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Robotization of Agricultural Vehicles (Part 1) — Component Technologies and Navigation Systems —

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Abstract
Studies on the robotization of agricultural vehicles have been conducted to perform labor-saving, high-precision operations, etc. Component technologies for the robotization were described in general, along with navigation systems. As an example of robotized vehicles, we planned to develop a tilling robot, To recognize the position with an error less than 5 cm and at intervals less than 1 s, we developed 3 types of navigation systems; an off-the -wire type, a kinematic global positioning system (GPS) with inertial navigation system (INS) type and an optical type.

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

Introduction—Objectives of robotization of agricultural vehicles

Currently, whether the agricultural industry in Japan will be able to survive is a cause for concern due to the difficulty in finding successors and the rapidly expanding market for imported agricultural products. Efforts are being made to promote the industry through labor-saving, lower costs, and enhanced product quality. In addition, studies on the robotization of agricultural vehicles have been conducted in recent years[2)] to achieve the following objectives[3)]:

1) Labor-saving through completely unmanned operations,
2) High-precision work superior to human work, and
3) Improvement of safety and amenity by eliminating operator intervention.

Subsequently, new working methods will be developed in response to the robotization of agricultural vehicles and the following additional benefits are anticipated[3)]:

1) Single operator can manage and operate many vehicles concurrently,
2) Through continuous day and night work, a small machine can cover a large area and solve problems such as soil compaction, and
3) The ability to detect vehicle positions will enable to obtain information on yield and soil conditions of each part of the field, and to execute precision farming.

This paper describes the navigation systems we studied, together with the control of vehicles with these systems and the performance of their prototypes.

Technology and conditions required for robotization of agricultural vehicles

1) Component technologies[3)]

The component technologies that support the robotization of agricultural vehicles are similar to the 5 main components for common mechatronics systems, which are listed in Fig. 1. Each component is described below.

(1) The energy supply and operating functions require technical developments, in addition to conventional technology, in the following areas:

a. While an actuator mechanism which provides excellent control is required for the steering, throttle, transmission, and brake operations in place of an operator, conventional systems for manual operation are also required for traveling to and from the field and teaching the field area.
b. Various adjustments of the implements must be automated to enable unmanned operation.
c. Power sources corresponding to the sensor and actuator are required.
d. Each part must be highly reliable since prompt detection of failures cannot be expected during unmanned operation.

(2) The information transfer and signal conversion functions require a keyboard and monitor for dialogues between the robotized vehicle and the operator. In addi-

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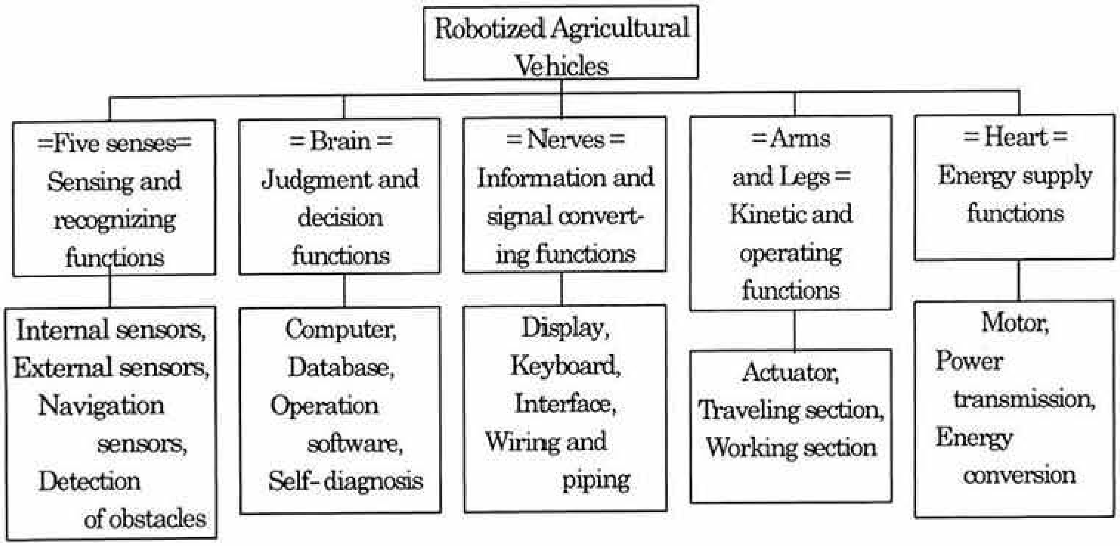

Fig. 1. Component technologies for the robotization of agricultural vehicles

tion, stable communication functions are required among the sensor, controller and actuator, depending on the navigation system used and also between the vehicle and an external device.

(3) Judgment and decision functions determine the vehicle behavior. These are the basis of the system, which is composed of a computer, hardware including peripheral devices and software. The know-how necessary to perform unmanned operations is incorporated into the software. A slight error in judgment and control may lead to an accident. Therefore methods such as a division of tasks are required for avoiding such malfunctions, and sufficient field tests under various conditions are also required.

(4) For the sensing and recognition functions, the robot itself must detect internal information such as the fuel level and operating conditions of each part, as well as external information such as the vehicle position, heading, and the status of the soil and peripheral conditions. Although the information about navigation is particularly important for the robotization of vehicles, since no navigation system currently in use efficiently meets the

Table 1. Conditions for using mobile robots for various purposes

	AGV in factories	Construction	Agriculture
Range of use	<Several hundreds of meters	<Several hundreds of meters	<Several hundreds of meters
Traveling distance	<Several kilometers	<Several hundreds of meters	<Several kilometers
Traveling method	Along the track	Whole surface Along the track	Whole surface
Road surface	Hard and flat	Slightly soft and irregular	Soft and irregular
Inclination	Horizontal	Nearly horizontal	Slopes are included
Dust, etc.	Small amount	Large amount	Large amount
Velocity	Low	Low	Low
Continuous operating hours	Short	Long	Long
Place of use	Indoor	Indoor and outdoor	Outdoor
Intrusion of outsiders	Can be prevented	Can be prevented	Cannot be prevented
Operator	Semi-professional	Professional	Non-professional
Annual operating hours	Long	Long	Short

Table 2. Classification of navigation systems for agriculture

Route	System	Object of detection	Example of target, sensors, facilities, etc.
Fixed	Mechanical system	Mechanical guides	Ridges, furrows, pipes, rails
	Non-contact system	Non-contact guides	Leader cables, laser beams
Semi-fixed	Spot mark system	Spot marks	Magnetic signs
Free	Internal information system with inertial navigation	Acceleration	Gyro+accelerometer
	Internal information system with distance and heading	Distance(velocity) +heading	Wheel rotation+gyro, geo-magnetic sensor
	Internal information system with differential wheel rotation	Right and left wheel rotation	Wheels, crawlers
	External information system with object tracking	Crop rows, work boundaries, etc.	TV cameras+image processor
	External information system with relative distance	Hedges, ridges, crop rows, etc.	Ultrasonic sensor, off-the-wire leader cable
	External mark system with triangulation surveying	Multiple relative angles	TV cameras, optical sensors +optical reflection marks
	External mark system with traverse surveying	Relative angles +distance	Transit+ranging sensor (with tracking vehicles)
	External mark system with hyperbolic navigation	Multiple distances	Radio beacons, laser beacons, GPS

Table 3. Applicability of navigation systems for agriculture

Navigation system	Restriction on use	Applicability to agricultural systems*					
		Paddy field	Upland field	Green-house	Orchard	Grass-land	Interior of facilities
Fixed route with mechanical system	Routes are limited	×	×	○	○	×	○
Fixed route with non-contact system		△	△	◎	◎	×	◎
Spot mark system	Requires concurrent use of other navigation methods	△	△	○	△	△	○
Internal information system	Cumulative errors become a problem in case of long distance or long time operation	△	△	△	△	△	△
External information system	Crop rows, etc. to be tracked are indispensable	○	○	◎	○	○	○
External mark system	No obstacles such as trees in case of an optical system	◎	◎	△	△	◎	△

* Applicability was estimated based on common field area and form.
◎ : Applicable to almost all types of operation. ○ : Applicable to selected types of operation.
△ : Applicable to limited types of operation and sizes of field. × : Not applicable to almost all types of operation.

requirements of cost, performance, and ease of use, new technology must be developed.

2) Conditions for development and introduction

Each component described before is required for robotization of vehicles to function under the conditions of use required by outdoor agriculture. Table 1 shows the conditions of use as compared with those in other fields. The conditions of use for agricultural vehicles, such as the operator, annual operating hours, and the capital of the managing body, differ markedly from those in other fields. Therefore, considerations for lowering the cost, enhancing the reliability, and improving the operation should be included from the beginning of development.

Navigation systems—classification and objectives

1) Classification and adaptability of navigation systems

Classification of navigation systems is shown in Table 2[5]. Because fields vary widely depending on the kind of crops and the stage of work, there is no universal navigation system that can adapt to every stage of agriculture. Table 3 shows the general adaptability of the respective navigation systems in the case of agriculture[6]. In the following, general conditions and the restricting factors are described.

(1) In paddy fields or upland fields, since the whole field is tilled, it is almost impossible to use a fixed route with a mechanical system. Furthermore, because the running route is fixed, a fixed route may lead to the deterioration of soil penetrability due to the pressure on the soil.

(2) When using the spot mark system, the other navigation systems must be applied between the marks.

(3) The accuracy of the internal information system will decrease in a large field or during long continuous work. A field with a slippery surface may cause an error in the estimation of the traveling distance based on wheel rotation.

(4) When visually observing external information from the vehicle, such as a known point, an error may occur due to the rolling and pitching of the vehicle, which requires a correction.

(5) Since no stable map in the field, is available, it is difficult to apply the map matching method used in the case of car navigation.

(6) The external information system may not be applied where the work boundary is unclear, such as during puddling, or in the absence of ridges or row edge.

(7) When using the external mark system, the measurement may be hindered by obstacles, depending on the observation medium. For example, when light is used as the medium, shade from trees in an orchard may occur, or the measurement may not be correct due to reflected rays from a glasshouse.

2) Navigation systems for tilling robot

As an example of robotized agricultural vehicles, we planned to develop a tilling robot that can recognize its

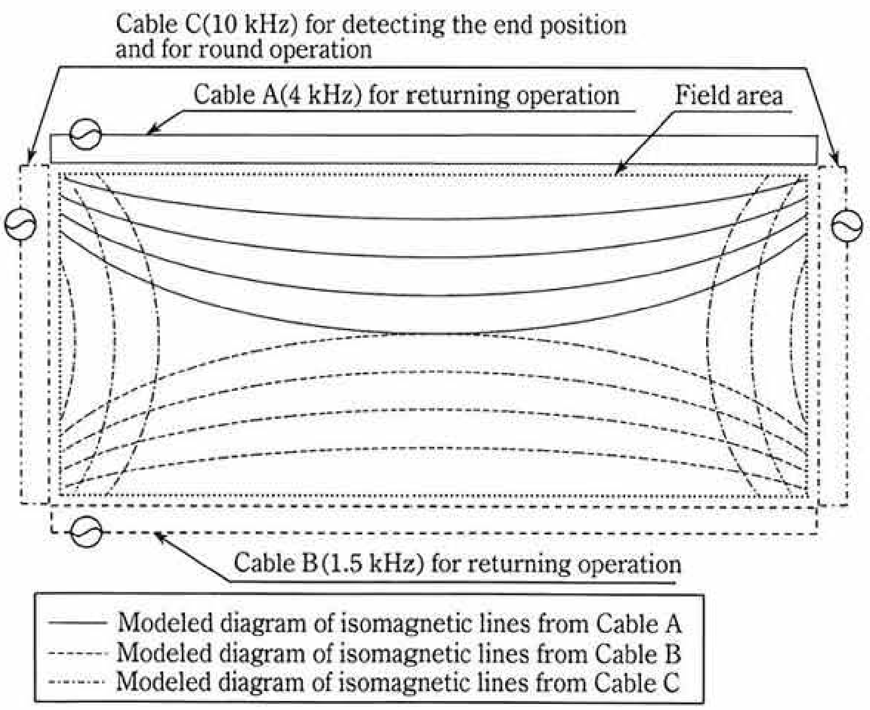

Fig. 2. Cable installation for LNAV

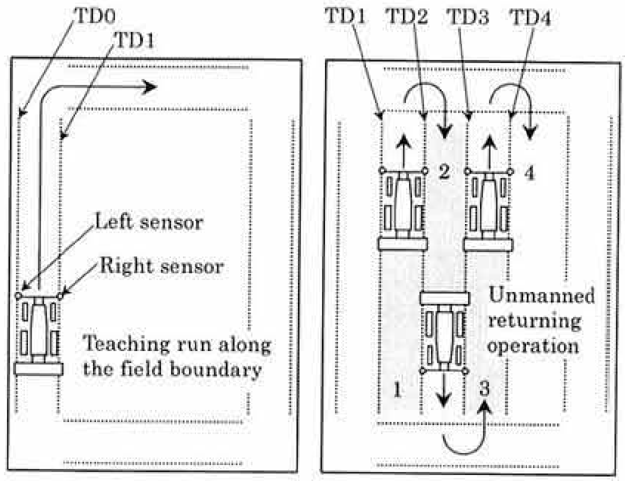

Fig. 3. Operation method of LNAV

own position and heading, while performing unmanned tilling at almost the same work rate as manual work.

Based on the above factors, external information system and the external mark system of a free route type were considered to be suitable for the position detecting system for tilling robots. Furthermore, we estimated that the concurrent use of an internal information system with distance and heading system is adequate for detecting the vehicle heading in the turning and for temporarily continuing the unmanned operation during a malfunction of the positional detecting system.

Among the navigation systems described in this section, the systems that have been studied are outlined below.

Navigation systems—positioning systems

1) Development of off-the wire type navigation system (LNAV) [6,7]

The LNAV developed by KUBOTA Co. is a navigation system characterized by a free route and external information with a relative distance. The cables for generating the magnetic fields for each modulation frequency are installed, as shown in Fig. 2. Although the magnetic fields are generated in the field depending on the distance from each cable, the relation between the strength of the magnetic field and the distance is not linear, since each cable has a finite length. Therefore, as shown in Fig. 3, a magnetic field sensor is mounted on the right and left front parts of the vehicle. The vehicle performs a teaching run along the field boundary by manual operation. The teaching data TD0 related to the boundary of the field are obtained from the left sensor, and the teaching data TD1 of the magnetic field distribution along the first returning path are obtained from the right sensor. Then, the magnetic field distribution data at the end of the path are also obtained. In the first returning path in an autonomous operation, while performing an autonomous straight run by referring to the TD1 from the left sensor, the vehicle automatically obtains the TD2 for the next path from the right sensor. After the 180° turn based on information on the end position, the vehicle performs the next straight run according to the TD2. In this way, the LNAV does not detect the absolute position in the field but guides the vehicle to repeat the magnetic field distribution initially obtained for performing the operation.

Based on the above description of the LNAV system, no test was performed to measure its positioning accuracy, but because it could accurately repeat the autonomous run on the taught path, it was estimated that with this system the error was 5 cm or less. Furthermore, the data sampling interval was 0.1 s or less. This system is not influenced by natural conditions like weather. However, the cost to construct the cable line and the fixed path for work are limiting factors.

2) Development of GPS type navigation system (SNAV) [6,7]

The SNAV developed by Japan Aviation Electronics Industries, Ltd., is a navigation system characterized by a free route and external marks with hyperbolic navigation.

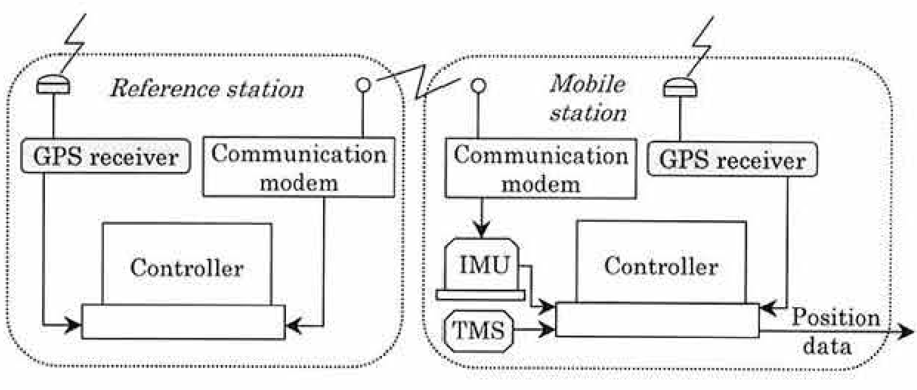

Fig. 4. Configuration of SNAV

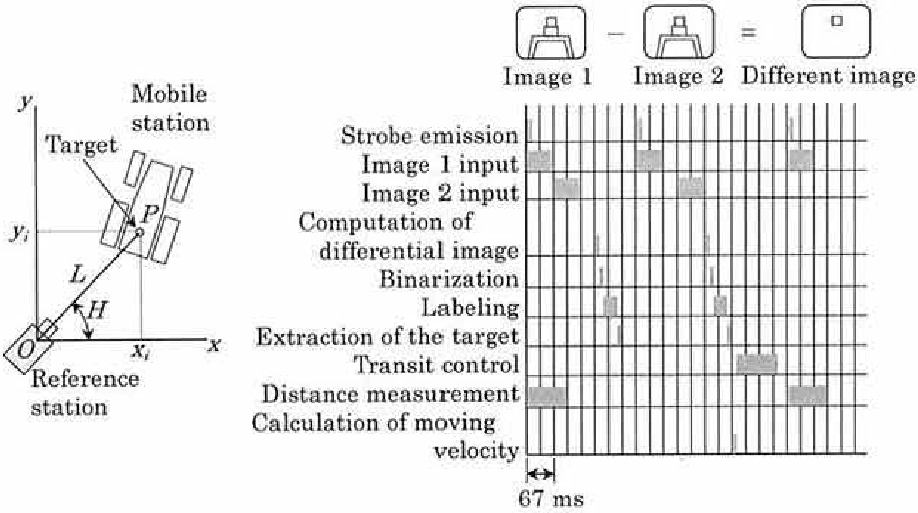

Fig. 5. Measurement principle and time chart of tracking in XNAV

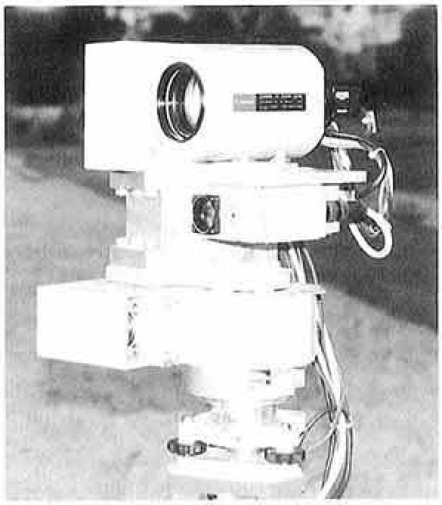

Fig. 6. Reference station of the prototype XNAV system

In the SNAV the differential GPS (DGPS), geomagnetic sensor (TMS) and the inertial measuring unit (IMU) are combined with the device configuration as shown in Fig. 4. The GPS system has a data sampling interval of 1s basically. As the communication and processing times are added, the calculated DGPS position data involve a considerable delay. The SNAV supplements the positions during such delays using an IMU.

Presently, satisfactory positional detection has been achieved at intervals of 0.1 s. The positioning error amounted to several cm or less over several hours of measurement when the mobile station was fixed to a position. And the errors in autonomous operation were 10 cm or less due to the decrease of the turning velocity in taking account of the capacity of the IMU.

Several types of GPS positioning systems have been commercialized by several companies. The accuracy and the sampling rate are sufficient in the double frequency real time kinematic GPS type. However, the cost and information service of the reference station are still unsolved.

3) Development of optical type navigation system (XNAV)[4,6]

The XNAV is a navigation system characterized by a free route and external marks with traverse surveying. The XNAV was developed by BRAIN–IAM and the manufacture of its prototype was assigned to Sanyo Electric Co., Ltd.

(1) System configuration and principle

The principle of the XNAV measurement is shown in Fig. 5. Target P, installed on the vehicle, was observed from the center 0 of the transit section of the reference station. The diagonal distance L between O and B, the horizontal angle H formed by the reference line and segment OP, and the vertical angle V are obtained. And then the coordinates of the target point P (x_i , y_i , z_i) are obtained through the principle of traverse surveying. Although segment OP can always be obtained by tracing and estimating the target from the reference station (Fig. 6), the steps to follow are shown in Fig. 5.

a. Input image 1 when the strobe light on the target is lit and image 2 when it is not lit at the shortest possible interval,
b. Compute the differential image between image 1 and image 2, and binarize it,
c. Extract the strobe image from the differential image,
d. Repeat steps a to c to calculate the traveling speed of the target,
e. Move the transit section so that the strobe image appears in the center of the image sensor, and

Fig. 7. Reference station of AP-L1

f. Measure distance L and calculate the position.

(2) Performance, precision, and ease of use

In the test results of the XNAV, the positions were detected during continuous operation of approximately 15 min at the velocity of 0.4 m/s in a roughly flat field 45×15 m in size. The positioning accuracy was 5 cm or less with an average data sampling interval of 0.52 s. However, sometimes the target was missed during a steep turn. Manual coordination was required on 2 occasions, and at other positions the measurements could be continued by using the self- tracking restoration function.

(3) Characteristics and problems

Although this system does not require field equipment other than one reference station in the field, there are shortcomings, including adaptation to the changes in natural lighting conditions and reliability of the self-restoration function.

(4) Total station of automatic tracking type AP-L1[1)]

Total station AP-L1, with an automatic tracking function for moving objects, was put on the market by TOPCON, Co., while the XNAV was under development. The AP-L1 is able to track and range the target automatically by a single laser beam, and is also equipped with automatic searching and retracking functions when the target is missed. In the same way as the XNAV, the AP-L1 measures the diagonal distance L and the horizontal and vertical angles, H, V while tracking the optical reflection target from the reference station (Fig. 7). It also calculates the 3-dimensional coordinate positions of the target point. As a result of field tests, we found that it fully reaches the target accuracy and tracks a moving object in a very stable manner. We confirmed that it can perform automatic tracking, position measurement, and data communication at a distance of 500 m in an area with good perspective. At that point, the modification and improvement of the XNAV were discontinued and the AP-L1 was used in place of the XNAV in subsequent tests. The main specifications of the AP-L1 are shown in Table 4.

Table 4. Specifications of the AP-L1

Automatic tracking section	Tracking angular velocity	: 10°/s
	Tracking accuracy	: ± 2 min (at 10°/s)
	Laser	: LED Laser (Class 1)
Range finder section	Range	: 7–700 m
	Accuracy	: ± (10 mm + 2 ppm)
	Intervals	: > 0.5 s
Transit	Accuracy	: 3s
Function, etc.	Automatic target searching and retracking function, Data communication : RS232C, Radio modem	

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