JARQ 47 (2), 153 – 164 (2013) http://www.jircas.affrc.go.jp

REVIEW

Enhanced Adaptability of Tilling Robot (2nd Report)*

- Execution of Various Operations by Tilling Robot -

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Abstract

A tilling robot capable of unmanned rotary tilling with the XNAV navigation system was examined to improve and expand the adaptability of the robot operation. Firstly, as an effective and safe method of using the robot, we proposed a method whereby one operator manually operated a conventional tractor while engaged in the unmanned operation of a robot tractor. As a result of the rotary tilling test, to which the use method was applied, the robot operation was performed without trouble, and one operator could perform the operation with efficiency about 1.8 times superior to manned operation. Secondly, as an application to farm work other than rotary tilling, operation software for seeding and soil paddling was created based on operation software for rotary tilling. From the results of robot wheat seeding field tests, it was proved that the operation could be successfully performed without trouble and that the conventional two-person work could be done by one operator. The robot soil paddling was also successfully performed with efficient operation paths compared to manned operation.

Discipline: Agricultural machinery
Additional key words: conventional operation, seeding, soil paddling, unmanned operation, work efficiency

Introduction

The purpose of this research is to apply a navigation system (hereinafter referred to as “XNAV”) capable of obtaining information on robot position and direction, and improve and enhance the adaptability of unmanned operation by a tilling robot to farm fields and works. In this research, program incorporated in a controller of the robot (hereinafter referred to as “operation software”) was modified and created depending on the purposes and its performance and effect were demonstrated by field tests[1,2,3].

In the previous report (Initial Report), as different path operations other than conventional rotary tilling, we proposed “diagonal operation”, in which the returning operation is performed in a diagonal direction against the longer side of a target plot of a farm field, and “round operation”, in which a straight-traveling operation parallel to the four sides of a target plot is performed for the entire surface of the same plot. We also reported on the creation of operation software to be executed and the results of field tests[1].

In this report, firstly, as a method of using the robot effectively and safely, we proposed a method whereby one operator manually operates a conventional tractor while engaged in the unmanned operation of a robot tractor, and reported the results of the field tests. Secondly, as an application to farm work other than rotary tilling, we created “seeding software” and “soil paddling software”, and reported the results of field tests. During the robot seeding, a test aiming to reduce the number of operators was performed, while during the robot soil paddling, a test confirming the efficiency and effectiveness of the robot operation was performed.

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Received 15 May 2012; accepted 13 August 2012.

Simultaneous Double-Vehicle Operation

Rotary tilling need not involve an operator dedicated to material replenishment during the operation. During the robot rotary tilling, the operator need only make the initial settings prior to starting the robot operation, e.g. for the navigation system, reading of information on the target plot of the farm field, and selection of the robot transmission gear, whereupon thus the farm operation will be performed for the entire plot surface by the robot alone. Conversely, the robot has the self-diagnosis function prior to operation, and the abnormality alarming function during operation to facilitate starting and execution of the robot operation.

However, when the conditions vary significantly in the target plot of the farm field, the transmission gear, PTO transmission gear, and depth of tilling may have to be changed in the course of the operation. Also, for farm fields which are often unfenced, it is assumed that individuals may enter any section of the farm field during operation. Detection of such incidents and decision on resumption and continuation of the robot operation are made via an abnormality alarming function. However, at present, the appropriate selection of transmission gear depends upon the operator's judgment and response.

Accordingly, as a method to perform robot operation both safely and reliably and improve work efficiency per operator, it is considered that an operator should periodically supervise the operation of the robot and perform manned operation in the same farm field or another farm field where he/she can view the robot operation. As an example of this operation mode, we proposed a "simultaneous double-vehicle operation" method, whereby one operator starts the robot operation, supervises the operation and performs the manned operation of a conventional tractor [4].

1. Method of Field Tests

(1) Test Conditions

The field test was conducted in a farm field after harvesting of oats in the Hokkaido Central Agricultural Experiment Station, with the field divided into three rectangular plots of 30 × 165 m (49.3a), with the central plot deselected from operation and one adjacent plot designated as a conventional operation area dedicated to manned operation, and the opposite adjacent plot as a robot operation area dedicated to robot operation (Figure 1). As a tractor for the manned operation, the same model as the robot tractor was used, i.e. Kubota GL321 (24.3 kW), Kubota Corporation. The rotary tiller was also identical, with an operation width of 170 cm.

As a precondition, it was assumed that the robot operation is regularly performed in the target plot and that the reference station of the XNAV navigation system, i.e. auto-tracking type surveying device AP-L1 (Topcon Corporation) is permanently installed at an appropriate location outside the plot. Also, teaching operation to obtain the operation plot information was already performed, and the operation plot information only had to be read from the controller prior to operation. These test conditions regarding the navigation system and teaching also apply to the following field tests of seeding and soil paddling.

The operation method for both experimental plots is the standard rotary tilling method, namely, a mode of operation where the portions of the plot, except for its peripheral area, are processed by the returning operation for neighboring rows and processing of the peripheral area, including the headland with round operation of three times. The robot operation software was the basic operation software described in the Initial Report. The operator was a worker in the same test field and familiar with the operation of tractor, and the operating velocity was about 0.5 m/s (at H-1 gear) for both the experimental plots. The operation was performed with a target tilling depth of 12 to 13 cm and using the tractor's automatic depth control system.

(2) Operation Procedure

Under the above-described conditions, the operation procedure for the operator was as follows:

(i) To start the simultaneous double-vehicle operation, activate the AP-L1 device installed out of the operation plot and configure the initial settings;

(ii) Manually operate the robot residing near the operation plot of the farm field to move into the operation plot, wherein the stop position within the operation plot may be any suitable position near the entrance of the field, and after the operation of the following step

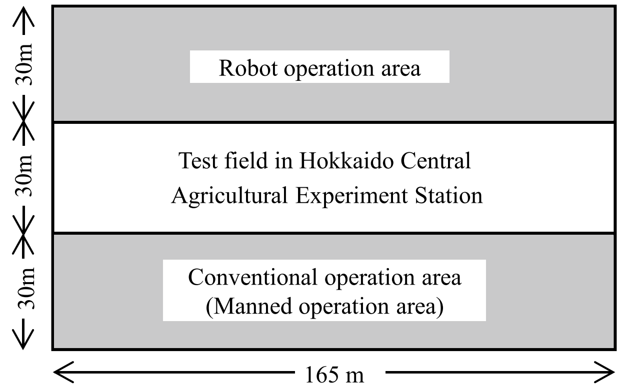

Fig. 1. Experimental plots to evaluate the simultaneous double-vehicle operation method

(iii) starts, the robot recognizes its position and moves to a predetermined operation starting point along an appropriate operation path;

(iii) Configure the initial settings for the robot; read the operation plot information, specify the transmission gear, perform self-diagnosis by the operation software, and start the robot operation;

(iv) Move the conventional tractor residing near the operation plot into the conventional operation area and start manned operation.

(v) Continue to perform manned operation and periodically supervise the behavior of the robot being operated, respond to any trouble if found, maintain preparation for an emergency such as the robot's runaway out of the operation plot, and carry a remote-control device for emergency stop at hand.

(vi) After completing manned operation, withdraw the tractor from the conventional operation area, and upon completing robot operation, perform termination processing for the robot, making it move out of the operation plot; and thus completing the simultaneous double-vehicle operation. Likewise, in the case where the robot operation is completed first, the robot is moved out of the plot last, whereupon the entire operation is completed.

(3) Survey and Evaluation Items in the Field Test

To operate both experimental plots, the time required for the operation procedures was measured and examined to evaluate work efficiency, and the traces of the operation, such as straightness and the presence of any remaining untilled area, were surveyed and examined to evaluate operating accuracy. Also, the ease-of-handling of the robot, including the navigation system, was evaluated. The performance evaluating indices were the same as in the Initial Report such as the work efficiency and operating accuracy including the following wheat seeding test.

2. Field Test Results and Evaluation

Figure 2 shows the field test, and Table 1 summarizes the measurement results regarding the major items on

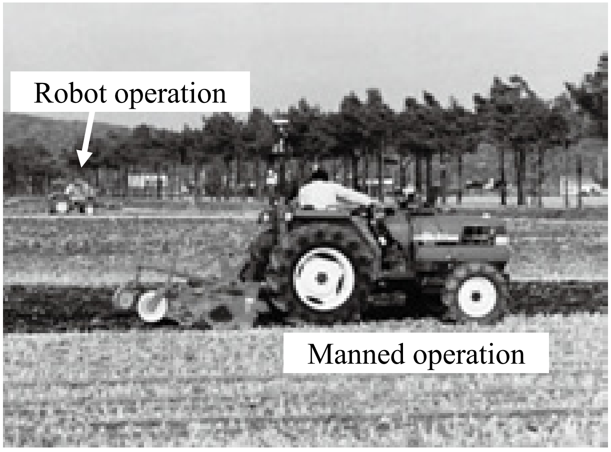

Fig. 2. Field test of the simultaneous double-vehicle operation method

Table 1. Test results of the simultaneous double-vehicle operation method

Item	Overall	Conventional operation	Robot operation
Tillable area (a)	98.6	49.3	49.3
Actual tilled area (a)	98.1	49.0	49.1
Whole time (min)	127.6	-	-
Initial setting time (min)	2.9	-	2.9
Unmanned work time (min)	123.9	-	123.9
Manned work time (min)	115.5	115.5	-
Settlement time (min)	0.8	-	0.8
Machine efficiency (min/10a)	24.4	23.6	25.2
Operator efficiency (min/10a)	13.0	23.6	0.8
Remaining untilled area (a)	0.04	0.04	0.00
Wheel tracks on tilled area (m)※1	96.4	49.3	47.1
Straightness of traveling (m)※2	-	0.11	0.04
Parallelism of straight traveling (°)※3	-	0.09	0.01

※1: The amount of wheel track distance on the tilled area by headland turning, sideways movement, etc.
※2: The standard deviation of the lateral deviation of straight travel trajectories in all returning operation legs.
※3: The angle of the regression line of straight travel trajectories to the long perimeter line of the field lot.

work efficiency and operating accuracy.

(1) Performance and Work Efficiency

For both experimental plots, the above-described procedures (i) to (vi) were performed without trouble, allowing rotary tilling maintaining the target depth of 12 to 13 cm for the entire surface of the target operation plot of the farm field.

In the manned operation of the conventional operation area, the returning and round operations were performed by the same transmission gear position H-1 as in the robot operation for the robot operation area. However, since the off-work running and turning were performed by shifting the gear up in a context-sensitive manner, the total operating time was shorter than that in the robot operation area, and the machine efficiency in conventional operation area was slightly higher than in the robot operation area. As a comparison of the work efficiency of the conventional manned operation with that of the simultaneous double-vehicle operation, in contrast to the machine efficiency of 23.6 min/10a for the conventional operation area shown in Table 1, the work efficiency for the simultaneous operation method was 13.0 min/10a, computed by dividing the total operation time of 127.6 min by the actual tilled area of 98.1 a, and thus revealing a ratio of 1.82. In other words, it was verified that simultaneous double-vehicle operation with the robot allows operation by a single operator with efficiency about 1.8 times that in conventional operation.

(2) Operating Accuracy

The results of the operating accuracy indicators in Table 1 show that the remaining untilled area for which no operation was performed was 0.04 a for the conventional operation area, but zero for the robot operation area. The wheel tracks on the tilled area, which is a sign of the fact that the vehicle entered the already tilled area while in off-work running or turning mode, showed no significant difference between the conventional operation and robot operation areas. However, the robot operation was evidently superior to the conventional operation in terms of straightness of travel and parallelism of straight traveling.

(3) Ease-of-Handling and Comprehensive Evaluation

With regard to the ease-of-handling of the robot, including the XNAV navigation system, an instruction manual was provided for the operator and about one hour of exercise was carried out. Consequently, there was no unfavorable feedback from the operator such as “the robot is slightly hard to handle”. The fact that the robot operation continued uninterruptedly and smoothly and was completed without any problem was largely due to the existence of a self-diagnosis function. The self-diagnosis function is for confirming the normal operation of various sensors, actuators and control adjustment before starting the robot operation, the function of which is incorporated into the operation software[3]. This feature is considered the main reason behind the positive impression of no problem concerning the ease-of-handling of the robot.

As described above, since it was proved that the simultaneous double-vehicle operation and robot operation were respectively conducted without problem, this method is confirmed as allowing one-man farm operation using a conventional tractor with efficiency about 1.8 times superior to that in conventional operation. This indicates that simultaneous double-vehicle operation is an operation method allowing the effective and safe utilization of robots.

Wheat Seeding

Seeding with fertilization for wheat (hereinafter referred to as “seeding”) in a large farm field is usually performed by two people, one of whom mainly acting as an operator who drives the tractor equipped with a seeder, and the other serving as an assistant who drives and moves a truck carrying seeds and fertilizers and feeds them to the seeder of the tractor. With a view to applying robot to this seeding process, usually performed in pairs for large farm fields, thus achieving one-man operation and saving labor, an operation software called “seeding software” was created for robot seeding and a field test was conducted[4].

1. Seeding Software

Seeding in a large farm field usually employs returning operation for adjacent rows extending along the longer side of the farm field. The seeding software was configured based on the components of the returning operation for neighboring rows of the basic operation software for rotary tilling. The intervals between the adjacent rows of the returning operation (operation pitches) was equal to the seeder’s operation width of 270 cm (ridge interval 30 cm × 9 ridges), and the steering angle, with 180-degree turns at the beginning or end of the operation rows, was defined by previously confirming that the turning radius was half that of the operation width. When turning, the tractor’s independent braking system and “bi-speed turning” feature were not enabled.

Given the fact that the longer side of the test field was 286 m, and taking the hopper capacity of the seeder and the mount of fertilization and seeding into account, it is necessary to replenish the seeds and fertilizers generally once every two round trips. Accordingly, the software was configured such that the robot would stop once every two round trips at the edge of the field. The procedures along with the seeding software's process flow (as indicated in the square brackets [ ]) for the returning operation for the neighboring rows to be performed while the seeds and fertilizers were being replenished are summarized as follows:

(i) Manually move the robot to the edge of the farm field where seed feeding is to be done, and configure initial settings for the robot. [Initial settings, e.g. activating seeding software → Read target plot information]

(ii) Manually feed seeds and fertilizers into the hopper of the seeder (placed in a lower position) and start the robot operation. [Wait for the robot operation start key to be pressed → Detect key input → Elevate the seeder → Make shuttle gear shifting: Move forward]

(iii) Move the robot forward until it reaches its seeding start position and start the seeding. Stop the operation at the operation end position for the operation row and make a 180-degree turn there. [Lower the seeder at the start position → Pull up the throttle → Elevate seeder at the end position and hold down the throttle → Make steering for turning → Restore steering after a 180-degree turn]

(iv) Repeat the above (iii) for two round trips.

(v) Make a 180-degree turn after two round trips, and move backward until reaching a position in which seeds and fertilizers can be replenished, whereupon the process goes to (ii). [After turning, shuttle gear shifting: Stop → Move backward → Stop → Lower the seeder]

(vi) Repeat (ii) to (v) until the operation for the target plot is completed.

During the robot operation, the operator is assumed to be around the farm field and performing other work. To replenish seeds and fertilizers, the operator goes up to the robot stopping at the edge of the field. After the replenishment, the robot does not start operation before the start key is pressed by the operator. This seems to be a safe procedure.

2. Method of Field Tests for Seeding

Field tests of robot seeding were conducted in a farmer's field in Memuro-cho, Kasai-gun, Hokkaido. Since the seeder used in this test (TW-7, TABATA NOKIGU SEISAKUSHO, a type modified for nine rows) is a relatively large device for being mounted to the robot tractor, a relatively lower operating velocity was specified for the field test.

The test was conducted for a rectangular plot of 286 × 65 m in the farm field, and, as mentioned above, a returning operation for neighboring rows was performed, in which seeds and fertilizers are replenished once every two round trips and the operation is performed along the longer side of the plot. With regard to the operator's positioning, in the same manner as in conventional operation, a chief operator and assistant operator were involved in the field test, the chief operator was for operating the robot and supervising the robot's behavior and the assistant operator was for driving the truck loaded with the seeds and fertilizers. Also, a conventional operation area of 286 × 22 m was provided, within which seeding was done with manual operation of the robot.

For both the robot and conventional operation areas, work efficiency was examined by measuring the time required for completing the seeding along with feeding of the seeds and fertilizers, and the operation traces were surveyed and examined to evaluate the operating accuracy e.g. in terms of straightness of travel and parallelism of straight traveling. Also, as for the field test for the simultaneous double-vehicle operation, ease-of-handling of the robot, including the navigation system, was also evaluated.

3. Results of the Field Test and Evaluation

Figure 3 shows the robot operation, and Table 2 summarizes the measurement results, including work efficiency and operating accuracy.

(1) Performance and Work Efficiency

The robot seeding was performed successfully. The operating velocity and operating capacity in the field for the robot operation area were 0.86 m/s and 0.68 ha/h. In contrast, those for the conventional operation area were 1.17 m/s and 0.86 ha/h, respectively. The difference is due to the lower operating velocity in the robot operation. In the robot operation, the transmission gear position H-3 specified prior to the starting of the operation remained unchanged until the end of the operation. In contrast, in

Fig. 3. Field test of the robot wheat seeding

conventional operation, the transmission gear was shifted along the way into the position H-4 in response to the operation load.

Examining the content of the operating times required for seeding and replenishing of the seeds and fertilizers, the ratio of seeding is relatively low in conventional operation area in which the operating velocity was high. However if it is assumed that the operating velocity was the same in both operation areas, the time ratio of the replenishment in both was also substantially the same.

For robot operation with two operators, the efficiency per operator over the total operating time ("operator efficiency 1") was 2.94 and 2.31 h/ha for the robot and conventional operation areas, respectively. The efficiency in conventional operation area exceeded that of the robot operation area because the operating velocity was also higher. Meanwhile, when the efficiency per operator is computed based on his/her engaging time ("operator efficiency 2"), the efficiency for the robot operation area was 0.34 h/ha, whereby two operators only engaged in the replenishment. The 0.34 h/ha was calculated by 37.51 min. (total engaging time with two operators = 163.1 min [operating time] × 0.115 [replenishment time ratio] × 2 [two operators]) divided by 1.85 ha (operating area). In conventional operation, conversely, one operator was engaged in the entire operation and the other operator was engaged in the replenishment, and the operator efficiency 2 resulted in 1.32 h/ha. The 1.32 h/ha was calculated by 49.24 min. (total engaging time with two operators = 43.0 min. [one's operating time] + 6.24 min. [another one's operating time = 43.0 min. × 0.145 [replenishment time ratio]]) dividing by 0.62 ha (operating area). Further, the observation of the operation indicates that the replenishment in the robot operation area can be successfully performed by one operator. It was also observed that seeding can be executed with labor-saving, even when the operating time required for replenishment increases.

(2) Operating Accuracy

The results of the field test shown in Table 2 indicate that the straightness of traveling was 4.7 cm for the robot operation area, 7.7 cm for the conventional operation area, and that operation was performed with high operating accuracy in the robot operation area. The transverse direction deviation with reference to the target straight path did not substantially exceed 5 cm. The robot operation area exhibited a higher degree of parallelism of seeding traces of the rows (parallelism of straight traveling).

The intervals of the neighboring seeding rows were an average of 31.8 and 31.5 cm for the robot and conventional operation areas, with the target interval 30 cm. Accordingly the results of the interval were substantially identical. The standard deviation among the neighboring rows was larger in the robot operation area than in the conventional operation area. This is considered attribut-

Table 2. Test results of wheat seeding

Item		Conventional operation	Robot operation
Operating area (ha)		0.62	1.85
Operating velocity (m/s)		1.17	0.86
Operating time (min)		43.0	163.1
Operating capacity at field (ha/h)		0.86	0.68
Operating time ratio (%)	Seeding	76.2	82.0
	Replenishment	14.5	11.5
	Movement, Turning	9.3	6.5
Operator efficiency 1 (h/ha) ※1		2.31	2.94
Operator efficiency 2 (h/ha) ※2		1.32	0.34
Straightness of traveling (cm) ※3		7.7	4.7
Parallelism of straight traveling (°) ※4		0.02	0.01
Interval of neighboring seeding row	Average (cm)	31.5	31.8
	Standard deviation (cm)	6.5	8.2

※1: Efficiency per operator over whole operating period
※2: Efficiency per operator at the time for which the operator was occupied in work
※3, ※4: Refer to the footnotes in Table 1

able to the fact that the headland of the end of the rows was specified as small, and the distance of the forward and sideways movement from the point of turning toward the next row's operation start position was relatively short for the robot operation.

(3) Ease-of-Handling and Comprehensive Evaluation

Evaluation of the ease-of-handling of the robot system is substantially the same as for the simultaneous double-vehicle operation field test results, and there was no unfavorable estimation from the operator such as "the robot is slightly hard to handle".

Since the seeding requires seeds and fertilizers to be replenished as required, the use of robots does not necessarily mean fully-unmanned operation. Nevertheless, the use of robots allows for one-man operation rather than the conventional two. Also, even during one-man operation, the operator will be freed from the task of maintaining the intervals between the neighboring rows over a prolonged period, and need only monitor the robot operation periodically and replenish as necessary. Thus, the robot seeding is an effective method of applying robots, allowing labor-saving and reducing the workload of farm operations.

There have been considerable needs for improvement in robot seeding through the shortened distance required for forward and sideways movement after the 180-degree turn at the end of the row. In addition, although not limited to the case of seeding, visual performance monitoring in large fields is usually confined to the range in the order of 300 m, hence the need for a method achieving remote monitoring and operational supervision.

Soil Paddling

Soil paddling for paddy fields (hereinafter referred to as "soil paddling") is generally performed using a tractor equipped with a soil paddling rotor and combining the returning and round operations for the peripheral area similarly to rotary tilling. The difference from the rotary tilling lies in the fact that the operation implement is often kept in the lowered or working position, even when the tractor is turning during the returning operation and at the end of the row in the round operation. Moreover, the turning radius is relatively large and the tractor turns slowly, to avoid roughening the field surface and causing ridging. Soil paddling for one field is also not performed once only but repeatedly in different operation directions for deliberate mixing and leveling of the soil, which is another feature of the soil paddling.

To achieve robot soil paddling, "soil paddling software" was created by modifying the basic operation software for rotary tilling. The modifications involved changing the turning-behavior-related components for the returning and round operations and repeating operation in different directions. A field test was also conducted using the same software[4].

1. Soil Paddling Software

For the vehicle guidance in the soil paddling software, it is important to note that vehicles are prone to considerable side-slip and drift under soft and muddy soil conditions in comparison with rotary tilling and wheat seeding operations. To minimize the side-slip and drift, turning without a large steering angle must be executed during the soil paddling operation, and the steering control gain for vehicle guidance must be adjusted according to the soil condition.

(1) Returning Operation

The returning operation in the case of rotary tilling takes place in the form of operation for neighboring rows. Meanwhile, the returning operation in the context of the soil paddling software differs somewhat. First, the returning operation starts from rows spaced by two rows from the edge of the target plot, and the 180-degree turn at the end of the row includes a relatively large radius. Furthermore, the straight-traveling operation after the turning starts from the row spaced by one row from that previously processed. This every-other-row returning operation is repeated starting from one end of the plot toward the opposite end. When the opposite edge of the plot approaches (when around two rows remain to the opposite edge), the tractor turns around and performs operation for the untreated rows. This operation is referred to as "returning operation for every other path" (see Figure 4).

The 180-degree turn at the end of each row takes place as follows. First, a 90-degree turn is performed at a steering angle (θ_0) that results in a relatively small turning radius (R_0) relative to the operation width for the soil paddling rotor. Next, the tractor moves straight to a position away from the operation path over the next one row by the distance of radius R_0, and again performs another 90-degree turn there with the same steering angle θ_0, resulting in a 180-degree turn. Turning at the end of the row, at a point close to the plot border, includes a relatively large steering angle so that the 180-degree turn takes place continuously to be ready for the next operation for the neighboring row.

Two modes of returning operation are contemplated, i.e. one in which the straight-traveling operation is done in the direction along the longer side of the target plot, and another in which the straight-traveling operation is done in the shorter side direction thereof. In the course of the repeated returning operations, these two modes are alternately executed. The operation method involving changing the returning operation directions during the soil paddling is generally referred to as "returning operation of length and breadth direction".

(2) Round Operation

The round operation in the context of the soil paddling software is performed as follows: After the one mode of returning operation is completed, the outermost peripheral area of the target plot is paddled for one round, whereupon the adjacent inner region is paddled for one round, which is referred to as "round operation 1" (outer 2 rounds). Further, the next inner region continuing to the previous inner region is paddled for one round, which is referred to as "round operation 2" (inner 1 round). The mode of implementation is designed as shown in Figure 4, depending on the specified number of soil paddling.

The 90-degree turn at the corner in the round operation is to take place in the same manner as for the first 90-degree turn during the 180-degree turn in the returning operation. The operation implement is kept in the lower or working position, so that the turning takes place during the paddling operation. After the turning, the operation reverts to the straight-traveling operation step in the forward direction.

(3) Selecting the Number of Soil Paddling and Carrying Out the Operations

A maximum four times of operation were selectable with regard to the number of paddling. As shown in Figure 4, if the paddling finishes by one time, the operation will be completed by performing the returning operation in the longer side direction, followed by the round operation for the outer 2 rounds and the round operation for the inner one round. In the case of two times' paddling, the process proceeds as follows: returning operation of one time; round operation for the outer two rounds; and the returning operation in the shorter side direction; and the round operation for the outer 2 rounds and the round operation for the inner 1 round. In the case of three times' paddling, after completing two times' paddling, again the returning operation in the longer side direction and the round operation series are performed. In the case of four

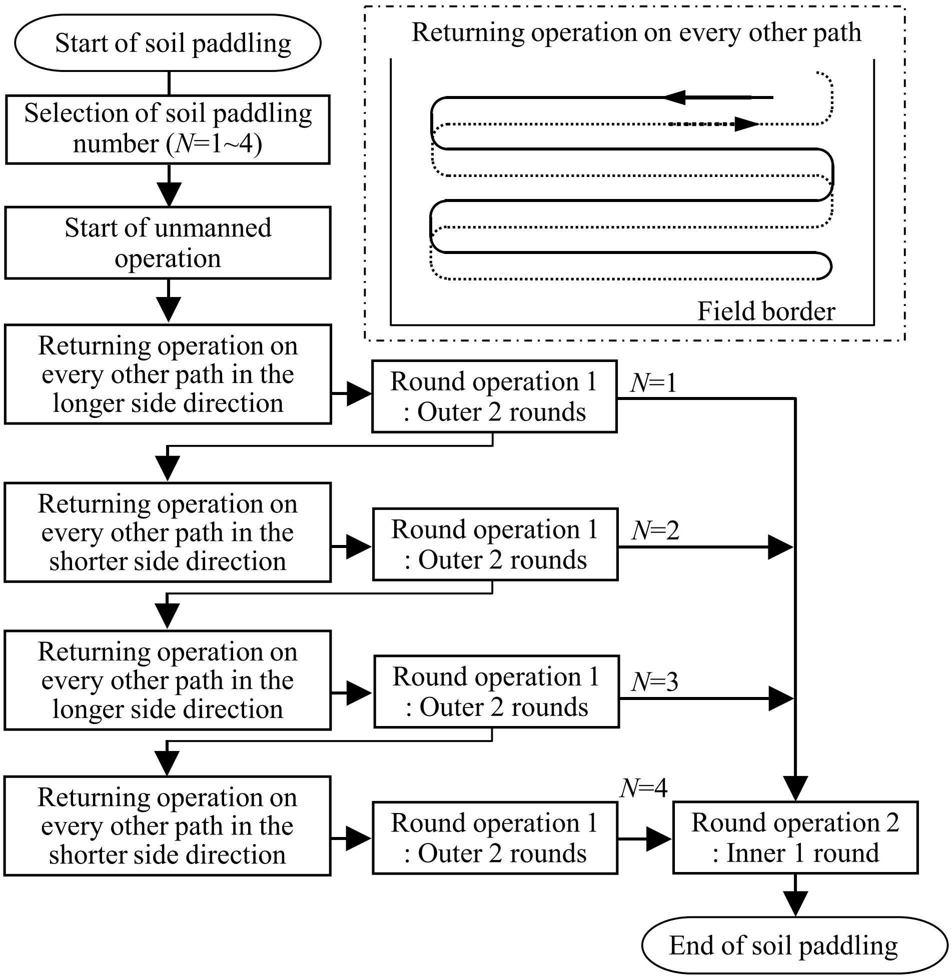

Fig. 4. Returning operation method of the robot soil paddling and the flow of operation software for soil paddling

times' paddling, after completing three times' paddling, again the returning operation in the shorter side direction and the round operation series are performed.

2. The Field Test and Results

(1) Method of Field Test

The field test was conducted in a paddy field in the experimental farm of the Bio-oriented technology Research Advancement Institution. On the one hand, a robot operation was performed in which the soil paddling software was executed (for the robot operation area). Conversely, a conventional operation was also performed in which a farm worker manually operated the robot (for the conventional operation area), and a comparison was made between the results of these two modes of operation. The soil paddling rotor has a 2.3 m operation width. For the robot operation area, the target plot was 30 a (50 × 60 m), and operation using the above soil paddling software was performed by two times (two times' paddling with the returning operation of length and breadth direction). With regard to the conventional operation area, two target plots were provided, i.e. the conventional operation area I : 50a (50 × 100 m) and the conventional operation area II : 30a (50 × 60 m). In conventional operation area I, two times' paddling with the returning operation in lengthwise and breadthwise directions was performed in the same manner as in the operation using the soil paddling software. Conversely, in area II, the soil paddling was performed by two times' paddling with "racetrack operation" often used in conventional operation. The racetrack operation is a mode of operation in which returning operation of two or several rows periodically is repeatedly performed with a 180-degree turn made at the ends of the rows, and in the course of the repetition, the row is shifted one at a time. Its operation paths assume a solenoidal shape and the unfinished rows are sequentially treated like painting out.

The transmission gear was set to position H-2 so that the operating velocity was in the order of 0.7 m/s for the robot operation area. The operating velocity for the conventional operation area may be selectable at any speed, but the operator was instructed to set the H-2 or H-3 position in the same manner as for the robot operation area, for which a relatively lower speed was specified. Since the robot could not change the lowered position of the operation implement during the operation, the height of the operation implement (i.e. the depth of paddling) was kept constant, i.e. the operation implement was held in its lowered working position for both the robot operation area and the conventional operation area I. Conversely, in conventional operation area II, the lower working position of the operation implement could be selectively adjusted by the operator. The manner of operation for the conventional operation area I is identical with that of the robot operation area, meaning the operating conditions are tuned to facilitate comparison of the work efficiency and performance with respect to the robot operation. In conventional operation area II, the operation manner was adjusted such that the operator could make arbitrary operation settings for an improved finish of the soil paddling. It should be noted that the automatic depth control feature of the base tractor was enabled for all the test areas.

The test items to be measured included operating time, operating velocity, remaining untilled area, number of operation overlaps with location, and land-leveling condition of the field surface after operation. The operating velocity, remaining untilled area, and number of operation overlaps with location for the robot operation area were computed by recording and analyzing the position outputs of the AP-L1 surveying device of the XNAV navigation system. These items in the conventional operation area were computed by measuring and recording the behavior of the manually operated robot using the AP-L1. The items of land-leveling condition after operation were determined by a light reflecting prism carried by a person, the prism being the position detection target of the AP-L1, namely the person walking in the farm field. The profile data of the field surface through the three-dimensional positional data, including height at 100 points, were measured and recorded in the robot operation area and the conventional operation area II, respectively.

(2) Test Results – Work Efficiency

Figure 5 depicts the robotized soil padding operation. Major test results are shown in Table 3, Figure 6 and Figure 7.

The robot soil paddling was performed successfully. The operating velocity was an average of 0.70 m/s for the robot operation area, 0.82 m/s for the conventional opera-

Fig. 5. Field test of the robot soil paddling

tion area I, and 0.78 m/s for the conventional operation area II. The average operating velocity in the conventional operation area was slightly higher as the operator made a context-sensitive adjustment to the operating velocity compared to the robot operation area. The operating capacity at field was dependent on the operating velocity, since the same operation method was used in the robot operation area and in conventional operation area I. Meanwhile, for the conventional operation area II, considerable overlap of operation was observed and the operating capacity at field resulted in lower values.

(3) Test Results - Operating Accuracy

For the soil paddling targeting two-time operation, the robot operation area had the least remaining untilled area that was not passed by the operation implement at all. The conventional operation areas I and II had substantially the same remaining untilled area per unit area. The results shown in Figure 6 indicate that with regard to the number of operation overlaps with location, target two-time operation was substantially performed in the area of the returning operation in the robot operation area. The conventional operation area I had relatively

Table 3. Test results of soil paddling

Item		Robot operation	Conventional operation I	Conventional operation II
Operating area	(a)	30	50	30
	(m)	50×60	50×100	50×60
Operation method		Returning operation of length and breadth direction		Racetrack operation
Operating velocity (m/s)		0.70	0.82	0.78
Remaining untilled area (a)		0.43	0.90	0.55
Operating capacity at field (ha/h)		0.22	0.28	0.14
Undulation of field surface	Maximum (cm)	14.0	-	10.0
	Standard deviation (cm)	2.7	-	1.8

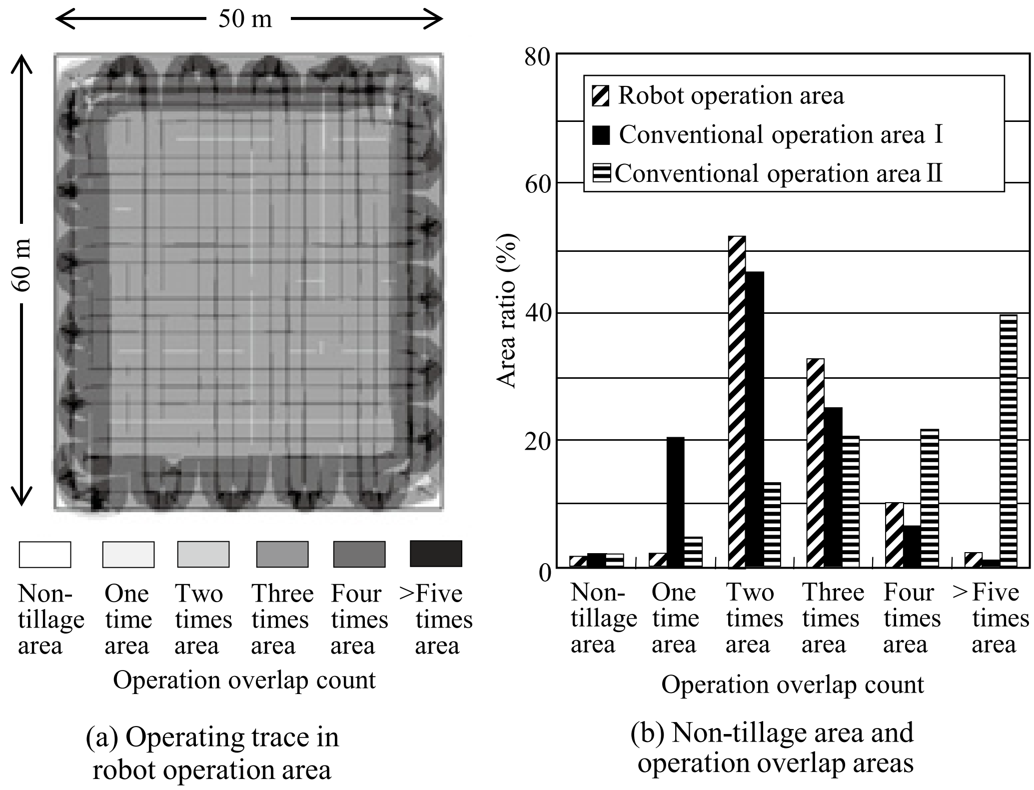

Fig. 6. Operating trace of the robot soil paddling and the ratio of the overlap area

many one-time areas. The conventional operation area II had overlap areas on three or more occasions which exceeded the target, as well as variation in the paddling. This result shows that, with regard to the operation overlap, the target two times were performed very efficiently in the robot operation area. In the case of soil paddling, it is difficult to visually discern the regions for which paddling was actually performed and the number of paddling overlaps made thereto. It also shows that, since paddling is often made with rows spaced, it is difficult to perform efficient operation for vision-based conventional manned operation. Conversely, the robot can perform operation by accurately tracing the specified operation paths, which, of course, allows for efficient soil paddling.

One of the purposes of soil paddling is to obtain favorable land-leveling performance for the field surface. In conventional operation area II, there was a relatively small difference in the height of the field surface, since the operator adjusted the operating velocity and the depth of operation with any unevenness in mind. However, in the robot operation area, although the automatic depth control system operated, the operating velocity and the lower position of the operation implement remained constant, meaning difference in height were more or less present (see Table 3, Figure 7).

(4) Comprehensive Evaluation and Challenges

The test results showed that robot soil paddling allows operation very faithful to the operation paths specified, and thus achieves efficient operation. Conversely, to ensure finish accuracy in soil paddling, features to adjust the operating velocity and the depth of operation must be included in response to the difference in height of the field surface, the conditions during operation, and combining robot and manned operations in a context-sensitive manner.

Conclusion

For the tilling robot using the XNAV navigation system, firstly as an effective use method, we proposed a simultaneous double-vehicle operation in which one operator manually operates a conventional tractor while he/she is engaged in the unmanned operation of a robot tractor. Secondly, operation software programs were created and field tests conducted to verify the programs for farm operations other than rotary tilling such as robot seeding and soil paddling.

1) The results of the rotary tilling via simultaneous double-vehicle operation proved that it allows one operator to perform robot and manned operations simultaneously, and that robot operation is superior to manned operation in terms of operating accuracy such as straightness of traveling.
2) It has been evaluated that the simultaneous double-vehicle operation allows rotary tilling with efficiency about 1.8 times that of manned operation, provided the robot operation is performed without trouble. This operation method proved an effective and safe way of utilizing robots.
3) The seeding software was created based on the basic operation software for rotary tilling, and the field test was conducted in a farmer's field. It was confirmed from the test results that it is possible to perform seeding with high accuracy where only one operator performs robot operation for seeding and replenishing seeds and fertilizers. Robot seeding proved an effective mode of robot utilization, saving labor and reducing the workload involved in farm operations.

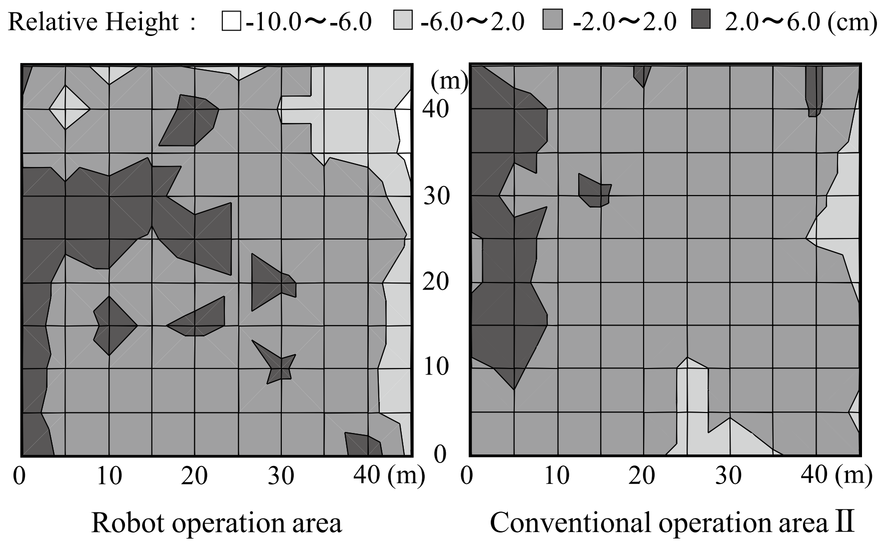

Fig. 7. Relative contour map of the field surface after soil paddling

4) Soil paddling software was created based on standard operation software and configured for optionally selectable repeated operations with different travel directions. The results of the field tests showed that robot soil paddling can be performed with effective and efficient operation paths. Meanwhile, to improve finish accuracy of paddling, it is necessary to incorporate features such as adjusting the operating velocity and the depth of operation in a context-sensitive manner.
5) The field tests showed that there was no problem with regard to the ease-of-handling of the robot, including the navigation system, and the robot operations were performed successfully.

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