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REVIEW

Enhanced Adaptability of Tilling Robot (Initial Report)
- Outline of a Tilling Robot and Enhanced Adaptability of Unmanned Operation -

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Abstract
The tilling robot mainly comprises: a robot vehicle called ROBOTRA, which is remodeled to control parts of commercially available tractors automatically, a navigation system called XNAV, which detects and outputs robot positioning information using an auto-tracking type surveying device, and a controller with read operation software to execute path planning and control the robot vehicle. The robot has ability almost equivalent to that of customary manned-driven tractors and can perform unmanned rotary tilling on a rectangular field. To improve its adaptability during unmanned operation, we remodeled it so that it could perform path operations differing from customary rotary tilling and performed field tests. We proposed two different path operation methods: “diagonal operation”; performing returning straight operations diagonally against the longer side of the field; and “round operation”; performing straight operations parallel to the four sides in the entire field area, and developed a software package for the same. Following field tests using the software, we confirmed that favorable unmanned operation could be achieved through both methods.

Discipline: Agricultural machinery
Additional key words: customary operation, diagonal operation, path planning, round operation, super labor-saving

Introduction

This research was performed with a view to easing the required labor and costs incurred in farm operation through the robotization of agricultural machinery. Specifically, the research targeted the improved adaptability of unmanned operation using robotized tractors; assuming the use of unmanned tractors for farm operation and effective labor-saving of agricultural production through robotization would be ensured.

Unmanned or robotized agricultural vehicles, typically tractors, will be realized, based on conventional manned vehicles, by researching and developing an automatic control mechanism for each vehicle component, a navigation system for self-driven vehicles and a controller which performs vehicle control with navigation and vehicle information. Built-in controller software must be developed to obtain navigation and vehicle information and perform unmanned operation following the path planning or planned operational path. One of the development examples of achieving unmanned or robotized customary operation by utilizing conventional agricultural vehicles is our own development of “tilling robot”. The tilling robot, using a commercial 24kW-class tractor as a base vehicle, has almost equivalent ability to customary manned-driven tractors and can perform unmanned rotary tilling on a rectangular field by applying a navigation system (called XNAV) which uses an auto-tracking type surveying device (Topcon Corporation’s AP-L1), for example[2,3,10,11].

Another development example which achieves unmanned operation on a practical level is a “robot tractor”, which is based around a commercial 55kW-class tractor and utilizes RTK-GPS and FOG as its navigation system[1].

One example of an unmanned or robotized agricultural vehicle other than a tractor, which is also capable of performing unmanned operation on a field of about 30a

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with long-mat type seedling is a “rice-transplanting robot”, which uses a commercial 6-row rice transplanter as a base vehicle and RTK-GPS and FOG as a navigation system[7]. A “cable navigation type unmanned speed sprayer”, which uses a speed sprayer as its basis and enables unmanned pest control operation[9] and a “lawn mowing robot,” an unmanned and robotized machine based on lawn mowers used on golf courses[8], are commercially available.

The aim of this research was to expand the adaptability of the unmanned operation of the above-mentioned tilling robot (hereinafter referred to as “Robot”). We strove to expand and improve its adaptability by improving and making a program (hereinafter referred to as “operation software”) to be incorporated into the Robot controller that applies a navigation system called XNAV, which can obtain information on the tractor’s positioning and travel direction, and demonstrated its effect through a field test[4-6].

In this (initial) report, we propose a “diagonal operation” method, whereby the returning operation is performed diagonally against the longer side of the field and a “round operation” method, whereby straight operation is performed in parallel to the four sides in the entire field area. We developed the operation software to execute the operation methods and conducted field tests, the results of which are reported here.

We propose the diagonal operation method to efficiently till and smooth a field, including ridge breaking after planting of ridge making, conducting the diagonal operation at the arbitrary angle required for unmanned operation in a non-rectangular field, and using the round operation method to perform unmanned harvesting, mowing, fertilizer application, etc.

The second report describes the test results of the simultaneous two-vehicle operation performed as research into unmanned operation with the Robot (an operation method whereby one operator performs manned-driven operation with a conventional tractor and unmanned-driven operation with the Robot simultaneously), and the development and test results of the operation software that implements seeding and soil puddling.

Overview of the Tilling Robot

The composition of the Robot and the operation software for rotary tilling, which have formed the basis of the current research, are outlined in this report, though they have already been reported[10,11].

1. Composition of the Robot

The Robot mainly comprises a “robot vehicle”, modified from a commercial agricultural tractor, to automatically control each component, a “navigation system” to detect and output information on robot positioning and direction, and a “controller”, in which navigation data from the navigation system and status data on each component of the robot vehicle are input to perform operation according to the operation software, the scope of which includes path planning and control of the robot vehicle.

The robot vehicle was modified using a commercial tractor with 24.3kW engine power (Kubota GL321) as the base to automatically control each component, such as the steering mechanism and shuttle gearshift (switching among forward, reverse, and stop). Figure 1 shows a photograph of the tilling robot. Figure 2 shows the measurement/control system of the Robot, comprising the robot vehicle, the navigation system and the controller.

2. Navigation System

For the XNAV navigation system used in this research, the AP-L1 auto-tracking type surveying device located outside the operational field automatically tracks the light reflector placed above the center of the rear tractor axle, and detects the tractor positioning information based on an approx. 0.5 second cycle. The detected positioning information is then transmitted wirelessly to the main controller on the Robot. Information on the travel direction of the Robot is detected by the geomagnetic direction sensor and the inclination information (roll and pitch angles) by the servo-type inclination sensor.

With regard to the status information of each component of the Robot, output data from the sensor already placed on the base tractor, as well as the potentiometer and limit switch placed on the control unit, are measured by the vehicle controller and input into the main controller as numerical data.

3. Basic Operation Software

A “basic operation” method performed by the Robot

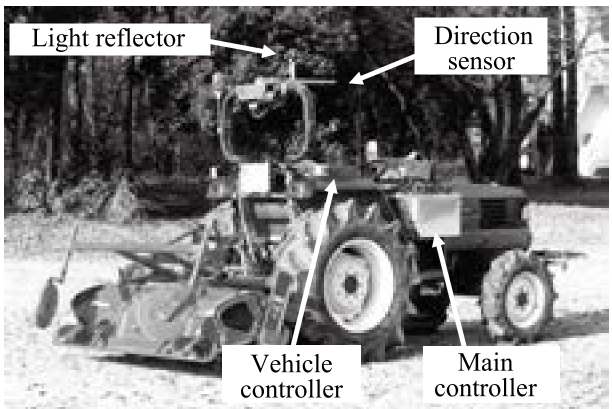


Fig. 1. Tilling robot

according to the customary rotary tilling method is as follows: in any area of the rectangular field, except the periphery, returning operation are performed repeatedly in the direction of the longer side. Subsequently, in the peripheral area of the field, including the headland, operations in several rounds parallel to each side (hereinafter referred to as "round operations") are performed several times. The basic operation software used to perform this operation method consists of the teaching and path planning modules, which respectively transmit the field data to the Robot, and the returning and round operation modules, which execute unmanned operation. The teaching module obtains positioning information on basic travel and operation directions and the operation field by manually moving the Robot round in the outermost path (11, 12, 13 and 14) along the field borders ① to ④ shown in Figure 3.

(1) Path Planning

In this research, the robot vehicle was made by putting a rotary tiller (the operation width W=170 cm) on the tractor. The number of rounds for round operations was set to 3.

In the path planning module, contrary to the actual operation sequence, the 3 rounds of round operations path with the operation pitch W_1 are set, followed by the number of strokes and the path to perform returning operation exceeding the target operation overlap width d_0 (10 cm in this example) in the area (returning operation area), after deducting the operation area from the entire field.

Figure 3 shows an example of the paths set in the basic operation method with 3 rounds. In the coordinate system used for the positioning information in the field, the longitudinal side direction of the rectangular field is parallel to the X-axis. If the positions of the field borders ① to ④ are supposed to be $x = X_{b0}$, $y = Y_{b0}$, $x = X_{b1}$, and $y = Y_{b1}$ in sequence, the length L_x and width L_y of the shaded returning operation area in Figure 3 ($L_x \geqq L_y$) can be represented by the following equations:

$$L_x = X_{b0} - X_{b1} - 6W_1 \qquad (1)$$

$$L_y = Y_{b1} - Y_{b0} - 6W_1 \qquad (2)$$

The number of strokes N_c and the operation pitch W_c of the returning operation are respectively determined by the following equations:

$$N_c = L_y /(W - d_0) + 1 \qquad (3)$$

(N_c is an integer obtained by omitting figures below the decimal point.)

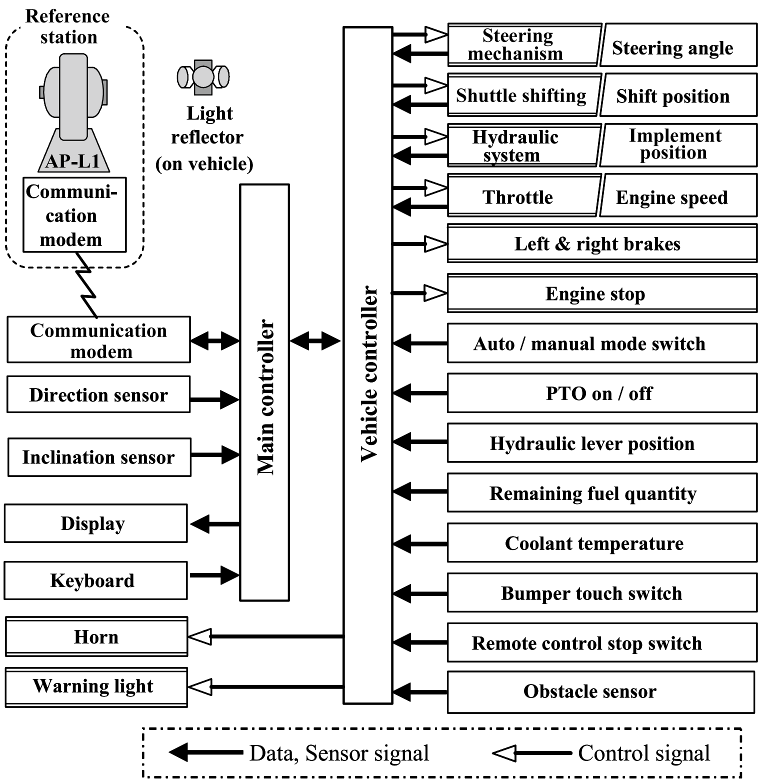


Fig. 2. Block diagram of the control and sensing systems

$$W_c = L_y / N_c \tag{4}$$

In the path in Figure 3, the entrance and exit are supposed to be near one corner (the bottom-right corner of Figure 3) and the starting point of returning operation is set on the shorter side near the entrance and exit. Figure 3 shows a path when the number of strokes N_c is even. When it is odd, the returning operation will finish on the left side of the field, whereupon the Robot will make a 180-degree turn and engage in idle travel to the starting point of round operations.

(2) Performing Unmanned Operation

Unmanned travel and operation on these paths are performed using the straight traveling control, the turning control, or the sideways movement control on paths such as previously reported. In the basic operation method intended for rectangular fields, all paths for straight operation are parallel to the axes. The straight operation on the paths can therefore be realized by vehicle guidance, through which X- or Y-coordinate values, sequentially obtained as the travel direction and positioning information of the Robot (vehicle), should be constant.

Diagonal Operation Method

An operation method in which returning operation is performed diagonally at an arbitrary angle against the longer side of the field in the returning operation area in the basic operation mentioned above. This operation method is referred to as a “diagonal operation” method, and we developed the operation software to execute such path planning and unmanned operation (referred to as the diagonal operation software).

When developing the diagonal operation software, we tried to make the algorithms for the positioning and control of the vehicle conform to those of the basic operation software with verified control performance for the vehicle as far as possible. Round operation in the peripheral area of the field, including the headland for the diagonal operation, was to be performed as with round operations in the basic operation method.

1. Path Planning and Vehicle Guidance

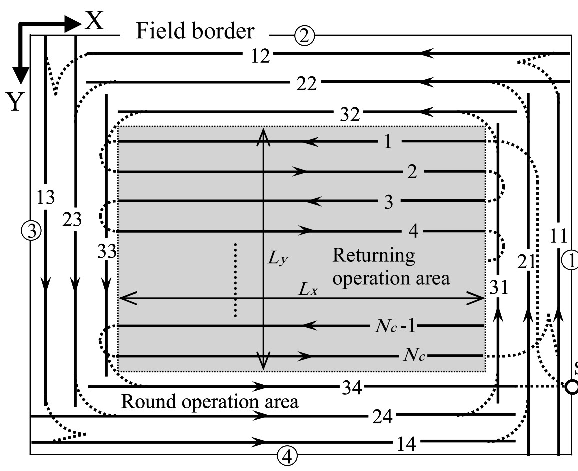
Figure 4 shows an example of the paths set in the diagonal operation method. In the position coordinate system during unmanned operation, the shorter and longer sides of the rectangular field are set to be parallel to the axes of the coordinates, and when the diagonal operation at angle θ against the longer side of the field is operated, the target path at the time of operation is the following straight line assuming X-intercept as D:

$$X = -Y / \tan\theta + D \tag{5}$$

To travel on this path, the vehicle should be steered so that the vehicle position (X_t, Y_t), which changes from moment to moment, can follow this straight line.

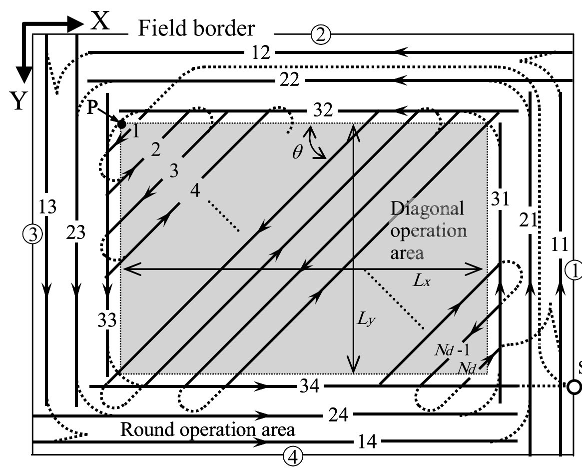
Here, to ensure the positioning and control algorithms of the vehicle for the diagonal operation conform to those of the basic operation software, the following geometric transformation at the diagonal angle θ was conducted for the vehicle position (X_t, Y_t) and target path:

$$\begin{matrix} Y' \\ X' \end{matrix} \quad \begin{matrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{matrix} \quad \begin{matrix} Y \\ X \end{matrix} \tag{6}$$



: Operation path, : Non-operation path (turning, sideways movement, etc.)

Fig. 3. Example of operation paths for the basic operation



: Operation path, : Non-operation path (turning, sideways movement, etc.)

Fig. 4. Example of operation paths for the diagonal operation

By steering the vehicle so that Y_i after geometric transformation can be kept constant, straight traveling on the path is ensured.

Assuming that the length L_x and width L_y ($L_x \geqq L_y$) of the shaded diagonal returning operation area in Figure 4 are the same as those in the basic operation method, the diagonal line length L_{xy} and diagonal line angle α in the area are determined as follows:

[illegible] (7)

$$\alpha = \tan^{-1}(L_x / L_y) \tag{8}$$

The operation pitch W_{ld}, number of strokes N_d, and practical operation pitch W_d diagonally in the diagonal returning operation are determined as follows, with the target operation overlap width d_0 to secure more than the actual operation overlap width:

$$W_{ld} = (W - d_0) / \cos(\alpha - \theta) \tag{9}$$

$$N_d = (L_{xy} / W_{ld}) + 1 \tag{10}$$

(N_d is an integer obtained by omitting figures below the decimal point.)

$$W_d = (L_{xy} / N_d) \times \cos(\alpha - \theta) \tag{11}$$

If the point of the upper left corner in the diagonal returning operation area in Figure 4 is P (P_x, P_y), the positions of the field border ① to ④ are $x = X_{b0}$, $y = Y_{b0}$, $x = X_{b1}$, and $y = Y_{b1}$ in sequence, the operation width is W, and the operation overlap width in round operation is d_1:

$$P_x = X_{b1} + 3W - 3\,d_1 \tag{12}$$

$$P_y = Y_{b0} + 3W - 3\,d_1 \tag{13}$$

The points V (V_x, V_y) on the path of the first stroke are determined as follows:

$$V_x = P_x + (W_d / 2) \sin\theta \tag{14}$$

$$V_y = P_y + (W_d / 2) \cos\theta \tag{15}$$

Here, the path Y_{d1} of the first stroke, which is a target value of Y_i in equation (6), is determined as follows by the geometric transformation of the point V:

$$Y_{d1} = V_x \sin\theta + V_y \cos\theta \tag{16}$$

The target paths of strokes after the first will be shown by adding the practical operation pitch W_d to Y_{d1} in sequence.

The start and end positions of the diagonal returning operation were to be determined whether or not the vehicle position (X_t, Y_t) changed from moment to moment inside the diagonal returning operation area. In practice, to avoid leaving any area untilled, the operation start and end position will be determined by widening both ends by ($W/2 \times \sin\theta$) in the X-axis direction and ($W/2 \times \cos\theta$) in the Y-axis direction. The diagonal operation software was configured and developed by adopting geometric transformation based on the returning operation method during the basic operation so that the diagonal angle θ could be chosen arbitrarily.

2. Turning Method in Diagonal Operation

At the 180-degree turn at the end of the stroke, the vehicle may run over the field border during the turning, depending on the diagonal angle against the field border and the turning direction. In addition, if the distance to the operation start position for the next stroke after turning is insufficient, adequate sideways movement may not be performed. We therefore tried to ensure that the vehicle did not run over the field during turning by moving back before turning if a 180-degree turn was made at the side where the angle against the field steepened (when turning on the lower and right headlands in Figure 4). For a turn in the opposite situation (when turning on the upper and left headlands in Figure 4), we ensured the sideways movement distance by moving the vehicle back after turning. For the vehicle guidance in these turns, its execution and extent (reverse movement distance) were to be selected and set based on diagonal angle θ.

Round Operation Method

With regard even to the returning operation area in the basic operation method mentioned above, we propose a “round operation” method, in which the vehicle operates while rounding the entire field by repeating straight operation parallel to the four sides of the field in sequence.

This round operation method can be seen as one in which round operations in the basic operation method is performed in the entire field. We conducted path planning, which ensures consistent and smooth operation, based on a module which executes path planning and round operations of the basic operation software. Moreover, we also developed the round operation software capable of enabling the round operation method, with the vehicle guidance method feature used for turning.

1. Path Planning

During the round operation, an operation in one round parallel to the four sides of the field is considered as a single unit, and the number of rounds for treating the entire field is initially determined. As one round operation in the longitudinal side direction is performed for two strokes, the number of rounds is determined so that the quotient obtained by dividing the length (width) of the shorter side of the field by the operation pitch, which is a proper operation overlap width, should be an even number. Namely, if the field border positions ① to ④ in Figure 5 are $x = X_{b0}$, $y = Y_{b0}$, $x = X_{b1}$, and $y = Y_{b1}$ in sequence, the field width is T_w, the operation width is W, the target operation overlap width is d_0, the number of operation strokes in the longitudinal side direction is N_r, and the number of rounds is N_m, the following can be obtained:

$$T_w = Y_{b1} - Y_{b0} \tag{17}$$

$$N_r = T_w / (W - d_0) \tag{18}$$

(N_r is an integer obtained by omitting figures below the decimal point.)

$$\text{If } N_r \text{ is an odd number: } N_m = (N_r + 1) / 2 \tag{19}$$

$$\text{If } N_r \text{ is an even number: } N_m = (N_r + 2) / 2 \tag{20}$$

The operation pitch between neighboring strokes W_r is determined as follows:

$$W_r = T_w / (N_m \times 2) \tag{21}$$

The round operation to be performed with the number of rounds and the operation pitch determined in this way can be implemented in two ways. One is on a path where the round operation is advanced from the peripheral area to the center area (“round operation 1”), and the other is on a path where the round operation is advanced from the center of the field to the peripheral area (“round operation 2”).

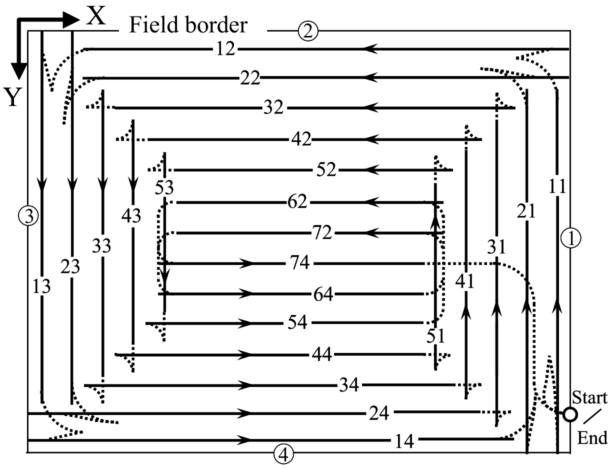
The round operation 1 is intended for harvesting, mowing, etc. Figure 5 shows an example of paths set using this method. For the sixth and seventh rounds near the center of the field, as the operational distance in the shorter side direction declines considerably, only operation in the longitudinal side direction (path numbers 62, 64, 72 and 74 in Figure 5) is to be performed. The round operation 2 is intended for tilling, fertilizer application, etc., and the path numbers in Figure 5 are in reverse order: 72 comes first and 14 comes last in the stroke.

2. Implementation of Unmanned Operation and Turning Method

As with the basic operation method, unmanned operation along the path is performed by using methods such as the straight traveling, turning and sideways movement controls as mentioned previously. However, since all turns between strokes are 90-degree turns in the round operation, we tried to keep the field surface as smooth as possible by forward or backward turning without using the independent braking system. When turning or moving sideways, vehicle guidance was performed to reduce wheel tracks in the untilled area in the round operation 1, and to reduce wheel tracks in previously tilled areas in the round operation 2.

For the vehicle guidance for turning, the turning when two rounds of operation are performed in the peripheral area of the field (11-24 strokes in Figure 5) is the same as that when round operations is performed using the basic operation method. For the rest (31-54 strokes in Figure 5), the vehicle moves forward by a constant distance after the straight operation, and then makes a 90-degree turn by moving backward with the steering angle constant (about 50 degrees). After turning, the vehicle moves sideways while moving forward, and when it reaches the operation start position, the tiller is lowered to start straight operation.

We developed the round operation software on the basis of the module, which executes the path planning and round operations of the basic operation software, by changing the vehicle guidance, etc. for turning between strokes.



: Operation path, : Non-operation path (turning, sideways movement, etc.)

Fig. 5. Example of operation paths for the round operation 1

Field Test and Evaluation of Each Operation Method

1. Field Test and Results

With regard to the basic and the diagonal operation methods, and the 2 round operation methods mentioned in the above Chapters, unmanned rotary tilling tests were conducted using the developed operation software. The field under test was a virtually flat test field (18.5 x 50 m) located within the premises of the Bio-oriented Technology Research Advancement Institution. The operation speed was about 0.5 m/s (velocity stage H1), and the diagonal angle in the diagonal operation method was 45 degrees.

Figure 6 shows how the test for the diagonal operation was conducted, while Figure 7 shows the operation trajectory of the round operation 2, and Table 1 shows the field test results. The operation trajectory in Figure 7 was produced from the positional data of the Robot, which, in turn, was measured by the auto-tracking type surveying device AP-L1, the reference station of the XNAV navigation system. The positional data is that of the light reflector placed in the middle position of the rear tractor axle, 2.1 m above ground and 1 m ahead of the rear of the rotary tiller.

The outlines of the indices of the test results shown in the Table are described in the notes of the same. The straightness and straight parallelism were calculated from the operational trajectory based on the positional data measured by the above-mentioned AP-L1.

The results shown in Table 1 and the traveling/operation trajectory at the time of unmanned operation indicate that in all the operation methods, there is no remaining untilled area; namely, no operation is left, or the Robot does not run over the field. Moreover, indices such as straightness and straight parallelism also indicate that the vehicle is properly controlled. While the operational (machine) efficiency was lower in the diagonal operation method with a greater number of turns, the efficiency of the round operation methods was within the same range as the basic operation method. With regard to wheel tracks on the tilled area, in the round operation 1, the area in which a 90-degree turn or sideways movement took place was often already tilled area, and naturally generated more wheel tracks. With regard to straightness and straight parallelism, the stroke is short in the diagonal operation method and it is considered that the declination towards sideways travel per stroke is larger. In the round operation 2, the fact that the area where turning and sideways movement were performed in the previous round is on the present operation path is considered to reduce the precision of straight traveling control.

Fig. 6. Field test of the diagonal operation with the tilling robot

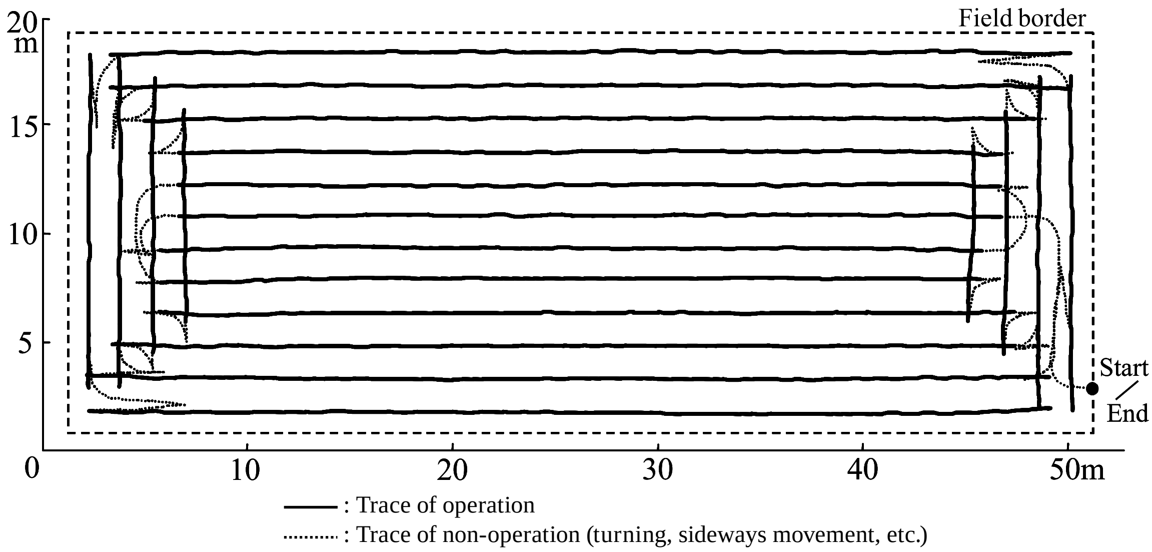


Fig. 7. Trace of unmanned operation in the field test of the round operation 2

2. Evaluation of Each Operation Method

Judging from the above-mentioned test results, it is clear that the Robot can perform not only the basic operation but also the diagonal and the round operations highly efficiently and accurately. Therefore, it seems that the tilling robot or structurally similar robot systems can perform fertilizer applications and mowing, etc. highly efficiently and accurately. Also, it seems that the diagonal operation method allows the Robot to perform unmanned operation, even in non-rectangular fields.

In the basic operation method, the travel direction at the time of operation is parallel to any of the four sides of the field, and using this operation method, it may be easier to set a target of judgment on operation direction or positioning, even when driven by an operator. Conversely, when using the diagonal operation method, it is difficult to determine the operation direction or the operation start and end positions, which hampers operation with a vehicle driven manually. Also, in the round operation 2, in which a vehicle moves from the center area of the field to the peripheral area, the path of the first stroke must first be precisely determined, followed by the operation start and end positions, to perform efficient operation, and if operation is performed by a vehicle driven manually, it is difficult to determine them with the operator's visual judgment alone.

Therefore, it can be said that the diagonal operation method and the round operation 2 can be performed highly efficiently and accurately only when there is the Robot to guide a vehicle based on path planning and positional information that changes from one moment to the next.

Conclusions

With regard to unmanned operation by the tilling robot using the XNAV navigation system, we proposed the diagonal operation method, in which forward traveling operation is performed diagonally against a side of the field and the round operation method, in which forward traveling operation is performed parallel to the four sides of the field throughout the entire field surface. We developed the operation software to perform these methods and field tests to confirm that unmanned operation was feasible.

1) With regard to the diagonal operation method, by applying geometric transformation with the diagonal angle for the path planning and vehicle guidance, based on the basic operation software, we have developed the diagonal operation software capable of arbitrarily setting diagonal angles.
2) With regard to the round operation method, we have developed the operation software which helps perform path planning and unmanned operation for utilizing a method in which operation is advanced from the center area to the peripheral area of the field, and one in which operation is advanced in the opposite direction, from the peripheral area to the center area of the field.
3) The results of field tests with software developed for each operation method revealed that unmanned operation could be properly performed without any remaining untilled area and running over the field, using any one of the methods.
4) The new operation methods we have proposed and developed this time can be operated efficiently and accu-

Table 1. Field test results of various unmanned operations

Operation method	Basic operation	Diagonal operation	Round ope.1 (from outside)	Round ope.2 (from center)
Operating velocity (m/s)	0.49	0.49	0.49	0.50
Machine efficiency (min/10a)	35.90	45.36	35.26	35.22
Operator efficiency (min/10a) ※1	3.78	3.78	3.78	3.78
Operator work time ratio (%) ※2	10.63	8.40	10.82	10.82
Remaining untilled area (a)	0.0	0.0	0.0	0.0
Wheel tracks on tilled area (m) ※3	47.54	57.41	234.68	21.37
Straightness of traveling (cm) ※4	1.9	3.4	1.9	3.5
Parallelism of straight traveling (°) ※5	0.05	0.18	0.05	0.13

※1: The time for which the operator is occupied in work within a unit area 10a.
※2: The ratio of the time for which the operator is occupied in work relative to the overall operation duration.
※3: The distance of wheel tracks on the tilled area generated by headland turning, sideways movements, etc.
※4: The standard deviation of the lateral deviation of straight travel trajectories in all returning operation legs.
※5: The angle of the regression line of straight travel trajectories to the long perimeter line of the field lot.

rately only when the tilling robot is used for unmanned operation.

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