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Research in autonomous agriculture vehicles in Japan

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Abstract

Much research on automation in agriculture has been presented in recent years at the annual meetings of the Japanese Society of Agricultural Machinery (JSAM). This research has been performed in universities and government institutes, and by agricultural machinery manufacturers. Because of funding limitations, research in universities has concentrated on methodologies, such as navigation, sensing, and application of control theory. Development of a one dimensional image sensor, and application of neural networks and genetic algorithms, has taken place at Hokkaido University; vision guidance and fuzzy logic application at the University of Tokyo; an automatic follow-up vehicle has been developed at Kyoto University; and an automatic transport vehicle at Ehime University. At research institutes and manufacturers, with their greater financial freedom, more practical systems have been developed. A tilling robot and a driver-less air blast sprayer is being developed in the Bio-oriented Technology Research Advancement Institute (BRAIN); and an autonomous rice planter, a tillage robot and autonomous forage tractor in the research institute of the Ministry of Agriculture, Forestry, and Fishery (MAFF). Kubota Co. Ltd has developed autonomous rice planting and husbandry vehicles. In Asian countries an autonomous speed sprayer is under study in Korea and an autonomous power sprayer in Taiwan, but little research is performed elsewhere in Asia. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Image processing; DGPS; Fiber optical gyroscope; Laser range sensor; Robot; Automatic guidance

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1. Introduction

In Japan, after the General Agreement on Tariffs and Trade (GATT) Uruguay Round was concluded in 1993, the Ministry of Agriculture, Forestry, and Fishery (MAFF) promoted a policy to improve production and strengthen the agricultural infrastructure. The policy was set out in the document Basic Direction of New Policies for Food, Agriculture and Rural Area (New Agricultural Policy) published in 1992. Under these guidelines the Agricultural Machine Development Project and the Practical Promotion Project were initiated in 1995; these included the development of agricultural robots and techniques for autonomous navigation in the field. Recently, national and public research institutes have been pooling their expertise in the new technology of autonomous navigation. Much research on automation in agriculture has also been performed in universities. Table 1 shows the number of presentations on autonomous vehicle guidance at the annual JSAM meetings for the past few years. In universities, due to funding limitations, most research has involved methodologies, such as navigation, sensing, and application of control theory. At research institutes and manufacturers more practical systems are tested. This chapter reviews university research projects, and work in official (governmental) research institutes and manufacturers, in Japan. Research in other Asian countries is also referred to.

2. Research in universities

2.1. Applications of image processing and image sensors

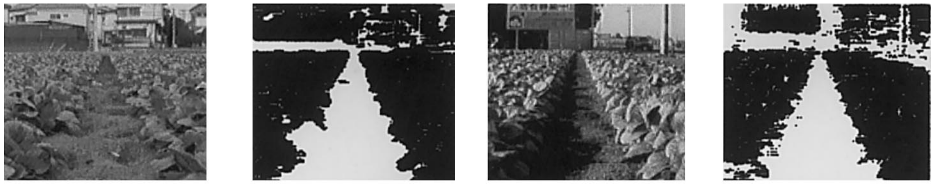
2.1.1. Vision-guided tractor

An image-processing algorithm for crops has been developed at the University of Tokyo. This algorithm has been applied to vision-guided navigation of a tractor for use in row crop husbandry, including mechanical weeding and the precise application of chemicals. For accurate vision guidance, image analysis of the crop row field is essential. Therefore discrimination of the crop area from soil or background with high accuracy, detection of boundary lines between crop and soil areas, and position identification using three dimensional perspective view transformation are all required.

Discrimination of the crop area was performed using color transformation of a HSI (hue, saturation, and intensity) transform (Torii et al., 1996). Fig. 1 shows the result of the HSI transform of cloudy and sunny day images taken at midday.

Table 1
Number of presentations on autonomous vehicles at the annual JSAM meeting

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999
Number of presentation	7	10	13	17	11	22	15	24	25



(1) Cloudy day (12:00)   (2) Sunny day (12:00)

Fig. 1. Results of HIS transformation.

Separation of the crop canopy and soil area was found to be successful using the HSI transform irrespective of the climate or time of day. The least squares method was used for boundary detection between the crop row and soil area, and a three dimensional perspective view transformation was used for position identification. Results show that the offset error was within 0.02 m and the attitude angle error was within 0.5°; these values are sufficient for guidance in the field (Table 2).

This algorithm has been applied to a vision-guided tractor (Torii et al., 1998). Fig. 2 shows the path trajectory with an offset error within 0.02 m at a speed of 0.25 m/s. This project is continuing in order to increase the speed, and vision guidance in a paddy field is also in progress.

2.1.2. One-dimensional image sensor

In Hokkaido University, a crop row detector equipped with a one-dimensional image sensor was developed for use in crop husbandry machinery (Hata et al., 1993). The principle was that the crop row image was converted, in the hardware, to a one-dimensional gray scale level signal, and the software estimated the offset and heading errors.

Fig. 3 shows the simulation image and the output signal of the crop row detector. Using the two detected peaks the crop row was taken to be a line, from which the offset and attitude error was derived using perspective transformation. From simulation, the offset error was within 0.02 m when the camera offset was within 0.2 m, and the attitude angle error did not exceed 1° when the attitude angle was

Table 2
Results of identified camera position by perspective transform

Camera position (m)			Attitude angle (°)		
Measured	Identified	Standard	Measured	Identified	Standard
0.2	0.18	0.012	0	0.0	0.1
0.4	0.41	0.018	+5	+5.3	0.1
0.6	0.61	0.007	+10	+10.9	0.4
0.8	0.83	0.026	−5	−5.2	0.2
1.0	1.01	0.005	−10	−10.6	0.2

no more than 12°. A prototype machine was developed based on this method, and tested using field images. The execution time was about 40 ms and the accuracy was sufficient for practical use when the camera offset was up to 0.10 m and the attitude angle not more than 6°. Finally, sensor performance tests were conducted on the following of the crop row.

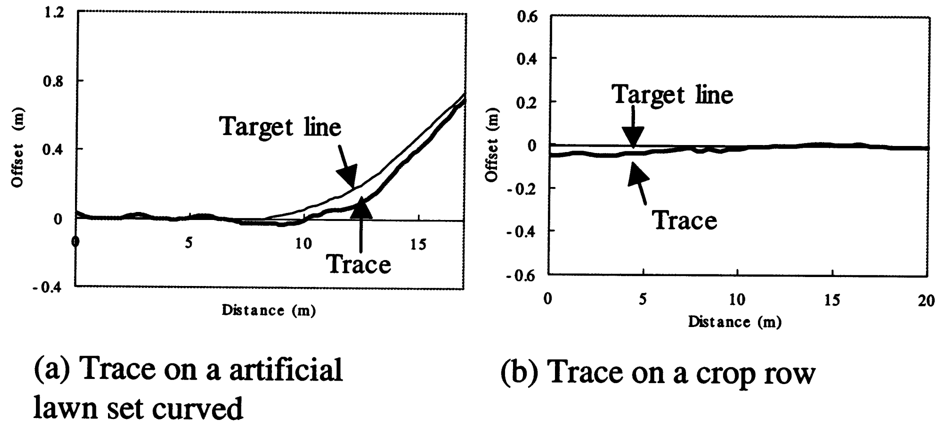


Fig. 2. Results of path trajectory.

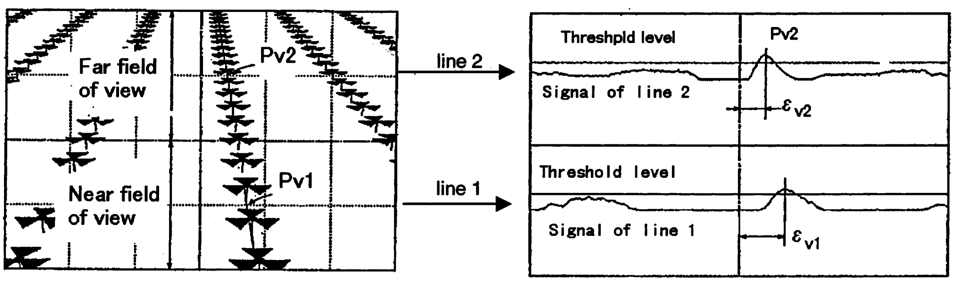


Fig. 3. Simulation image and output level of line 1 and 2 (Hata et al., 1993).

Table 3
Accuracy of row following on straight and curved rows of spinach (Hata et al., 1993)

Velocity (m/s)	Wheel	Straight line		Curved line	
		RMS (m)	Maximum (m)	RMS (m)	Maximum (m)
0.22	Front	0.02	0.04	0.04	0.09
	Rear	0.02	0.05	0.04	0.07
0.52	Front	0.03	0.05	0.06	0.13
	Rear	0.03	0.05	0.05	0.09

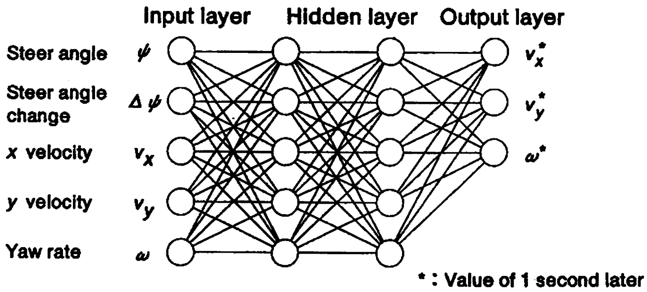


Fig. 4. NN model (Noguchi and Terao, 1997).

The vehicle was also equipped with a ridge detector in the infrared. Table 3 shows errors between detected and real offsets on a curved row of spinach plants. The error in the offset was just over 0.05 m.

2.2. Applications of soft computing

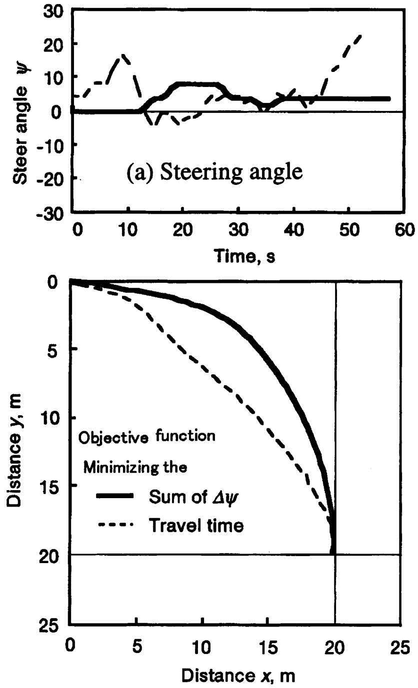
2.2.1. Applications of neural networks and genetic algorithms

In Hokkaido University, a neural network (NN) vehicle controller was designed in which the motion of the mobile agricultural robot was specified as a nonlinear system with high learning ability (Noguchi and Terao, 1997). The input variables were the steering angle, steering angle change, velocity in x and y direction, and the yaw rate. The output variables were the velocity in the x and y directions, and the yaw rate 1 s later (Fig. 4). This NN model was applied to navigation on an asphalt surface, with an accuracy of 0.08 m in the offset. It was applied to navigation along an optimal working route determined using a genetic algorithm (GA). Fig. 5 shows path creation for differing objective functions: minimizing the sum of steering angle and the travel time.

The NN model was used to correct the geomagnetic direction sensor for the inclination of the vehicle (Noguchi et al., 1997). The field test was conducted on a square path of side 40 m in the meadow. Fig. 6 compares path trajectories for NN and conventional methods. The maximum directional angle error was 14° in the conventional method, and for the NN just 1°.

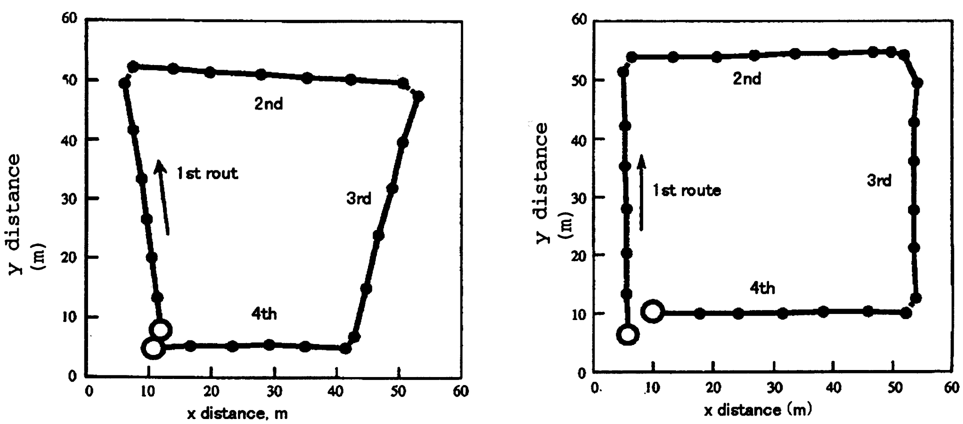
2.2.2. Application of fuzzy control

In The University of Tokyo, a navigation method has been used using sonar-based mapping of the crop row and fuzzy logic steering (Toda et al., 1993, 1999). The test vehicle was designed as a feasibility study, for use in a room, and ten ultrasonic sensors were attached to the side of the vehicle at 0.050 m intervals. The mapping test was performed using a maze; its shape generated complex range data. A non-zero range data set in consecutive channels are taken to indicate a block. Any data 30 mm apart from the mean value of the block is eliminated as an outlier, and the crop row line is determined using least squares fitting for the remaining data.



(b) Comparison of path trajectory by simulation :Minimizing the steering angle and the travel time

Fig. 5. Comparison of created path under different objective function (Noguchi and Terao, 1997).



(a) Conventional method

(b) NN method

Fig. 6. Comparison of the refining accuracy between the NN and the conventional method.

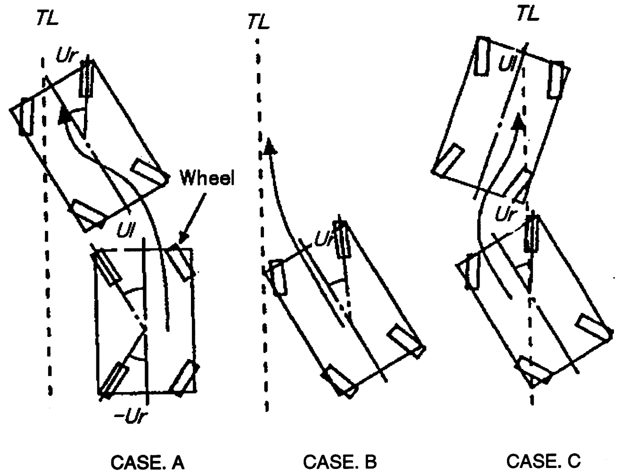


Fig. 7. Three cases of path of mobile robot (Toda et al., 1999).

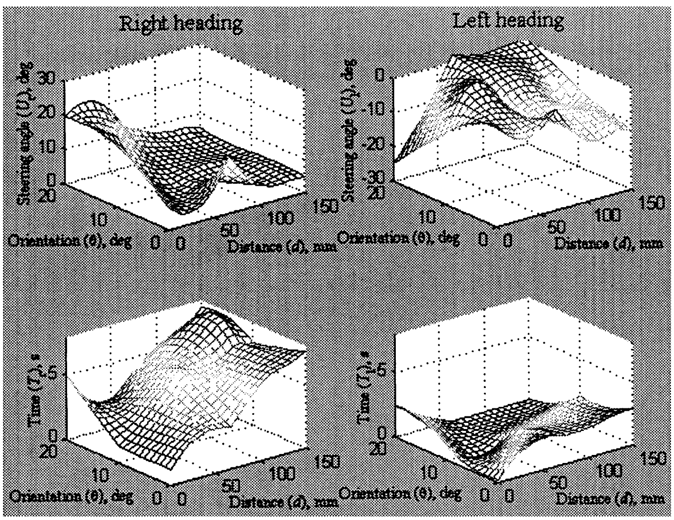


Fig. 8. Outputs from the fuzzy logic control-based steering model (Toda et al., 1999).

Necessary steering actions depend on three positional situations as shown in Fig. 7, and for each case the steering angle U_l, U_r and time period T_r, T_l are determined according to the output of the fuzzy logic controller (FLC) as shown in Fig. 8. The results are shown in Table 4. The mapping error in position was 0.012 m and 2.4° in direction. The straight line tracking errors using FLC were 0.016 m, 2.2°, and the overall test errors using maze were 0.033 m, 3.2° (Table 5).

2.3. Cooperation by multiple autonomous mobile robots

For a large field, cooperation of multiple small machines is useful and has recently been demonstrated, for example cooperation of two small combines, or of a forage harvester with a transport vehicle. In both cases, a man controls one vehicle (the main vehicle), and the other vehicles follow the main vehicle using ultrasonic or other sensors.

At Kyoto University an automatic follow-up vehicle, using two small head-feeding combines, is under development (Iida et al., 1998). A human operator in the front vehicle controls it, and a computer automatically controls the follow-up vehicle. The relative position between the two vehicles is measured using ultrasonic and infrared sensors as shown in Fig. 9. Two ultrasonic transmitters (40 kHz) and

Table 4
Steering angle (Toda et al., 1999)

Case	$t=0$	$0<t<T_1$ (T_r)	$T_1(T_r)<t<T_1+T_r$	$t=T_1+T_r$
A	0	U_1	U_r	0
B	0	U_r	Not defined	0
C	0	U_r	U_1	0

Table 5
Results of mapping and navigation test (standard errors)

	Mapping	Steering	Navigation
Position (m)	0.012	0.016	0.033
Direction (°)	2.4	2.2	3.2

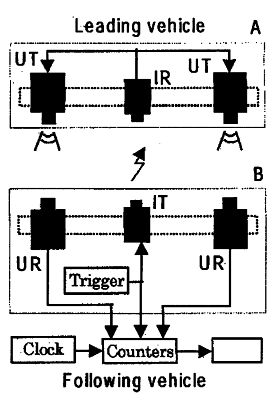


Fig. 9. Ultrasonic and infrared sensors. UT/S, ultrasonic transmitter/receiver; IR/T, infrared transmitter/receiver (Iida et al., 1998).

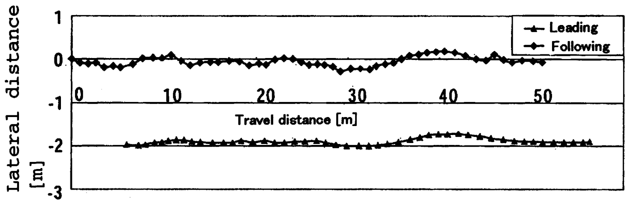


Fig. 10. Path of two vehicles (Iida et al., 1998).

Table 6
Results of the error between the two vehicles (Iida et al., 1998)

Error (mm)		Offset (m)		
		0	0.6	1.8
Offset	Mean	26	45	17
	Standard	59	61	71
	Maximum	253	229	206
Distance	Mean	12	12	1
	Standard	26	31	43
	Maximum	74	102	140

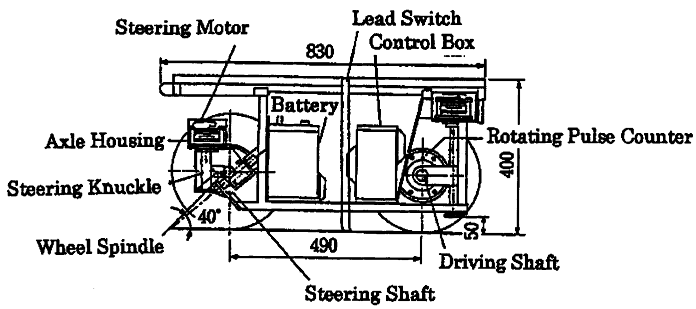


Fig. 11. Automatic transport vehicle (Yamashita et al., 1991).

an infrared red receiver are mounted on the leading vehicle, and two ultrasonic receivers and an infrared transmitter on the following vehicle. The ultrasonic transmitter and receiver were synchronized by a trigger signal (40 Hz) driven by the infrared sensor. In the field test the offset between the two vehicles took values 0, 0.6, and 1.8 m. The distance between the vehicles was 3 m and the velocity was 0.55 m/s. The paths followed are shown in Fig. 10. The offset error is given in Table 6. Performance is good for use in paddy fields.

2.4. Other research

At Ehime university, a small automatic transport vehicle (Fig. 11) equipped with a carriage self-correction mechanism was developed for use in greenhouses (Yamashita et al., 1991). In Japan, the area of greenhouses is up to 47 000 ha. Fig. 12 shows the carriage correction mechanism of this vehicle. The front wheels move along the line *c–d*, which is perpendicular to the steering shaft *b–a*. When the left front axle moves on the ridge to height *H*, the center of the wheel moves from o to o′, producing a steering angle β. The vehicle therefore turns right, correcting the attitude angle automatically. This vehicle can move for 9.5 h with a weight of 52 kg with the battery fully charged.

3. Research in institutes

3.1. BRAIN (Bio-oriented technology research advancement institute, http://www.brain.go.jp/)

'BRAIN' is a research institute, which was re-organized from the previous governmental Institute of Agricultural Machinery (IAM). The Ministry of Agriculture, Forestry, and Fishery (MAFF) started the Agricultural Machine Development Project in 1993 to develop new machines, and the development of a tillage robot and a driverless air blast sprayer were included. The driverless air blast sprayer is now in use.

For practical use of the tillage robot, the target specifications are listed in Table 7. Since BRAIN's foundation many research projects have been executed, and technologies accumulated (Table 8) (Yukumoto et al., 1995, 1997). The AP-L1

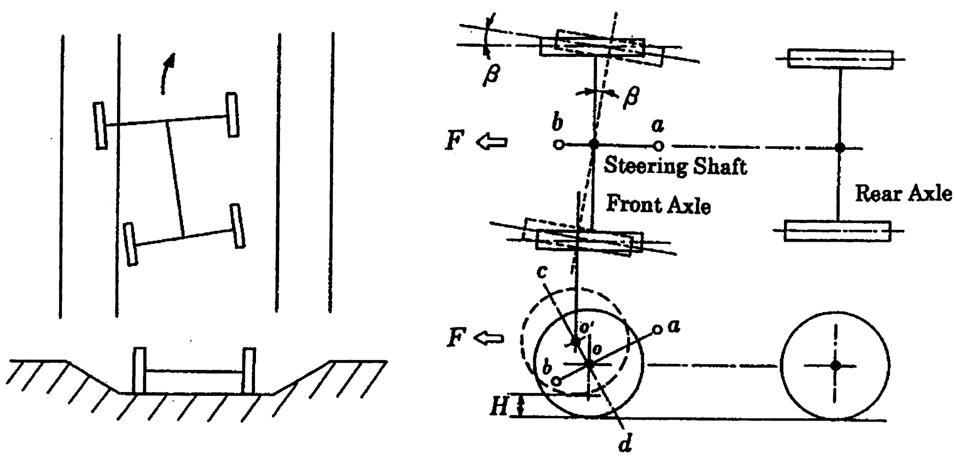


Fig. 12. Carriage self-correction mechanism (Yamashita et al., 1991).

Table 7
Desired specification of tillage robot (Yukumoto et al., 1997)

Field	Re-adjusted, flat and rectangular field size $<100\times50$ m
Operator	One man can supervise several robots and operate another job at the same time
Vehicle	Type: 4WD, 20–25 kW tractor Implement: rotary tiller Control object: steering, shuttle, brakes, throttle, hydraulic system and fuel system Equipment: automatic implement control system, bi-speed turning system
Navigation system	Position: detecting error <0.05 m, detecting interval <1 s Vehicle heading: detecting error $<0.1°$
Controller	PC (in the trial mode)
Operation software	Applicable operation: tillage, soil pudding, ridging Operation method: returning operation (including head-land operation)
Safety system	Emergency stopping system, system monitor, obstacle detection system, radio controlled system for vehicle stopping

station (TOPCON, Co. Ltd.) with automatic tracking for moving objects has now been employed. Fig. 13 shows AP-L1 and the navigation test in the field. A self-diagnosis function and an alarm function are also installed. Table 9 gives the specification of the AP-L1. Performance in automatic tracking, position measurement, and data communication was adequate at a distance of 500 m. Fig. 14 shows the trace of autonomous operation using XNAV at a speed of 0.45 m/s. The tillage work was finished in 2 h and 15 min.

A driverless air blast sprayer was developed using a guiding cable set on the working path in the orchard (Tosaki et al., 1995). Fig. 15 is a schematic of the driverless sprayer, and Fig. 16 shows examples of the setting of guiding cables. The

Table 8
Research projects of tillage robot in BRAIN

Sensor	Status
Image processing for tracking the boundary between mowed and unmowed areas, or plowed and unplowed areas	Completed
Laser beam and poles with reflector	Completed
Position detection using an image processor and a laser range sensor (XNAV)	Completed
Improved XNAV using AP-L1	Continuing
Geomagnetic heading sensor	Completed
DGPS (SNAV)	Continuing
Navigation using magnetic field strength (LNAV)	Continuing
Remote control by vision	Continuing

guiding cable was set in the ground at 0.3 m depth and the signal was an alternating current (1.5 kHz, 185 mA). Fuzzy control was used for guidance along the cable. The offset error was about 0.1 m at a speed of 0.76 m/s, increasing to 0.3 m in the turn.

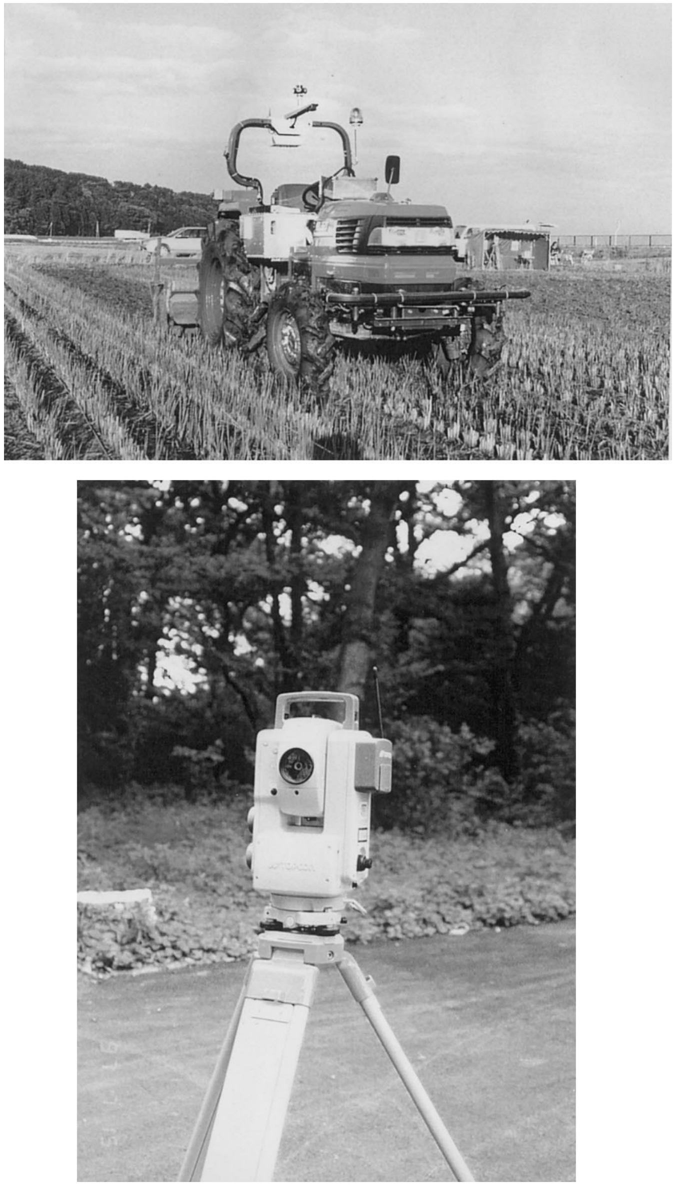


Fig. 13. AP-L1 and navigation test of improved XNAV (Yukumoto et al., 1997).

Table 9
Specification of AP-L1 (Yukumoto et al., 1997)

Automatic tracking section	Tracking angular velocity: 10 °/s Collimation accuracy: 2′ (at 10 °/s) Laser: LED laser (class 1)
Range finder section	Range: 7–700 m Accuracy: 10 mm + 2 ppm Interval: > 0.5 s
Transit section	Accuracy: 3°

3.2. Ministry of Agriculture, Forestry and Fishery

In the National Agricultural Research Center (NARC, http:/ss.narc.go.jp/) at Tsukuba, Inoue et al. (1997) applied DGPS and an optical fiber gyroscope (three axis) mounted on a 55 kW (75 HP) tractor for tillage. A Kalman filter was used in estimation of the instantaneous position. The accuracy of DGPS was 0.15 m (sampling speed: 1 Hz), and of the optical fiber gyroscope 0.3°. A rotary tillage test was performed in the field (100 × 160 m) at a speed of 1 m/s. The offset error was within 0.1 m, and that of the U-turn was 0.12 m.

Nagasaka et al. (1997) used real-time kinematics GPS (RTKGPS) with an optical fiber gyro in an autonomous rice planter. Fig. 17 shows the rice planter as tested. Since the GPS data has a delay time (about 2.8 s) in communication, compensation for this delay was incorporated in the real time position estimation. The GPS antenna was mounted on the top of the vehicle, resulting in an error of 0.1 m at a roll angle of 3°. This inclination error was also corrected. The steering angle was determined according to the difference in attitude angle error. Fig. 18 shows the measured and estimated deviation when the rice planter traveled 100 m at 0.7 m/s. The offset error was less than 0.06m. This error may decrease when the steering angle is determined by the attitude angle and offset errors.

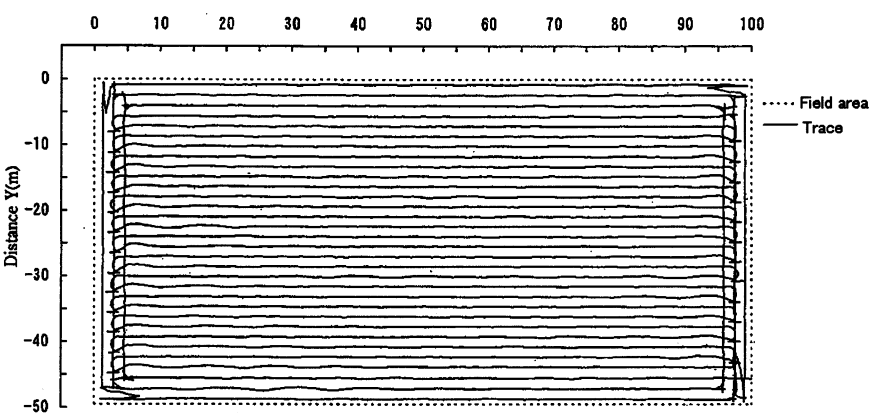


Fig. 14. Trace of tillage robot (Yukumoto et al., 1997).

At the National Grassland Research Institute (NGRI, http://ss.ngri.affrc.go.jp/), an autonomous tractor for forage production was developed in collaboration with Utsunomiya University (Okado et al., 1998). A fiber optic gyroscope and ultrasonic Doppler speed sensor was used for position identification. Fig. 19 shows the result of a typical traveling test at a speed of 1.2 m/s for straight running and 0.8 m/s for turning. The position error was about 1–2 m in a travel of 600 m.

4. Research by manufacturers

4.1. Kubota

The crop engineering system laboratory, Inc. was founded by Kubota Co., Ikegami Tsushinki Co., Ltd. and BRAIN. The following research on automatic farm machine systems for rice has been performed (Yoshida, 1996).

1. A tracking laser finder system was developed to process navigation data available at 30 ms intervals over a 200 m span. The system was used for a rice planter.

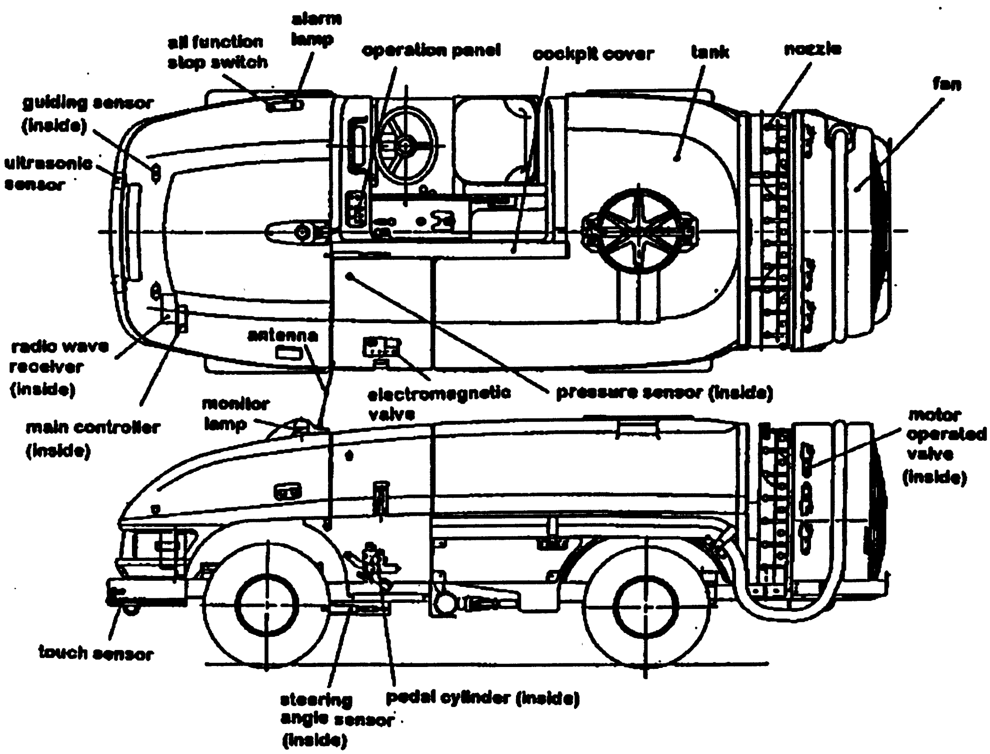
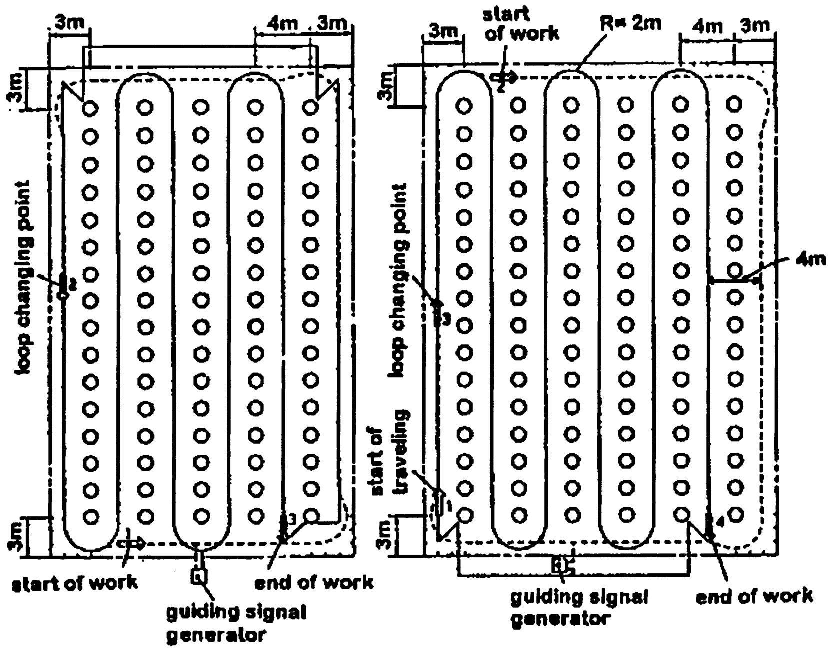


Fig. 15. Driverless speed sprayer (Tosaki et al., 1995).



(a) Odd number tree row

(a) even number tree row

Fig. 16. Setting of guidance cable (Tosaki et al., 1995).

2. Navigation by a tracking laser beam mesh system was applied to automatic rice planting and mechanical weeding.
3. Navigation by vision, laser range sensor, and directional control with terrestrial magnetism were studied. Transplanting, weeding, and pesticide application was performed using these devices. Fig. 20a shows a photograph of the weeding rotor in a transplanted rice field. The machine was working on five rows at a width of 1.9 m (width of crop working device, 0.18 m; row width, 0.3 m). The working velocity was 0.3–0.7 m/s. Fig. 20b shows a photograph of the spraying of agricultural chemicals. The application width was 5.4 m and the volume of the tank was 135 l.
4. Navigation by DGPS and inertial guidance (INS) was achieved with an accuracy of 2 cm. This was the most useful system in the field compared with the other three described above.

4.2. Mitsubishi

An autonomous riding-type rice planter using an acceleration sensor and angular velocity sensor was tested at speed of 0.7 m/s. The offset error did not exceed 0.1

m (Nonami et al., 1993). An autonomous crop husbandry vehicle having a touch sensor (Fig. 21) was also developed (Sato and Shigeta, 1995).

5. Research in other Asian counties

In Korea, Taiwan, and China some research has been performed, but in other Asian countries, in Indonesia, or in AIT, there has been no research in autonomous guidance.

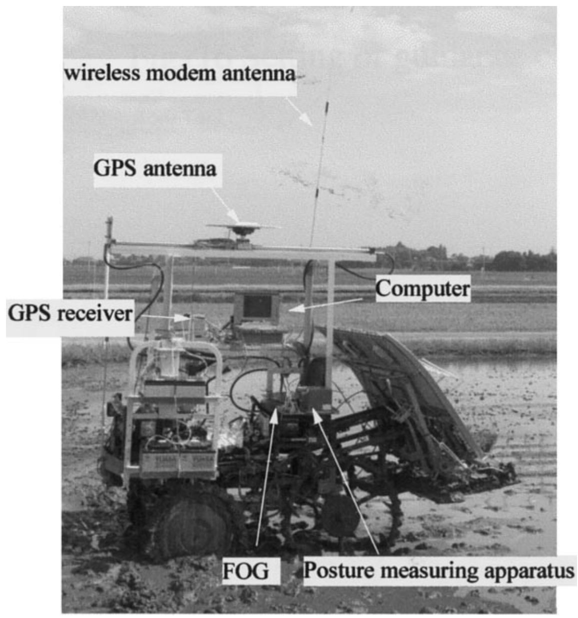


Fig. 17. Autonomous rice planter.

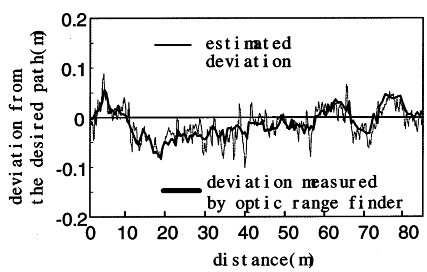


Fig. 18. Measured and estimated deviation of rice transplanter (Nagasaka et al., 1998).

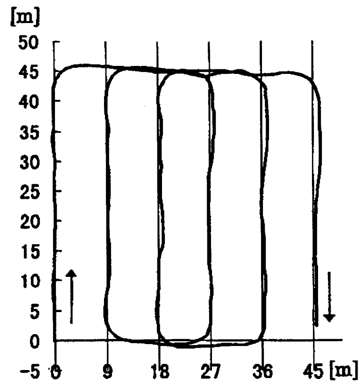


Fig. 19. Trace of autonomous forage tractor (Okado et al., 1998).

5.1. Korea

An autonomous speed sprayer for orchards has been developed using machine vision and fuzzy control (Cho et al., 1996; Cho and Ki, 1996). Image analysis of the orchard, which was used for the direction of motion, and signal processing of ultrasonic sensors, used to measure the distance from obstacles, were performed in real time. An autonomous speed sprayer using DGPS and fuzzy control was also implemented, with RMS errors not exceeding 0.3 m (Lee et al., 1998).

5.2. Taiwan

Guidance using an ultrasonic sensor has been performed in the field (Sheng et al., 1997). Plants were simulated by pillars 0.027 m in diameter, and the resulting deviation was not more than 0.06 m in traveling a distance of 15 m.

5.3. China

Two research projects are listed in the CAB Abstract, which are written in Chinese with English abstracts (Yu et al., 1997; Wang et al., 1998). Little information is given.

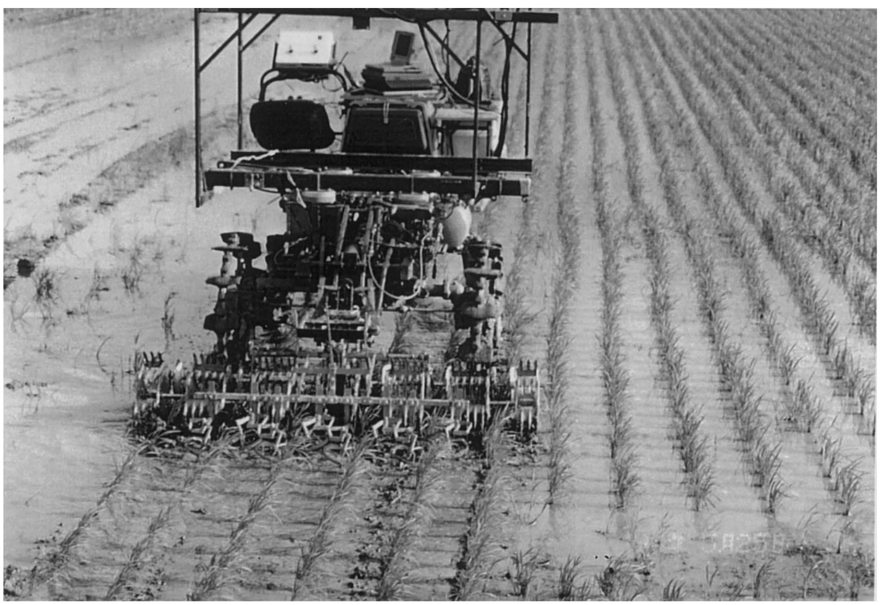
6. Conclusion

The New Agricultural Policy, following the GATT Uruguay Round, has emphasized the Agricultural Machine Development Project and Practical Promotion Project, which includes the development of agricultural robots with autonomous navigation. Universities, national and public research institutes, and agricultural machinery manufacturers are now pooling their new technologies of autonomous navigation in the field. Some results of the research on navigation are set out in Table 10.

Table 10
Results of navigation tests

Institute	Machine	Sensor	Velocity (m/s)	Errors (m)	Main publication	Progress
University of Tokyo (1998)	Tractor	Vision	0.25	0.02	Torii et al. (1998)	Continuing
Hokkaido University (1992)	Tractor	One dimensional image sensor	0.26	0.04	Hata et al. (1993)	Continuing
Hokkaido University (1997)	Tractor	Geomagnetic direction sensor	0.5	0.4	Noguchi et al. (1997)	Continuing
Kyoto University (1998)	Combine	Ultrasonic sensor	0.55		Iida et al. (1998)	Continuing
Ehime University	Transport vehicle	Not used	0.5	Not described	Yamashita et al. (1991)	
MAFF(NARC) (1997)	Tractor	DGPS and optical fiber gyroscope	1.0	0.1	Inoue et al. (1997)	Continuing
MAFF(NARC) (1997)	Rice planter	RTKGPS and optical fiber gyroscope	0.8	0.15	Nagasaka et al. (1998)	Continuing
MAFF(NGRI) (1998)	Tractor	Optical fiber gyroscope and ultrasonic Doppler speed sensor	1.2	1–2	Okado et al. (1998)	Continuing
BRAIN (1996)	Tractor	Image processor and laser range sensor	0.4	0.05	Yukumoto et al. (1997)	Continuing
BRAIN (1997)	Speed sprayer	Guiding cable	0.7	0.1	Tosaki et al. (1995)	Practicable
Kubota (1994)	Rice planter	Laser range sensor	0.7	0.05	Yoshida (1996)	Completed
Mitsubishi (1995)	Rice planter	Angular velocity sensor and acceleration sensor	0.7	0.1	Nonami et al. (1993)	Completed

(a)



(b)

Fig. 20. Automation in rice husbandry (Yoshida, 1996).

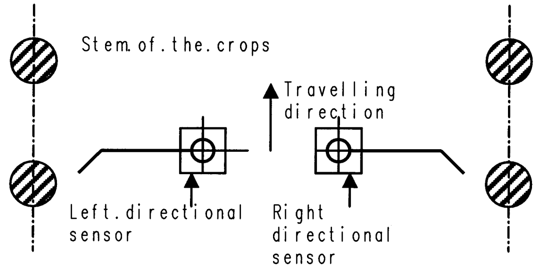


Fig. 21. Top view of touch sensor (Sato and Shigeta, 1995).

Since the price of RTKDGPS is rapidly decreasing, and the performance of image processing is increasing; the combination of vision and RTKDGPS appears to be the most promising system for the future.

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