Controller for Single Line Tracking Autonomous Guidance Vehicle Using Machine Vision

B. S. Shin, Y. D. Choi, Y. Ying

Abstract: AMachine vision is a promising tool for the autonomous guidance of farm machinery. Conventional CCD camera for the machine vision needs a desktop PC to install a frame grabber, however, a web camera is ready to use when plugged in the USB port. A web camera with a notebook PC can replace existing camera system. Autonomous steering control system of this research was intended to be used for combine harvester. If the web camera can recognize cut/uncut edge of crop, which will be the reference for steering control, then the position of the machine can be determined in terms of lateral offset and heading angle. In this research, a white line was used as a cut/uncut edge of crop for steering control. Image processing algorithm including capturing image in the web camera was developed to determine the desired travel path. An experimental vehicle was constructed to evaluate the system performance. Since the vehicle adopted differential drive steering mechanism, it is steered by the difference of rotation speed between left and right wheels. According to the position of vehicle, the steering algorithm was developed as well. Evaluation tests showed that the experimental vehicle could travel within an RMS error of 0.8cm along the desired path at the ground speed of 9～41 cm/s. Even when the vehicle started with initial offsets or tilted heading angle, it could move quickly to track the desired path after traveling 1.52～3.5 m. For turning section, i.e., the curved path with curvature of 3 m, the vehicle completed its turning securely.

Keywords: Machine vision, Web camera, Autonomous guidance system, Differential-drive steering, Steering control

Introduction

Necessity of agricultural robots has been gradually increasing by the change of social and economical environments such as avoiding dangerous and tedious agricultural works, and lack of potential farmers. This is because an autonomous guidance system for agricultural vehicle could be used to remove a machine operator from such a working condition and/or to assist him in performing the mentally demanding and fatiguing task of vehicle guidance (Reid and Searcy, 1988).

Machine vision must be one of promising sensor system for potential agricultural robots such as tractors for plowing and cultivating, combine/vegetable harvesters and planters, where multiple crop rows, cut/uncut edge of crop, tree rows are widely used as a reference of guiding vehicles. Reid and Searcy (1988) developed a method to separate the guidance information from row crop image using a statistical -based automatic thresholding algorithm. Hata *et al.* (1993) developed a crop row detector using a color line sensor for autonomous tractor. They have used Red and Green channels in a RGB camera to calculate heading angle and offset between the crop rows and detector. Torii *et al.* (2000) could find a guiding reference by separating the crop and furrow rows using a YUV color transformation, and applying the least squares method for boundary lines. Then the heading angle error and the offset from the desired line were identified by a 3D perspective view transformation. Benson *et al.* (2003) developed a guidance algorithm to separate the uncut crop rows from the surrounding background material, parameterized the crop rows, and calculated a guidance signal. Using a single monochrome camera their system was capable of guiding the combine at the same accuracy level as the GPS reading system available at a speed of 1.3 m/s, which was around 13 cm in RMS error. Zhang *et al.* (2005) used a correlation analysis -based image segmentation to extract the features of cut/uncut edge in rice field at the time of harvesting. They divided the crop image into small rectangular windows and a pair of 1-D arrays was constructed in each windows. Then the correlation coefficients of every small window constructed the features

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to segment image. Although the machine vision is suited for the guidance system as a sensor for estimating steering corrections to guide a vehicle through a field relative some guidance course, or directrix, observed by the vision sensor, it is still difficult to be implemented in a real agricultural machine because the system needs a desktop computer to equip a frame grabber. In this research, a web camera with a notebook computer will replace normal CCD camera with the frame grabber to be more cost-effective system. It is also assumed that the edge of cut/uncut in rice crop for a combine harvester can be obtained by the image segmentation algorithm developed in Zhang *et al.* (2005). A single white line on dark ground surface was simulated as the edge. Experimental vehicle is constructed using a differential -drive type steering mechanism, which is steered by the difference of rotation speeds between left and right wheels to track the single line as the desired travel path.

This research was intended to develop an autonomous guidance system for agricultural vehicles as a basic research for agricultural combine harvester. The specific objectives of the research were :

1) to develop machine vision system using a web camera,
2) to develop steering control algorithm, and
3) to evaluate system performance at straight- and curved -path in a laboratory environment.

Materials and Methods

1. Experimental model vehicle

Figure 1 shows the battery-powered experimental vehicle equipped with 2-wheel drive and 4 casters for the support like a wheel chair. The size of vehicle was 0.6×0.6 m made of AL profiles (30×30 mm). Two DC geared-motors (120 rpm, 120 W, Won-il, Korea) were used for the separate driving for right and left driving wheels. Two rotary encoders (500 pulse/rev, Autonics, Korea) were mounted to each driving shaft to pick up the rotational speeds of each vehicle. The vehicle could be steered by differentiating rotational speed of each driving wheel. The advantage of this kind of steering mechanism is very simple and easy to be steered, however, it is rather difficult to move straight forward without the feedback of rotational speeds of driving wheels. The maximum forward speed of the vehicle was 62.2 cm/s.

A PIC microprocessor (PIC18F448, Microchip, U.S.A.) was used to control the rotational speeds of both wheels. Figure 2 shows the interface circuit between the PIC microprocessor and the motor driving circuit. Two timer/ counters of PIC were functioning to count the pulses from the rotary encoders every 100 ms and to feedback the rotation speed of each wheel to the vehicle controller. LMD 18200 was a motor driving IC with 3 control signals consisting of 8 bits of pwm (pulse width modulation) and two single bit for rotational speed, direction and brake controls, respectively. MAX232 was for the serial communication between vehicle controller and notebook PC which provides the steering command, where the baud rate was set to 57,600 bps. The control program written in C was compiled with PCW compiler (Custom Computer Service, USA) and downloaded to the memory of PIC microprocessor through MRPIC-IDE (Comfile Technology Co., Korea).

The characteristics of DC motors used in the experimental vehicle were shown in figure 3. Although the rotation speeds of motors were linearly dependent on pwm values (0~255) for the speed control, their characteristics turned out to be different between both motors due to little misalignment in the vehicle structure and there existed some hysteresis on each motor. It was, therefore, needed to take account of these characteristics in controlling the motor speed.

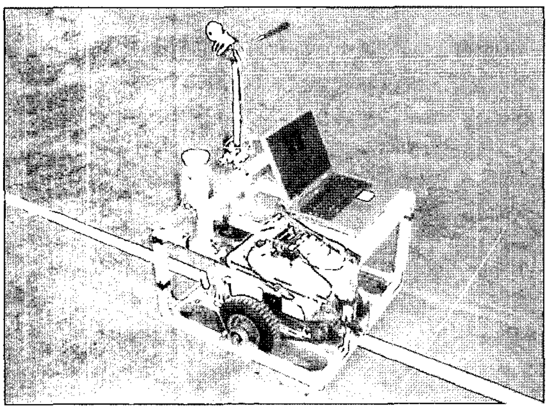


Fig. 1 Experimental vehicle.

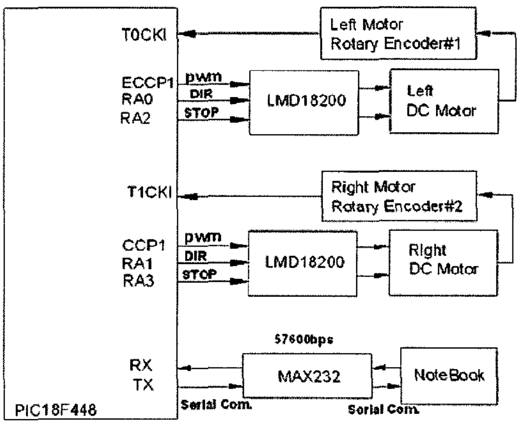


Fig. 2 Schematic diagram of vehicle controller.

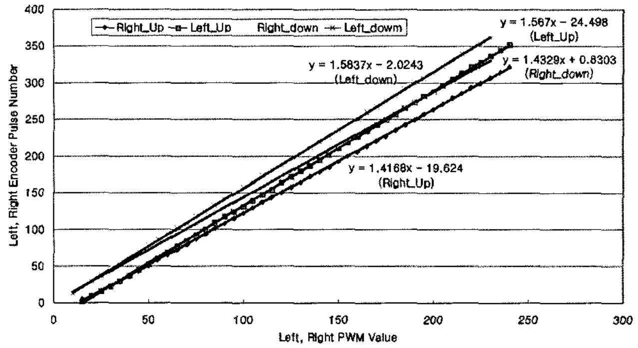


Fig. 3 Characteristics of DC motors used in the experimental vehicle.

2. Machine vision system

Machine vision system detects the cutting edge of rice crops at harvest to determine the vehicle position in terms of the lateral offset and the heading angle, and calculates the required steering angle, and then transmits that information to the motor controller through RS232 serial communication. It consists of a web camera (Lebeca Pro, PANWEST, Korea) and a notebook PC with USB port. The program was written in MFC under Visual C++6.0 (Kang and Ha, 2003). The web camera outputs the image at the rate of 20~50 frames/s depending on the file format. The camera was mounted 940 mm above the ground surface with a tilt angle of 30°, which resulted in placing a horizontal center line on the image 465 mm ahead of the camera location.

Figure 4 shows the original and the processed image of cut/uncut edge of rice crop, where the edge line could be easily found. As stated in the introduction, a while line of 6 cm width simulated this edge line in this research.

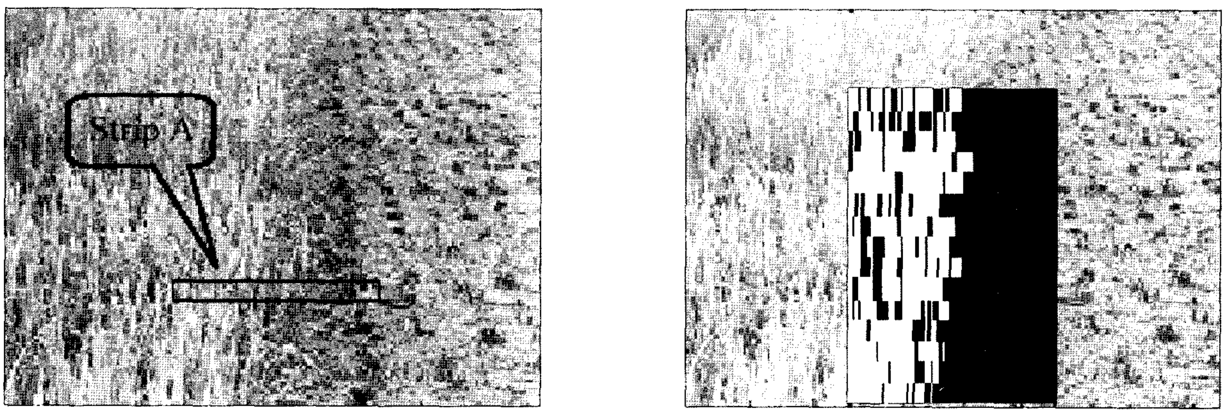
Determination of vehicle position

When the position of vehicle coincides with the edge line, that is, for zero lateral offset and heading angle, the line is shown straight in the vertical center of the window on the captured image, as shown in figure 5. Otherwise, the line is off and/or slanted from the vertical center line. Then, it is possible to calculate true lateral offset and heading angle of the vehicle after converting the image coordinate into the real world coordinate by the geometric calibration. If only the interested points on the image are processed, the computing time can be reduced dramatically. Therefore, two horizontal lines on the image are chosen; one is a horizontal line in the near-view field while the other in the far-view field. There exist two distinct points when the cutting edge line crosses two horizontal lines, which is enough to determine the vehicle position. The output image format from the web camera was SIF (320×240 pixels) and, therefore, the horizontal line in Far_View is set to 20^{th} pixel and one in Near_View to 220^{th} pixel toward the bottom from the top-left origin.

3. Steering control algorithm

As mentioned earlier, the steering angle is determined by the difference of pwm values between left and right driving wheels. It is needed to investigate the operating characteristics of both wheels first to build a steering control algorithm. Table 1 presents the steering angle during the control time of 100 ms by the pwm difference of both DC motors.

Based on true vehicle position in real world coordinate and the steering angle information presented in Table 1, the required steering angle at a given vehicle position was determined by a rule-based algorithm. First of all, the



(a) original image **(b) processed image**

Fig. 4 Image of true cut/uncut edge of rice (reproduced from Zhang *et al.* (2005)).

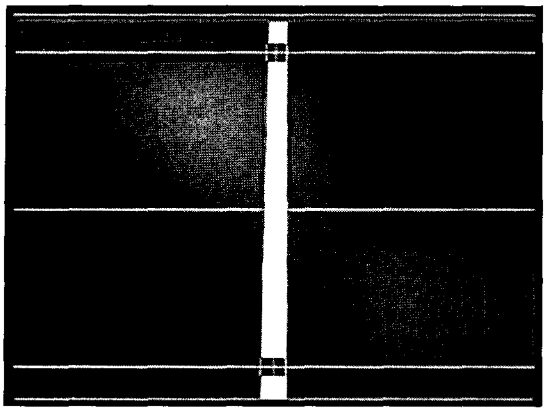


Fig. 5 Processed image of simulated edge line.

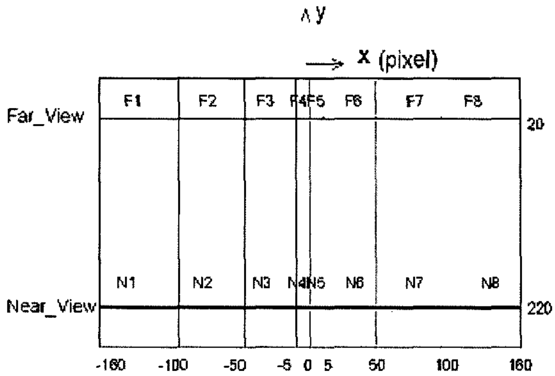


Fig. 6 Division of sections on image coordinates.

horizontal lines on Near_View and Far_View areas were divided into 8 sections, as shown in figure 6. Two points on both horizontal lines belonged to one of sections in Near_View and Far_View areas according to the vehicle position. The necessary pwm difference for each case was determined through a tuning process based on trial and error. Table 2 presents these results.

4. Integration of controller

From the machine vision system, the steering angle information such as pwm values for left and right motors is sent to the microprocessor for motor control in a predefined format. By the RS-232 receive interrupt, the steering angle information is stored into two 8 bit buffers for left and right pwm values. Current rotational speeds of both wheels were measured by the rotary encoders every control time. Comparing these with the desired motor speed, the final pwm values for each motor were calculated considering the motor characteristics equation in figure 3. Overall control time was set to 100 ms using a software timer 3 of the microprocessor. Figure 7 shows the flowchart of motor controller.

5. System evaluation

The performance of developed autonomous vehicle was evaluated at the straight path and the curved path in a lab. The first test was intended to investigate how accurately the guidance system could steer the vehicle on the straight path at three different ground speeds with the initial offsets of 0 cm and heading angle of 0°. The actual path of vehicle was manually recorded every 10 cm on the vehicle trajectory which a special marker makes. The deviations between the actual path and the desired path (white line on

Table 1 Steering angle by pwm differences between left and right motors

Left-Right (pwm value)	10	20	30	40	60	80	90	100	120	140
Steering angle (deg)	0.06	0.12	0.15	0.19	0.25	0.33	0.35	0.38	0.45	0.52

Table 2 Value of pwm difference for corresponding sections on Far_View and Near_View areas

Near_View \ Far_View	F1	F2	F3	F4	F5	F6	F7	F8
N1	-60	-30	-40	-40	80	80	100	100
N2	-80	-20	-20	-20	-40	-40	80	120
N3	-90	-60	-20	-20	20	20	60	140
N4	-90	-60	-20	0	0	20	60	140
N5	-100	-80	-5	0	0	37	40	80
N6	-100	-80	-5	-5	37	37	40	80
N7	-100	-80	-20	-20	40	40	40	60
N8	-120	-100	-80	-80	-5	-5	20	60

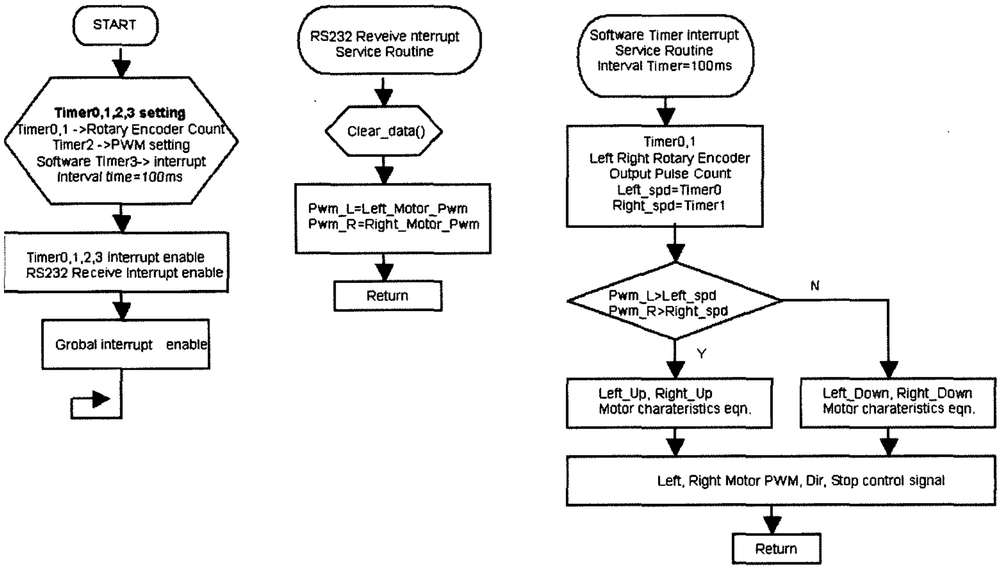


Fig. 7 Flowchart for motor control.

Table 3 Deviations of actual paths in RMS

Ground speed	Rep. 1	Rep. 2	Rep.3	Average
Low	0.61 cm	0.5 cm	0.44 cm	0.52 cm
Middle	0.78 cm	0.42 cm	0.75 cm	0.65 cm
High	0.77 cm	0.79 cm	0.69 cm	0.75 cm

the ground surface) were calculated. The system performance was represented by the root mean square (RMS) value of deviation (Shin *et al.*, 2001). The second test was conducted to investigate how quickly the vehicle was able to track the desired path, even when it started from a position with an initial offset and heading angle. Tests were conducted at three levels of initial offsets, heading angles, and ground speeds along the total travel distance of 5 m. The initial lateral offset of the vehicle were 0 cm, 10 cm, 20 cm on the right from the desired path, while the heading angles were 0°, 20°, 40° to the left. The third tests were conducted on the turning section of the rolling radius of 3 m at three ground speeds, where total traveled distance was 9.42 m. The levels of ground speed for the test were 8.88 cm/s, 16.87 cm/s and 40.68 cm/s for low, middle and high speeds, respectively.

Results and Discussion

For the straight path at zero initial offset and zero heading angle, the RMS of deviation on different ground speeds with three replications were presented in Table 3. The deviation seemed to be increased as the ground speed, however, there was no significant difference among ground speeds statistically. Therefore, it was concluded that the proposed steering control algorithm was able to steer the vehicle within the deviation RMS of 0.8 cm regardless of the ground speeds. Figure 8 shows a typical actual path of vehicle.

As a result of second test, figures 9~11 shows the typical actual path of vehicle when somewhat initial offset and/or heading angle existed. As shown in figure 9, in case of zero heading angle at the start, the vehicle could track the desired path after a certain time of deviation correction period has been completed, which was 1.5 m for all ground speed levels (figure 9(a)). However, at large initial offset it

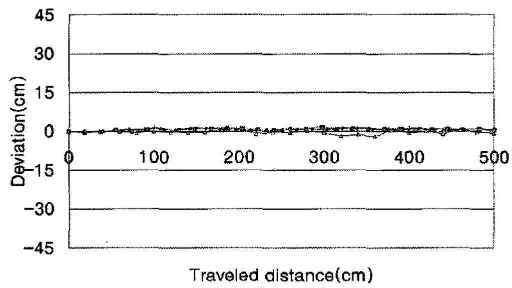
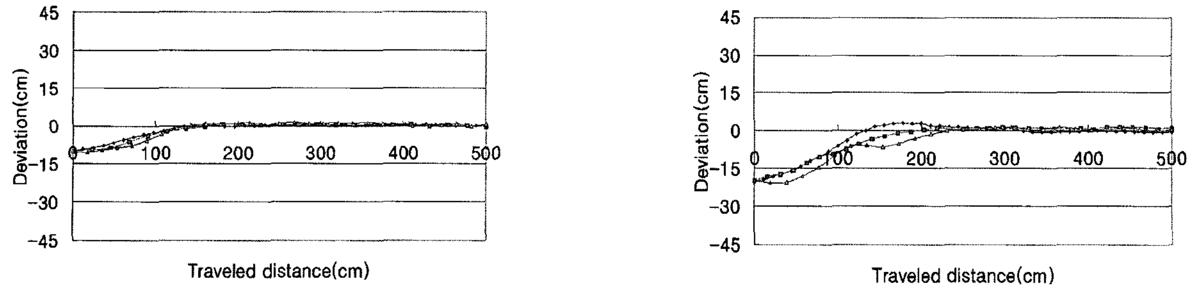


Fig. 8 Typical actual path of vehicle at no initial offset and heading angle.



(a) initial offset of 10 cm

(b) initial offset of 20 cm

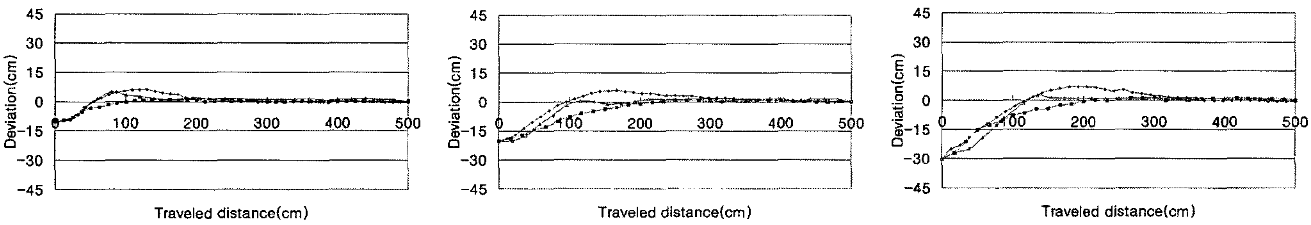
Fig. 9 Actual path for the different initial offsets with zero heading angle.

needed 2.5 m to be traveled within a tolerable deviation of straight path. In addition, it tended to pass over and return back to the desired path at the low ground speed, as shown in figure 9(b).

Figure 10 shows the actual paths of the vehicle started with a 20° of initial heading angles at three levels of lateral offsets. It took approximately 2～3 m for the vehicle to be steered within the acceptable range from the desired path. The larger initial offset existed, the longer distance was required. Like the previous results, the overshoot movement was observed at the low ground speed. The maximum deviation at the overshoot did not exceed 7 cm in any case.

Figure 11 shows the actual paths of the vehicle starting at the initial heading angle of 40° for different levels of initial offsets. In case of excessive initial heading angle like this, the reference line might not be visible at the initial offset 0 cm. Since the vehicle at this position needed to be sharply steered, its actual path tended to be over-steered near the starting position. The maximum deviations where the overshoot occurred were around 7～15 cm, and its magnitude decreased as the initial offset increased. This was the reason why the heading angle of vehicle was small for large lateral offset if the vehicle directed toward the desired path. After traveling 2.5～3.5 m, as usual, the vehicle started to track the desired path over all range of given ground speeds.

All trials with diverse initial offsets and heading angles showed that the final destinations were surely close to the desired path. Compared with other ground speeds, especially, the autonomous guidance system worked smoothly without

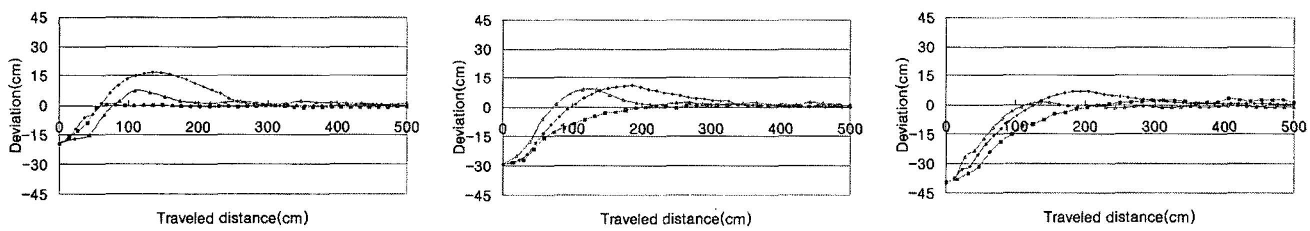


(a) initial offset of 0 cm

(b) initial offset of 10 cm

(c) initial offset of 20 cm

Fig. 10 Actual path for the different initial offsets with heading angle of 20°.



(a) initial offset of 0 cm

(b) initial offset of 10 cm

(c) initial offset of 20 cm

Fig. 11 Actual path for the different initial offsets with heading angle of 40°.

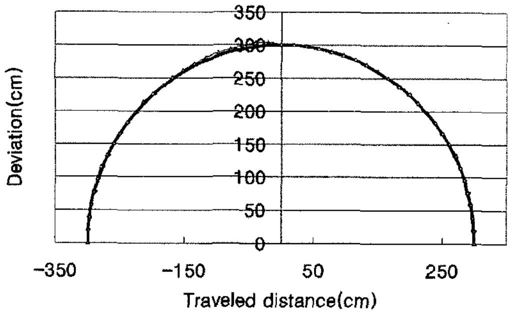


Fig. 12 Actual path of vehicle over curved path at middle speed.

any overshoot on the middle ground speed. For low ground speed, however, the vehicle tended to have the characteristic of overshoot at large initial heading angle. This was the reason why DC motor would not exert sufficient torque to steer the vehicle at low range of rotational speed when large steering angle was needed.

Figure 12 shows a typical actual path of the vehicle moved along the half circle of 3 m in radius at middle ground speed. It was observed that the vehicle could track the guide line on the ground surface, when the deviations were 1.25 cm, 2.18 cm and 1.55 cm at low, middle and high ground speeds, respectively. The test results have confirmed that no additional control algorithm was necessary over this type of turning section.

Conclusions

For the simple and cost effective autonomous guidance vehicle, a steering control system was developed using a web camera and notebook PC, and it was adapted to a vehicle with differential driving steering mechanism. The vehicle could be autonomously moved along a white line on the ground surface simulating cut/uncut edge of rice crop at the ground speed rate of 8.88 cm/s~40.68 cm/s. After sensing the vehicle posture such as lateral offset and heading angle through the machine vision, the amount of steering angle was calculated and then transmitted to the motor controller made of PIC18F448. The motor controller performs the speed control of DC motors on right- and left-wheels independently with the feedback of current rotational speeds of each wheel. The steering control algorithm was developed and evaluated in a laboratory environment.

The evaluation tests showed that the vehicle could travel within the deviation RMS of 0.8 cm along the straight path. It did not take much time for the vehicle to track the desired path even if the vehicle started with an initial lateral offset and/or tilted heading angle. For the curved path with the radius of 3 m, the vehicle could securely track the desired path within the deviation RMS of 2.18 cm.

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