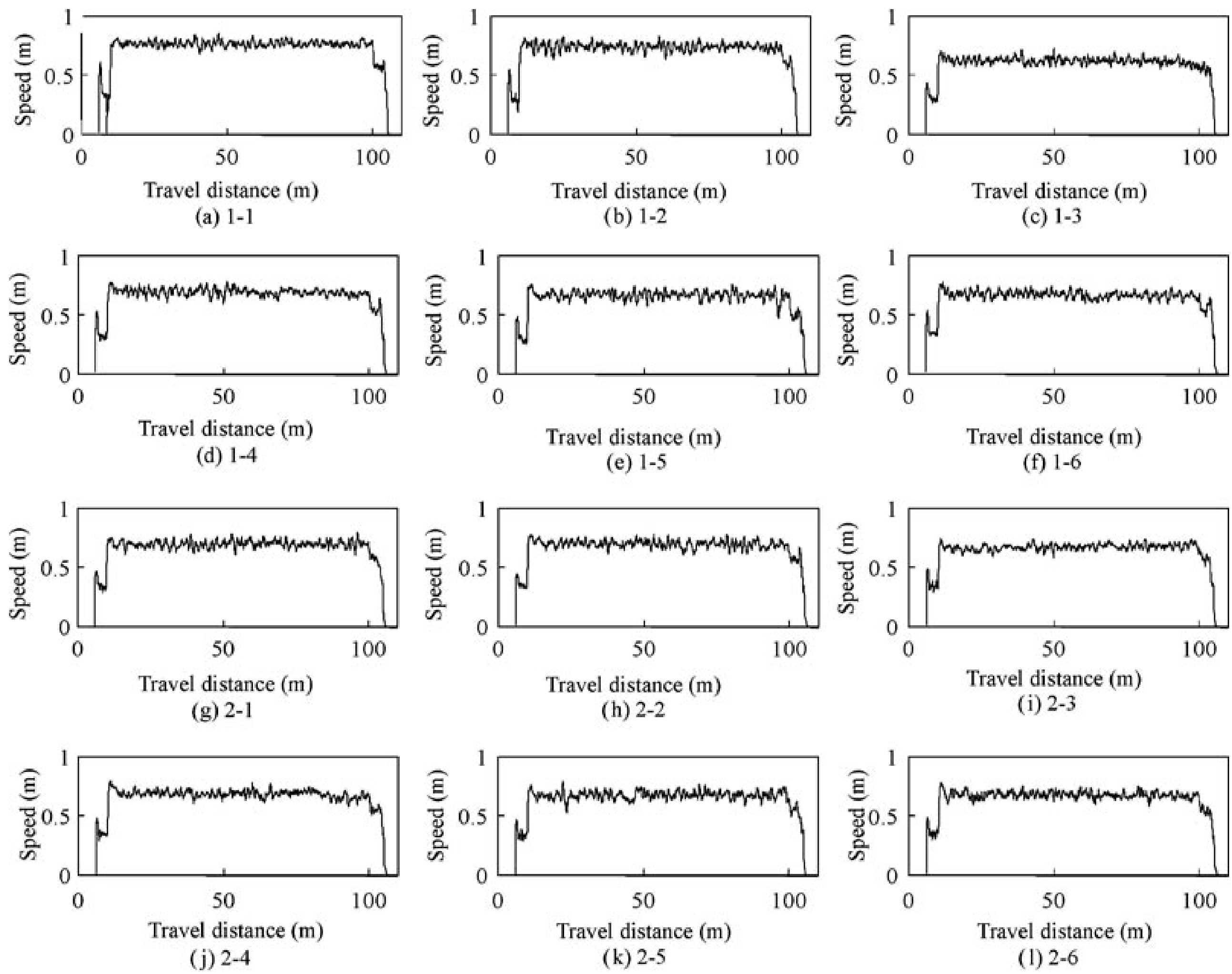

Figure 15. The speed conrol results for each path.

As can be seen in Table I, the difference between the maximum and minimum lateral deviations was 0.15 m or less and for the heading angle error was less than 5.0 deg.

As shown in Figure 15, the difference between desired and real speeds was less than 0.1 m/s in a high-speed area. In the low-speed area of the end, the difference was more than 0.2 m/s. The HST lever offered resistance to the motion when the lever was set between the 0- and 0.5-m/s speed area. When the rice transplanter speed was reduced, the PWM duty was set to 70% even though the error remained 0.034 radian. It is necessary to improve the transmission control algorithm or to reduce HST lever resistance to the motion.

The precision in rice transplanting influences the required precision in other operations such as weeding, spraying, and harvesting. For weeding and spraying, a vehicle must be driven between the crop rows. The distance between the crop rows is 0.3 m. If the rice crop row is sufficiently straight, then an efficient weeding and spraying operation can be carried out, thereby minimizing the damage to the plants. For harvesting, a combined harvester must follow the crop rows. When the lateral deviation is small, then the harvester can be driven smoothly.

Table II. Ratio of the deviation less than 0.06 m from desired path.

Path number	Ratio (%)
1–1	97
1–2	92
1–3	99
1–4	99
1–5	93
1–6	95
2–1	96
2–2	92
2–3	93
2–4	94
2–5	91
2–6	96

Table III. Lateral deviation from the desired path at the starting position of the operation.

Path number	Lateral deviation (m)
1–1	−0.04
1–2	0.05
1–3	0.06
1–4	0.01
1–5	−0.08
1–6	0.08
2–1	0.03
2–2	0.09
2–3	−0.03
2–4	0.09
2–5	−0.02
2–6	0.06

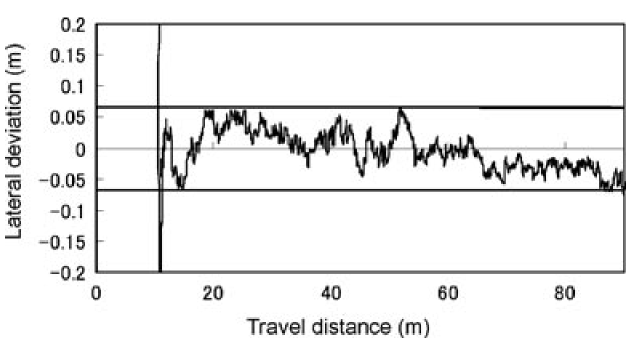

Figure 16. A path that a skilled operator drove a rice transplanter manually.

5. CONCLUSIONS

An automated rice transplanter using the CAN bus was developed, and an experiment on the automated operation was conducted. A single CAN bus line was demonstrated to provide sufficient performance for a small system such as this automated rice transplanter.

The rms lateral deviation from the desired path was found to be no greater than 0.04 m, and the mean lateral deviation was 0.03 m or less at an operating speed of around 0.7 m/s. More than 90% of the measured points on the traveled path were located within 0.06 m of the desired path. The tracking performance of the automated rice transplanter was observed to be comparable to that of a skilled operator in two paths of operation. In the other 10 paths, the tracking performance was worse than that of a skilled operator but could provide sufficient accuracy during rice transplanting. However, for spraying and mechanical weeding operations after rice transplanting, more precise operations would be required to ensure minimal plant damage and smooth operation. In this study, a simple proportional controller was used for steering control. Other control algorithms need to be developed for more precise operations in order to perform automated weeding or spraying.

ACKNOWLEDGMENTS

Kubota Corporation provided the base rice transplanter for this research.

REFERENCES

Barawid, O. C., Jr., Mizushima, A., Ishii, K., & Noguchi, N. (2007). Development of an autonomous navigation system using a two-dimensional laser scanner in an orchard application. Biosystems Engineering, 96(2), 139–149.

Bell, T. (2000). Automatic tractor guidance using carrier-phase differential GPS. Computers and Electronics in Agriculture, 25(1/2), 53–66.

Benson, E. R., Reid, J. F., & Zhang, Q. (2003). Machine vision-based guidance system for an agricultural small-grain harvester. Transactions of the ASAE, 46(4), 1255–1264.

Billingsley, J., & Schoenfisch, M. (1997). The successful development of a vision guidance system for agriculture. Computers and Electronics in Agriculture, 16, 147–163.

Chen, B., Tojo, S., & Watanabe, K. (2003). Machine vision-based guidance system for automatic rice transplanters. Applied Engineering in Agriculture, 19(1), 91–97.

Coen, T., Vanrenterghem, A., Saeys, W., & De Baerdemaeker, J. (2008). Autopilot for a combine harvester. Computers and Electronics in Agriculture, 63, 57–64.

Darr, M. J., Stombaugh, T. S., & Shearer, S. A. (2005). Controller area network based distributed control for autonomous vehicles. Transactions of the ASAE, 48(2), 479–490.

Gan-Mor, S., Clark, R. L., & Upchurch, B. L. (2007). Implement lateral position accuracy under RTK-GPS tractor guidance. Computers and Electronics in Agriculture, 59, 31–38.

Iida, M., & Yamada, Y., (2006, September). Rice harvesting operations using an autonomous combine harvestor with a GPS and FOG. Paper presented at the the Automation Technology for Off-road Equipment, Bonn, Germany.

Kaizu, Y., & Imou, K. (2008). A dual-spectral camera system for paddy rice seedling row detection. Computers and Electronics in Agriculture, 63, 49–56.

Kise, M., Zhang, Q., & Rovira-Más, F. (2005). A stereovision-based crop row detection method for tractor-automated guidance. Biosystems Engineering, 90(4), 357–367.

Leemans, V., & Destain, M. F. (2007). A computer-vision based precision seed drill-guidance assistance. Computers and Electronics in Agriculture, 59, 1–12.

Matsuo, Y., Yamamoto, S., & Yukumoto, O. (2002, July). Development of tilling robot and operation software. Paper presented at the Automation Technology for Offroad Equipment, Chicago, IL.

Nagasaka, Y. (2008). Development of an automated rice transplanter. Unpublished Ph.D. thesis, Kyoto University, Kyoto, Japan.

Nagasaka, Y., Kitagawa, H., Mizushima, A., Noguchi, N., Saito, H., & Kobayashi. K. (2007). Unmanned rice-transplanting operation using a GPS-guided rice transplanter with long mat-type hydroponic seedlings. Agricultural Engineering International: the CIGR Ejournal, Vol. IX, ATOE 07 008.

Nagasaka, Y., Otani, R., Shigeta, K., & Taniwaki, K. (1999, July). An automated rice transplanting in paddy fields. ASAE, Toronto, ON (ASAE Paper 99–1045).

Nagasaka, Y., Taniwaki, K., Otani, R., & Shigeta, K. (2002). An automated rice transplanter with RTKGPS and FOG. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Manuscript PM 01 003. Vol. IV.

Nagasaka, Y., Umeda, N., Kanetai, Y., Taniwaki, K., & Sasaki, Y. (2004). Autonomous guidance for rice transplanting using global positioning and gyroscopes. Computers and Electronics in Agriculture, 43(3), 223–234.

Rovira-Más, F., Zhang, Q., & Reid, J. F. (2004). Automated agricultural equipment navigation using stereo disparity images. Transactions of the ASAE, 47(4), 1289–1300.

Rovira-Más, F., Zhang, Q., & Reid, J. F. (2008). Stereo vision three-dimensional terrain maps for precision agriculture. Computers and Electronics in Agriculture, 60, 133–143.

SAE. (2001). Truck and Bus Control and Communication Network Standards Manual. Warrendale, PA: Society of Automotive Engineers, Inc.

Subramanian, V., Burks, T. F., & Arroyo, A. A. (2006). Development of machine vision and laser radar based autonomous vehicle guidance systems for citrus grove navigation. Computers and Electronics in Agriculture, 53, 130–143.

Sutiarso, L., Kurosaki, H., Takigawa, T., Koike, M., Yukumoto, O., & Hasegawa H. (2002). Trajectory control and its application to approach a target: Part II. Target approach experiments. Transactions of the ASAE, 45(4), 1199–1205.

Takigawa, T., Sutiarso, L., Koike, M., Kurosaki, H., & Hasegawa, H. (2002). Trajectory control and its application to approach a target: Part I. Development of trajectory control algorithms for an autonomous vehicle. Transactions of the ASAE, 45(4), 1191–1197.

Tasaka, K. (1998, September). Outline of raising and transplanting technology for long mat type hydroponic rice seedlings. Paper presented at EurAgEng, Oslo, Norway.

Tellaechea, A., BurgosArtizzub, X. P., Pajaresc, G., Ribeirob, A., & Fernández-Quintanillad, C. (2008). A new vision-based approach to differential spraying in precision agriculture. Computers and Electronics in Agriculture, 60, 144–155.

Thrun, S., Montemerlo, M., Dahlkamp, H., Stavens, D., Aron, A., Diebel, J., Fong, P., Gale, J., Halpenny, M., Hoffmann, G., Lau, K., Oakley, C., Palatucci, M., Pratt, V., Stang, P., Strohband, S., Dupont, C., Jendrossek, L.-E., Koelen, C., Markey, C., Rummel, C., van Niekerk, J., Jensen, E., Alessandrini, P., Bradski, G., Davies, B., Ettinger, S., Kaehler, A., Nefian, A., & Mahoney, P. (2006). Stanley: The robot that won the DARPA Grand Challenge. Journal of Field Robotics, 23(9), 661–692.

Tian, L., Reid, J. F., & Hummel, J. W. (1999). Development of a precision sprayer for site-specific weed management. Transactions of ASAE, 42(4), 893–900.

Urmson, C., Anhalt, J., Bagnell, D., Baker, C., Bittner, R., Clark, M. N., Dolan, J., Duggins, D., Galatali, T., Geyer, C., Gittleman, M., Harbaugh, S., Hebert, M., Howard, T. M., Kolski, S., Kelly, A., Likhachev, M., McNaughton, M., Miller, N., Peterson, K., Pilnick, B., Rajkumar, R., Rybski, P., Salesky, B., Seo, Y.-W., Singh, S., Snider, J., Stentz, A., Whittaker, W., Wolkowicki, Z., Ziglar, J., Bae, H., Brown, T., Demitrish, D., Litkouhi, B., Nickolaou, J., Sadekar, V., Zhang, W., Struble, J., Taylor, M., Darms, M., & Ferguson D. (2008). Autonomous driving in urban environments: Boss and the Urban Challenge. Journal of Field Robotics, 25(8), 425–466.

Yukumoto, O., & Matsuo, Y. (1995, June). Research on autonomous land vehicle for agriculture, Paper presented at the International Symposium on Automation and Robotics in Bioproduction and Processing, Kobe, Japan.