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Robotization of Agricultural Vehicles (Part 2) — Description of the Tilling Robot —

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Abstract
We have developed a tilling robot that can recognize its own position and heading, while performing unmanned tilling at almost the same work rate as manual work. The tilling robot is composed of navigation systems for positioning and heading, a robotized vehicle, a controller, and an operation software. A geomagnetic sensor (TMS) is utilized for the navigation system for heading. The operation software consists of teaching, path planning, vehicle controlling, self-diagnosis, and abnormality alarming sections. We found that the tilling robot can perform unmanned tilling operations over a whole field area of 50 a with almost the same efficiency and accuracy as manual work.

Discipline: *Agricultural machinery*
Additional key words: mobile robot, unmanned operation, operation software, tractor, navigation

Development of tilling robot

1) Tilling robot

The BRAIN–IAM has accumulated data related to technology for robotization of agricultural vehicles from several trials since 1988 [1,2,5]. The Ministry of Agriculture, Forestry and Fisheries launched an agricultural machine development project in the fiscal year 1993. A 5-year plan for the development of a tilling robot (1993 to 1997) was implemented under this project. This development was performed jointly with KUBOTA Co., Japan Aviation Electronics Industries, Ltd., Hokkaido Univ. and BRAIN–IAM.

The objective of the tilling robot is to develop a working vehicle that can recognize its own position and heading, while performing unmanned tilling, including headland treatment, at the same work rate as a manual operation. The target specifications are shown in Table 1. The fields are limited to paddy fields and upland fields that cover an almost flat and rectangular area. In our study, the robot works within sight of the operator, which enables the operator to stop the robot by remote control in case of emergency.

2) Target specifications for the navigation system

The performance required for the navigation system of tilling robots or robotized agricultural vehicles is outlined in Table 1. This table specifies the concurrent provision of positional information and the vehicle heading information. For position accuracy, we assume that the overlap width of the implement should be approx. 10 cm. The tolerance was set for half of that value to avoid untreated areas. The heading accuracy was set so that the overlap width of the implement would be maintained if the vehicle was operated autonomously, depending only on the heading information for a length of approx. 100 m of the assumed field and taking into consideration the capacity of the present heading sensor. Although the sampling interval for the position data was set at 1 s or less, it is assumed that the transitory changes of position during this interval, as required, are complemented by dead reckoning, etc.

Navigation systems

1) Navigation systems for positioning

We developed 3 types of navigation systems for positioning, namely an off-the-wire type, a kinematic GPS with inertial navigation system (INS) type, and an optical type.

The details of these navigation systems were described in "Robotization of Agricultural Vehicles (Part 1)".

2) Navigation system for heading[6]

(1) System configuration and principle

Geomagnetic sensor (TMS) is a heading sensor used for the navigation system characterized by a free route and internal information with distance and heading type.

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Table 1. Required specifications of tilling robot

Field	Re-adjusted, flat and rectangular field		
Operator	One man can supervise several robots, and perform other tasks at the same time		
Vehicle	Type	4WD, 20–25 kW Tractor	
	Implement	Rotary tiller	
	Controlled systems	Steering, shuttle system, brakes (right and left), throttle, hydraulic system and fuel cut system	
	Equipment	Automatic implement control system, bi-speed turning system	
Navigation systems	Position	Detecting error	: < 5 cm
		Detecting intervals	: < 1s
	Vehicle heading	Detecting error	: < 0.1°
Controller	Personal computer utilized in the trial model		
Operation software	Operations	Tillage, soil puddling, ridging, etc.	
	Operation method	Returning operation (including head-land operation)	
Safety systems	Emergency stopping system, system monitor, obstacle detecting system, radio-controlled system for vehicle stopping		

A flux gate type TMS was adopted, which displays a relatively high reliability and is commonly used in the field of traffic. Principle of measurement is shown in Fig. 1. Heading of the vehicle is represented by the relative angle from magnetic north by measuring the horizontal components x and y, which are detected by the intersected coils X and Y, and by calculating $\tan^{-1}(x/y)$. However, if the TMS mounted on the vehicle tilts together with the vehicle, it is impossible to detect the horizontal components of geomagnetism. Therefore, the geomagnetism must be detected as a 3-dimensional vector and the horizontal components must be calculated by measuring the pitching and rolling angles of the TMS using a clinometer. This operation is referred to as "calibration of inclination". In addition, because the vehicle itself is a magnetic substance, it is necessary to correct the error due to the influence of its magnetism. This correction is referred to as "calibration of magnetic environment". The influence of a magnetized substance is represented by the vector OO' in Fig. 2. The vector OO' can be measured beforehand by running the vehicle in a loop in an area free of any magnetism from buildings, etc., and then the calibration of the magnetic environment is achieved using that value.

(2) Performance, precision, and ease of use

Table 2 shows the main specifications of the TMS we used. After incorporation of the measured value into the computer and calibration of the inclination and the magnetic environment, a reproducibility of 0.3° was secured based on the trace of autonomous straight running with the TMS.

(3) Characteristics and problems

Although the cost of TMS is low and it has no driftage, TMS measures a very small magnetic field. This can cause a problem when the measured value is affected by

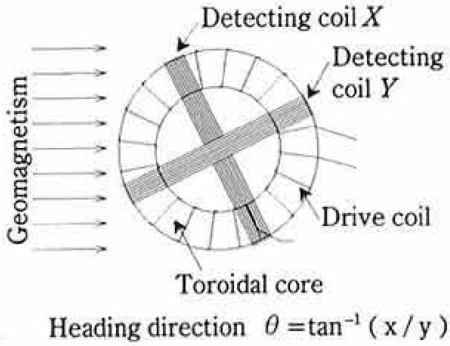

Fig. 1. Principle of measurement of geomagnetic sensor

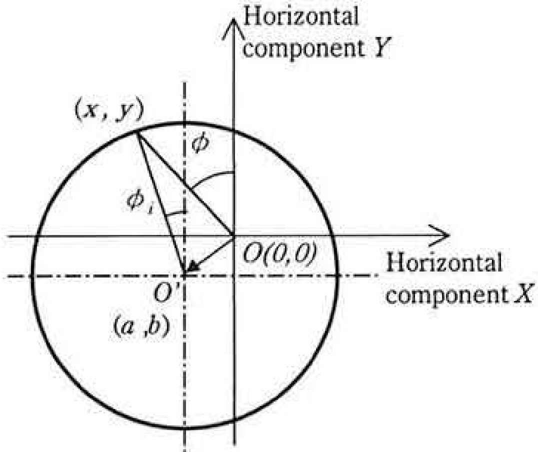

Fig. 2. Influence and calibration of magnetic environment

Table 2. Specifications of TMS
(Watson Industries Inc. Model FGM-200A)

Type	3-Axes fluxgate type
Axis alignment	± 1° to case
Range	± 1,000 mG
Zero field bias	0V ± 1% full scale
Linearity error	Less than ± 0.5%
Frequency response	DC to 15 Hz
Input voltage	+6 to +15 VDC

surrounding structures, whose influences can not be corrected.

Vehicle (ROBOTRA) and control systems[7, 8]

1) Vehicle

To test the navigation systems and autonomous operation software, the ROBOTRA (Fig. 3) was developed by trial using a stock tractor as the base vehicle. Although the new original vehicles designed for a tilling robot could have been developed in this study, commercialized tractors were eventually used due to their versatility as well as the lower development cost. The respective specifications as listed in Table 3, and presently the ROBOTRA is designed for rotary tilling work. Since this base vehicle has a shuttle gear, bi-speed turning system, and automatic depth and level control functions for rotary tiller, it is possible to simplify the control parts of the vehicle.

Control of each part is achieved through an exclusive vehicle controller, as shown in Fig. 4. For steering control, the steering angle is detected by the potentiometer mounted on the output shaft of the steering gear box and fed back to the servomotor driver in the vehicle controller so that the specified steering angle can be obtained. To simplify the system, shift positions are manually set prior to the test so that the velocity is controlled by switching between the part throttle previously set and full throttle. To ensure safety, the ROBOTRA has an emergency stopping mechanism that is activated by either a bumper switch or through radio control.

2) Control system

The main controller inputs information items related to navigation as well as various internal information, determines the control value for each part of the vehicle according to a path plan, and outputs them to the vehicle controller. A personal computer is presently used for the main controller. Inputs and outputs are processed through various boards that are suitable for each type of signal. A communication modem of spectrum spread type (developed by Cralion, Co.) was used for the data transfer between the reference station of the navigation system and the controller on the ROBOTRA.

Implementation of autonomous operation

1) Autonomous operation of tilling robots using the LNAV or SNAV[8]

The operation using the LNAV is executed by detecting the position of the vehicle through comparison of a signal with the magnetic reference. In the returning

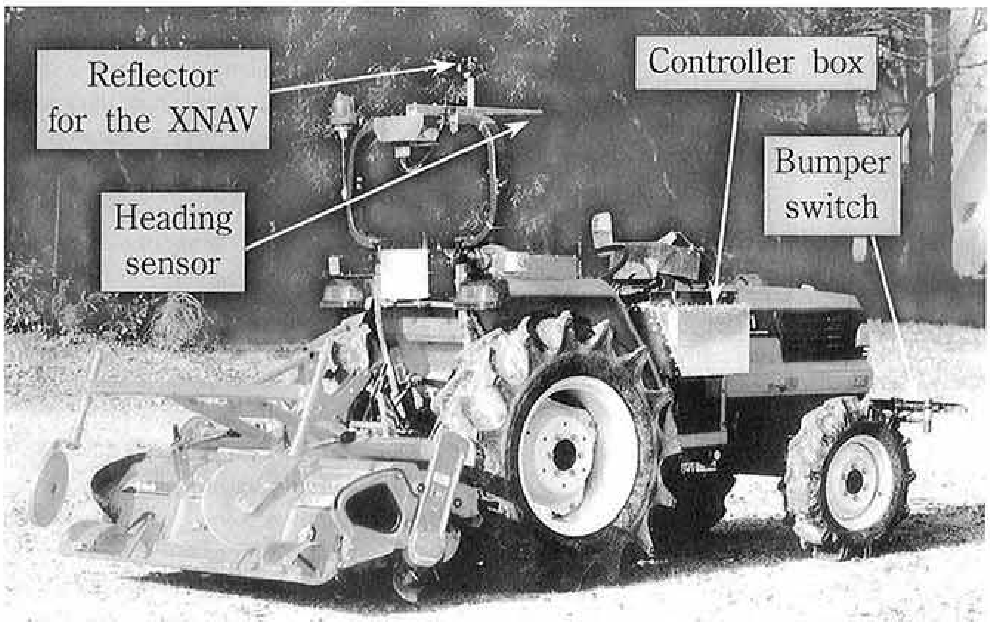

Fig. 3. Robotized vehicle "ROBOTRA"

Table 3. Specifications of the base vehicle

Base vehicle		
Model	KUBOTA GL-320	
Type	4WD with front wheel steering	
Engine	23.5 kW / 2800 rpm	
Dimensions	L 3,180 × W 1,455 × H 1,985 mm, Weight 1,280 kg (excluding the implement)	
Additional equipment	Automatic implement control system (depth and level), bi-speed turning system, shuttle gear, power shift mechanism	
Control of each section		
Steering	DC servomotor	(position control)
Throttle	DC motor	(two-stage control)
Shuttle gear	Electric servo cylinder	(position control)
Brake system	Hydraulic cylinder	(two-stage control)
3P. linkage system	Electrical signal	(two-stage control)
Engine stopping system	Solenoid	
Others	Emergency stopping device by radio control and safety devices	

operation, an original method is applied to obtain the reference value of the next path, while performing the operation on the present path. Since the SNAV uses absolute latitude and longitude as its coordinate system, it differs from the XNAV. Therefore, the operation software applied to the SNAV uses a different method of managing the coordinate system from that for the XNAV, but the method is identical in other areas.

Presently, the performance of the autonomous operation using the LNAV or SNAV is almost equivalent to that of the autonomous operation using the XNAV described in the following section. Detailed explanation will be given separately.

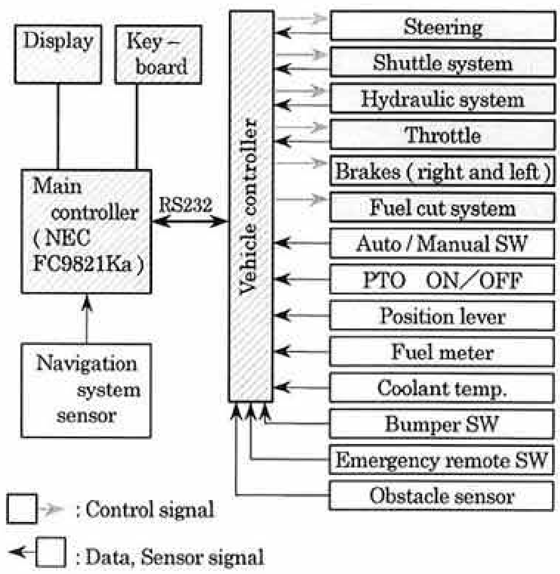

Fig. 4. Control systems of the ROBOTRA

2) Autonomous operation of tilling robots using the XNAV

(1) Concept and strategy[9)]

In the autonomous operation with the XNAV, the TMS is also used concurrently for the navigation system with the AP-L1. Detecting intervals of positional data are slightly long and heading information for the vehicle is required for turning and sideways movement. The operation of the whole field is performed by first making returning operations around the center of the field, assuming that the field has a rectangular shape, and then making a round operation around the peripheral areas of the field, including the headlands. For the tilling operation using the ROBOTRA, triple round courses are needed to perform the operation in the peripheral area, because a headland length of nearly 5 m is required for a returning operation. To generate the operation paths, one manual teaching run was performed along the field boundary, as shown in Fig. 5. Information on positions P_{0s} to P_{3e} and information on directions ϕ_0 toϕ_3 were obtained during the teaching run. As shown in Fig. 5, the operation paths consisted of,

a. The transference path 1 from a corner of the field, the entrance to the field,
b. Returning operation paths 1 to n, including the 180° turns in the headland,
c. Transference path 2 from the end of the returning operation path to the starting point of round operation, and
d. Round operation paths 11, 21, 31, ..., including the 90° turns in each corner of the field.

In path planning, it was assumed that the operation ended near the entrance to the field. By following the procedures of the actual operation reversely, the routes of 3

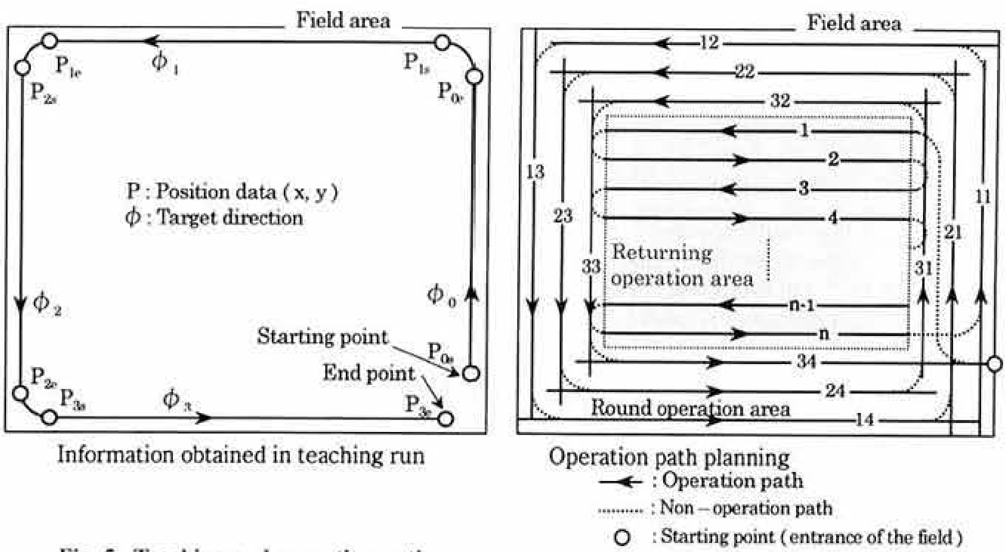

Fig. 5. Teaching and operation path

round operation paths were set so that the overlap between work areas was 10 cm, and the number of paths and routes of returning operation were set for the remaining area with proper overlap.

(2) Operation software[10,11]

Operation software to perform "teaching", path planning and autonomous operation consists of multiple software modules. Fig. 6 shows the flow of general software. These software modules include "straight operation routine", "180° turning routine", "90° turning routine", "sideways movement routine", etc.

A returning operation consists of a straight run control and a 180° turn control. In the straight operation control routine (Fig. 7), an interval of 0.5 s was used to obtain position data and steering control. It was specified that heading data from the TMS would be applied to the straight run control for the period of time when normal position data could not be obtained. In addition, countermeasures were implemented, such as temporary retraction after an 180° turn to facilitate sideways movement for adjusting overlap at the starting point of tilling.

In the round operation module, highly precise positioning is required to avoid any extrusion beyond the border of the field area, to ascertain that there are no untreated areas and to minimize stamping of the treated area. Therefore, the following measures were incorporated:

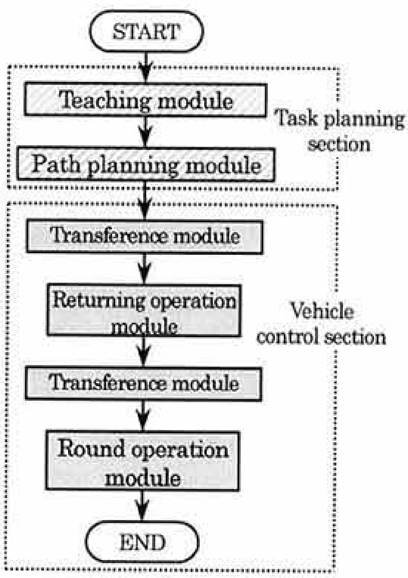

Fig. 6. Main flow chart of operation

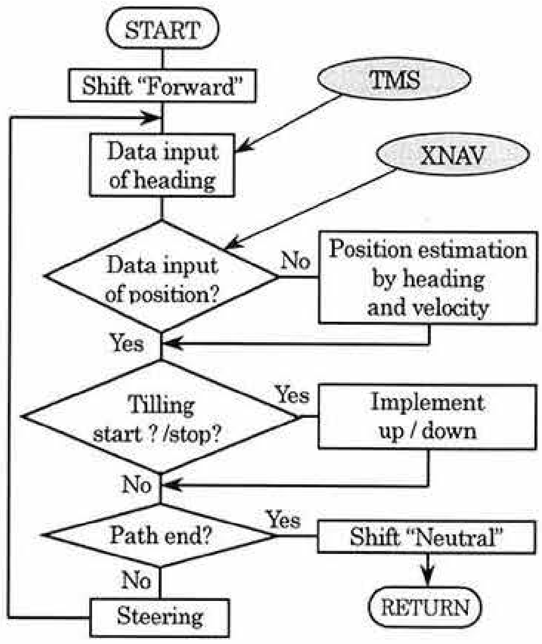

Fig. 7. Flow chart of straight operation routine

Table 4. Examples of self-diagnosing objects

No.	Item	Check criteria
1	Position data	1) normally acquired ? 2) in the field area ? 3) fluctuation is small ?
2	Heading data	1) normally acquired ? 2) in the direction along the longer side of field ? 3) fluctuation is small ?
3	Inclination data	1) normally acquired ? 2) almost level ?
4	Operation mode	automatic control mode ?
5	Gear position	set position ?
6	Position lever	in controllable position ?
7	PTO	turned on ?
8	Fuel	level > 1/2 ?
9	Steering	automatically actuated ?

Table 5. Checking of abnormalities

No.	Abnormal state
1	Position data abnormality-1 (data cannot be updated / data are abnormal)
2	Position data abnormality-2 (auto-recovery cannot be operated)
3	Position data abnormality-3 (data are outside of the field)
4	Excessive speed due to "dashing", etc.
5	Decrease in speed due to slippage, etc.
6	Excessive inclination
7	Overload to engine
8	Fuel shortage
9	Detection of obstacles

a. Small retraction or switchback before a 90° turn,
b. Guidance to the target route after the turn, by sideways movements of forward and backward runs, and
c. Providing learning function for the turning radius.

Options to change the operation method depending on the conditions of the field have been provided, such as performing round operations of the whole field or returning operations to diagonal directions of the rectangular field.

In addition, the positioning accuracy was improved at the end of the path by concurrently using dead reckoning at intervals of 0.1 s, based on the heading information and vehicle velocity.

Table 6. Results of work performance tests (area: 50 a)

Operation	Unmanned with XNAV	Manual operation
Operating velocity (m/s)	0.50	0.50
Machine efficiency (min/10a)	25.7	24.6
Operator efficiency (min/10a)	2.7	25.3
Remaining untilled area (a)	0.0	0.4
Wheel tracks on tilled area (m)	67.4	13.1
Deviation of straight ope. (cm)	2.7	19.1
Parallelism of straight ope. (°)	0.01	0.44
Recovering time in case of trouble (min)	–	3.4

(3) Self-diagnosis and abnormality alarming[3]

To secure the reliability and safety of unmanned operations, this system is required with the following functions:

a. A "self-diagnosis" function for confirming the normal operation of various sensors, actuators and control adjustment before starting the operation, and
b. An "abnormality alarming" function for detecting the abnormalities of the system, and indicating any abnormalities to the operator (supervisor) during the operation, and/or temporarily discontinuing the operation until the abnormal state is eliminated.

These functions are incorporated into the operation software, as shown in Tables 4 and 5.

(4) Work performance[4]

To evaluate the performance of unmanned operation, we planned and executed 3 categories of evaluation tests as follows:

a. Work performance tests to check the work efficiency and accuracy,
b. Operation tests to check the ease of use and safety in the installation and setting of the robot, and
c. Reliability tests to check the resistance to environments and the safety and reliability of work.

To evaluate the effect of labor-saving by unmanned operation, in the work performance tests, we introduced such indexes as operator efficiency which refers to the time during which the operator works in a unit area. And to evaluate the work accuracy, indexes on straight running performance were introduced, too.

Evaluation tests were executed in several fields. In some of the work performance tests, conventional manual operations were performed with the ROBOTRA by a skilled worker as well as under the conditions of unmanned operations. Examples of test results are

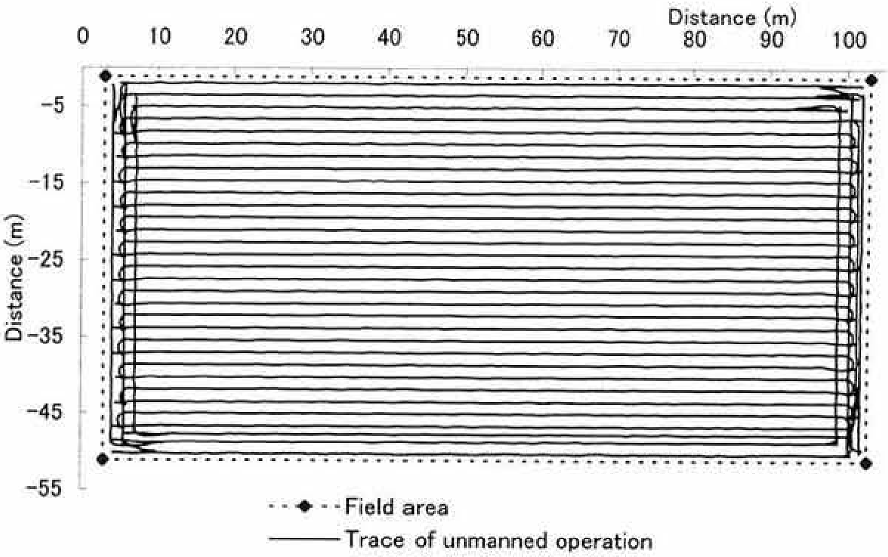

Fig. 8. Trace of unmanned operation with XNAV in a paddy field

shown in Table 6, and the trace of unmanned operation with the ROBOTRA and XNAV system in a paddy field 100 × 50 m in size is shown in Fig. 8. The overlap between work areas was set at 10 cm for both returning and round operations with a 1.7 m width implement. We found that the work efficiency and the work accuracy were nearly equivalent to those of conventional manual operations. In the straight running performance, the robot was superior to a skilled operator. Throughout the evaluation tests, no trouble occurred and there was no problem in the resistance to environments and the durability of the robot.

Conclusion and prospects

The authors carried out studies on navigation systems such as LNAV, SNAV, XNAV and TMS for tilling robots. Using these navigation systems, the position of the moving vehicles can be recognized with an error less than 5 cm and at intervals less than 1 s. During these studies, we attempted to use them for field operations as far as possible and investigated the feasibility of robotizing agricultural vehicles.

The tilling robot was composed of these navigation systems, the prototype vehicle, the controller and the operation software. We observed that the tilling robot can perform unmanned tilling over a whole field area of more than 50 a with almost the same efficiency and accuracy as manual work. However, when an unmanned vehicle performs an operation such as tractor work, any abnormality or problem of hardware or software may lead to a serious accident. Therefore, the tilling robot was fitted with the self-diagnosis and abnormality alarming functions, which conferred a high reliability and provided a fail-safe system for any emergency.

Furthermore, when these technologies are introduced into actual fields, the following applications must also be studied.

1) A single operator supervises several tilling robots that operate simultaneously.
2) The operator performs other tasks while supervising the operation of the tilling robot.
3) The tilling robot is also used for such operations as soil puddling, ridging, etc.
4) New working methods are developed to maximize the use of the robot's ability.

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