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Research Article

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Cooperation of Two Robot Tractors to Improve Work Efficiency

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Abstract

A system for cooperation of two robot system was developed to solve the problem of shortage of labor and to improve efficiency of field work. A safety model of a robot tractor was proposed for coordination and cooperation of two robots. Each robot has its own pre-determined path, and tracking the path is independent of the other robot. Thus, by controlling the velocity of each robot, the robots can keep a certain shape when working due to radio communication between the two robots. As for headland turn, the two robots turn together as long as they are in a safe condition. Computer simulation was conducted to confirm the effectiveness of this system. The results showed that it is possible for two robots to work safely together applying the developed safety model. Compared with work by a single robot, this system using two robots can improve work efficiency by at least 80 percent.

Keywords: Leader-follower pattern; Formation control; Safety model; Robot tractor

Introduction

Many efforts have been made by engineers in advanced countries to reduce labor and work time in agriculture due to the decreasing agricultural labor forces. Global demand for higher productivity in agriculture field has led to the need for more cooperation between agricultural machines. Advances in industrial mechanization and automation have inspired engineers to develop robots that can perform various agriculture field tasks. There are two major categories of research on agricultural robotics: ground sensing systems that use machine vision, odometers, accelerometers, etc. [1-4] and satellite-based system that use GPS for navigation [5-7]. The error in accuracy of a real-time kinematic (RTK) GPS system is now only 1 to 2 cm per 10 km [8]. Generally, the error in accuracy of a guidance system using RTK-GPS is 3 to 5 cm.

As for robot technology, many researchers have developed sweep coverage algorithm for multi-agent robot system [9-11]. The agriculture robot tractor is similar to the sweep coverage robot. Both of them need to cover the whole area using the minimum time. The difference between the robot tractor and sweep coverage robot is that the robot tractor need to cover each place only one time. In many cases, cooperation and coordination of two robots is necessary to improve work efficiency and to reduce work time and work strength. For instance, for a robotic combine harvester harvesting in a field, an on-the-go unloading system with a transport robot that moves the harvested products to collection positions helps improve harvesting efficiency since the harvester does not need to stop. Another example is that a robot tractor doing tillage can be followed by another robot seeding and fertilizing at the same time. In these operations, the two robots need to be controlled carefully to prevent loss of harvested products and collision of the robots. In agriculture, researchers have focused on the master-slave approach for coordination. Noguchi et al. [12] developed a master-slave robot system to conduct farm work. The system mainly includes GOTO and FOLLOW algorithms. The master controls the slave to follow a parallel path at a given distance and angle from the master or to go to a certain point along any path as long as it does not collide with the master. Zhang [13] proposed an intelligent master-slave system that enables a semi-autonomous agricultural vehicle (slave) to follow a master with a given lateral and longitudinal offset. They used a state space dynamic model and a proportional-derivative controller with state feedback and disturbance feed-forward for the tractor. Vougioukas [14] proposed a distributed control framework to coordinate the motions of teams of autonomous agricultural vehicles operating in the same field. The framework includes master-slave and peer-to-peer modes, which are based on nonlinear model predictive tracking controllers that communicate with each other.

However, the use of two robots also has some disadvantages. If it is not properly constructed, the two robots may actually increase the complexity of the system instead of simplifying it. The multiple robot system has to address many issues that do not appear in single robot system, such as communication and interaction with the other robot, formulation and headland turn cooperation. Generally, research on coordination of robots has mainly focused on formation control [15-19], which means the control of a group of robots in a coordinated way to maintain the formation of a certain shape. Formation control was also part of this article. The main aim of this article was to determine how to use two robots in one field and how much work efficiency can be improved by simultaneously using two robots compared with using one robot. Two robots can cooperate in many different patterns. For instance, they can start from different sides of the field and work to the center or they can work from the center to the sides. In addition, the two robots can work in parallel and share the same performance or they can work like a master-slave system with one following the other. The collaboration of two robots differs depending on the field conditions or work operations. In this study, we classified the cooperation patterns into two categories: 1) a leader-follower pattern, which means the two robots keep a constant shape during the operation, and 2) a free pattern, which means the formation shape of two robots is unlimited. It would be easier to understand the leader-follower pattern since the two robots will maintain a certain shape, regardless of whether they are in parallel or front and back form. In this kind of pattern, each robot needs to adjust its velocity to maintain the formation shape. However, the free pattern does not limit the formation shape of two robots, which

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means that even though the two robots communicate each other, they will not adjust their velocities as long as they are in a safe condition. In this article, we focus on the leader-follower pattern because it has more applications than the free pattern. For instance, the on-the-go unloading system is a typical application of leader-follower pattern.

Two robot tractors were used in this study, and the desired positions were given to each robot. Unlike a master-slave robot system, in the newly developed system, each robot tracks its own desired path, which means steering control is independent. Each robot adjusts its velocity to formulate a certain shape during the operation. However, during headland turn, the two robots do not need to keep a certain shape considering the best use of the headland. If the two robots continue to keep the shape in the headland turn operation, there would need to be more space in the headland, which would decrease the cultivating area of the field. Thus, during a headland turn, each robot uses its own turn method, and the trajectory of the robots may collide. A safety model for a robot tractor is proposed for cooperation by two robots during headland turn to avoid collision.

The cooperation system by two robots has several advantages. Firstly, two robots are used simultaneously, which increases work efficiency compared with the use of one robot. Secondly, compared with a large robot tractor, the use of two small robot tractors helps for reduction of damage to the crops and severe soil compaction. Finally, each robot's navigation is independent, which means it is easy to use them separately as a single robot. This autonomy of each robot enhances the usefulness of the two robot system.

The rest of this article is structured as follows. The method used for the cooperation system, including the safety model, formation control and turning cooperation are presented in section 2. Results of simulation and experiment of the cooperation system are presented in section 3, and the improved work efficiency of this system is also discussed. Finally, conclusions are given in section 4.

Methods

Communication structure

A robot tractor used in this study had already been developed [20]. In that study, an RTK-GPS and an IMU were used to provide position and posture data for robot's navigation. A computer was used as a controller to communicate with the tractor's ECU through CAN BUS. In this study, the navigation method was the same as Yang's work [20].

ROBOT-1 (abbreviated as RT1) and ROBOT-2 (abbreviated as RT2) were used as unmanned tractors. Both of them are basically commercial tractors. RT1 is wheel-typed tractor, while RT2 is type of half-track crawler, as shown in Figure 1. The length, width and height of RT1 are 3.9 m, 1.75 m and 2.62 m, respectively, and the length, width and height of RT2 are 4.26 m, 1.81 m and 2.68 m, respectively. The weights of RT1 and RT2 are 2840 kg and 3820 kg, respectively. The power of RT1 is 61.0 kW, and that of RT2 is 77.2 kW. The specifications of each tractor include steering control, a switch for forward and backward movements, easy-change transmission, a switch for power take off, hitch functions, engine speed set, engine stop and brake.

Figure 1 shows the structure of the communication method between two robots. The robot tractor's navigator software communicates with the tractor's ECU through a CAN BUS and exchanges information with the robot tractor's Client/Server software through a memory. The robot tractor's Client communicates with the Server through Bluetooth. The tractor's navigator software was developed to follow a predetermined path, and the steering control is independent from other software. The tractor's Client/Server were developed for cooperation work. For instance, the Client was on RT1 and the Server was on RT2. The Client reads information about RT1 and sends it to the Server. The Server obtains information from RT1 and RT2, do calculation and send a command to the Client, and the Server sends a command to RT2.

Tractor model for safety evaluation

If the two robots are far away and can do their work without colliding, we can skip this issue. For example, if the two robots work in separate fields, there is no need to worry about the robots colliding. However, if the two robots work in the same field, as long as the two robots are cooperating, the safety issue has to be considered. In this study, the safety zone of the robot is defined as a circle or rectangle. It can be concluded whether the two robots are safe by judging the relative positional condition of two safety zones. Take a circular zone as example, if the two circles are separated throughout the work task, then we can conclude that it is a safe situation; on the other hand, if the two circles are intersected, which means the two robots have collided, then we can conclude that it is a dangerous situation.

Circle model: Firstly, each robot's safety zone was simplified as a circle, as shown in Figure 2a, where $RT_i.x$, $RT_i.y$ are central coordinates of the circle and $RT_i.r$ is the radius of the circle. Eq. (1) shows the definition of $RT_i.r$ where $RT_i.l_{width}$ is the width of the equipment carried by RT-*i*, $RT_i.l_{front}$ is the distance from the center to front, and $RT_i.l_{rear}$ is the distance from the center to back. The distance between two circles can be calculated by Eq. (2), where $d_{1\ to\ 2}$ is the distance between

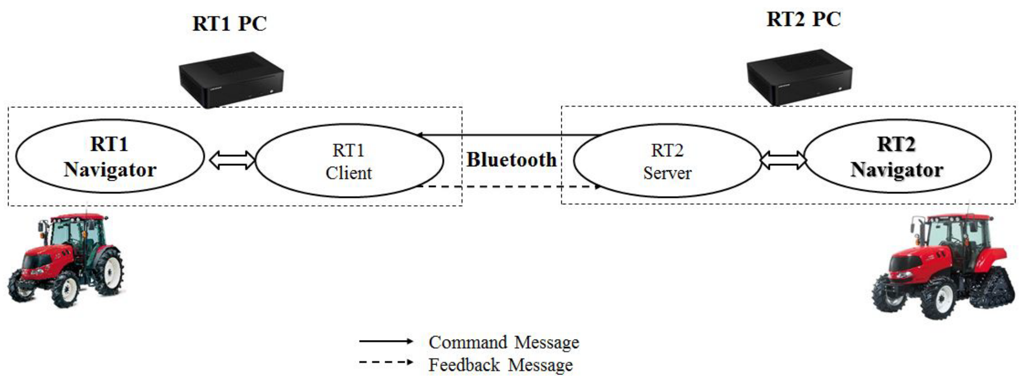

Figure 1: Communication structure of cooperation system.

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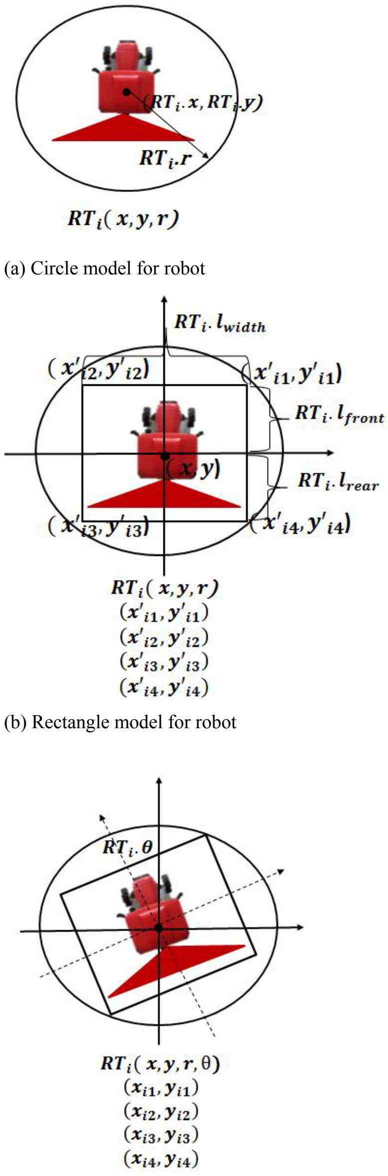


(a) Circle model for robot

(b) Rectangle model for robot

(c) Rotation of a robot

Figure 2: Model of robot tractor.

two safety zones. If $d_{1\text{ to }2}$ is more than zero, the two robots are safe; otherwise, the two robots are in danger.

$$RT_i.r = \sqrt{\left(0.5RT_i.l_{width}\right)^2 + \left(\max\left(RT_i.l_{front}, RT_i.l_{rear}\right)\right)^2} \tag{1}$$

$$d_{1to2} = \sqrt{\left(RT_1.x - RT_2.x\right)^2 + \left(RT_1.y - RT_2.y\right)^2} - RT_1.r - RT_2.r \tag{2}$$

Rectangle model: The safety zone of the robot tractor can also be simplified as a rectangle, as shown in Figure 2b. The rectangular zone is more compact than the circular zone, thus it is more effective on space utilization. However, a rectangular zone needs more calculation since it is more complex than a circular zone. The coordinates of the four corners are different depending on the size of the tractor and equipment. The four corners can be simplified as $P'_{i1}(x'_{i1}, y'_{i1})$, $p_{i2}(x'_{i2}, y'_{i2})$, $p_{i3}(x'_{i3}, y'_{i3})$ *and* $p_{i4}(x'_{i4}, y'_{i4})$ where *i* represents the ID of robot.

Eq. (3) shows the equation to calculate the coordinates of the four corners. However, when a robot is used in the field, it always rotates and changes direction, especially in a turning operation, as shown in Figure 2c, and the coordinates of the four corners should thus be transformed according to the rotation. Eq. (4) shows the transformation equation. Finally, for each robot, we have central coordinates $RT_i.x$, $RT_i.y$ $(i\ \{1,2\})$ circle radius $RT_i.r$ $(i \in \{1,2\})$ rotation yaw angle $RT_i.\theta$ $(i \in \{1,2\})$ and four corners' coordinates

$P_{ij}(x_{ij}, y_{ij})$ $(i \in \{1,2\})$, $j \in \{1,2,3,4\}$),

$$\begin{cases} x'_{i1} = RT_i.x + 0.5RT_i.l_{width} \\ y'_{i1} = RT_i.y + RT_i.l_{front} \\ x'_{i2} = RT_i.x - 0.5RT_i.l_{width} \\ y'_{i2} = RT_i.y + RT_i.l_{front} \\ x'_{i3} = RT_i.x - 0.5RT_i.l_{width} \\ y'_{i3} = RT_i.y - RT_i.l_{rear} \\ x'_{i4} = RT_i.x + 0.5RT_i.l_{width} \\ y'_{i4} = RT_i.y - RT_i.l_{rear} \end{cases} \tag{3}$$

$$\begin{cases} x_{ij} = x'_{ij}\cos RT_i.\theta + y'_{ij}\sin RT_i.\theta \\ y_{ij} = y'_{ij}\cos RT_i.\theta - x'_{ij}\sin RT_i.\theta \end{cases} \tag{4}$$

The two rectangles are checked to see whether they are intersected. If they are intersected, it means the two robots have already collided. However, in the field, the rotation angles of the two robots are different, which means we cannot judge whether the two robots are intersected by absolute coordinates. The following methods are used to check whether the two rectangular zones are intersected.

Each rectangle can be simplified as four segments, which means we can judge whether the 8 segments are intersected. Suppose there are segments L_{1k} (p_{1i}, p_{1j}), $(i,j \in \{1,2,3,4\})$ from RT1 and L_{2k} (p_{2i}, p_{2j}), $(i,j \in \{1,2,3,4\})$ from RT2, where $p_{1i}, p_{1j}, p_{2i}, p_{2j}$ are start points and end points of these segments. Firstly, suppose two rectangles T_1 and T_2 are in an absolute coordinate system and their sides are parallel with the *x-axis* or *y-axis*. The diagonal line of T_1 isL_{1k} and the diagonal line of T_2 is L_{2k}. If the two rectangles T_1 and T_2 are not intersected, then the two segments are not intersected, as shown in Eq. (5). If the two rectangles are intersected, further judgment is needed. Secondly, if the vectors $v_{1i}(p_{1i}, p_{1j})$, $v_{2i}(p_{2i}, p_{2j})$, $s_1(p_{1i}, p_{2i})$, $s_2(p_{1j}, p_{2i})$, $s_3(p_{2i}, p_{1i})$ and $s_4(p_{2j}, p_{1i})$ satisfy Eq. (6), the two segments are separated; otherwise, they are intersected.

$$x_{1i} > x_{2j} \| x_{1j} < x_{2i} \| \max\left(y_{1i}, y_{1j}\right) < \min\left(y_{2i}, y_{2j}\right) \| \min\left(y_{1i}, y_{1j}\right) < \max(y_{2i}, y_{2j}) \tag{5}$$

$$\begin{cases} s_1 \times v_{2i} * s_2 \times v_{2i} > 0 \\ s_3 \times v_{1i} * s_4 \times v_{1i} > 0 \end{cases} \tag{6}$$

The minimum distance between two rectangular zones, $d_{1\text{ to }2}$ is also needed for safety evaluation. Normally, the distance between two robots means the distance between two GPS receivers. The minimum distance between two rectangular zones indicates the space between two robots. As mentioned before, each rectangle can be simplified as four segments, and thus the minimum distance between two rectangular zones can be represented by the minimum distance between two sets of segments. Firstly, suppose there are segments L_{1k} (p_{1i}, p_{1j}) from RT1 and L_{2k} (p_{2i}, p_{2j}) from RT2. Suppose point M(X,Y) is on $L_{1,k}$ and point N(U,V) is on $L_{2,k}$. The coordinates of *M* and *N* can be expressed as Eq. (7), where s,t ∈ (0,1). Thus, the length of $\overline{MN}$ can be expressed as Eq. (8). Secondly, suppose *f (s,t)* is equal to the square of $\overline{MN}$, as shown in Eq. (9). To find the minimum value of *f (s,t)* derivative *f (s,t)* on the *s* and *t* partial derivatives and let them equal zero, as shown in Eq. (10). Thus, we can get Eq. (11) to obtain the values of *s* and *t*. If the calculated values of *s* and *t* belong to 0 to 1. These values can be taken back to Eq. (7) and Eq. (8) to calculate $\overline{MN}$. Thirdly, if the values of *s* and *t* do not belong to 0 to 1, $\overline{MN}$ should be the minimum value of each point of RT1 to the segments of RT2, as shown in Eq. (12).

$$\begin{cases} X = x_{1i} + s\left(x_{1j} - x_{1i}\right) \\ Y = y_{1i} + s\left(y_{1j} - y_{1i}\right) \\ U = x_{2i} + t\left(x_{2j} - x_{2i}\right) \\ V = y_{2i} + t\left(y_{2j} - y_{2i}\right) \end{cases} \tag{7}$$

$$\overline{MN} = \sqrt{\left(X-U\right)^2 + \left(Y-V\right)^2} \tag{8}$$

$$f\left(s,t\right) = \overline{MN}^2 = \left(X-U\right)^2 + \left(Y-V\right)^2 \tag{9}$$

$$\begin{cases} \dfrac{\partial f\left(s,t\right)}{\partial s} = 0 \\ \dfrac{\partial f\left(s,t\right)}{\partial t} = 0 \end{cases} \tag{10}$$

$$\begin{aligned} &\left[\left(x_{1j}-x_{1i}\right)^2 + \left(y_{1j}-y_{1i}\right)^2\right]s \\ &-\left[\left(x_{1j}-x_{1i}\right)\left(x_{2j}-x_{2i}\right) + \left(y_{1j}-y_{1i}\right)\left(y_{2j}-y_{2i}\right)\right]t \\ &=\left[\left(x_{1i}-x_{1j}\right)\left(x_{1i}-x_{2i}\right) + \left(y_{1i}-y_{1j}\right)\left(y_{1i}-y_{2i}\right)\right] \\ &-\left[\left(x_{1j}-x_{1i}\right)\left(x_{2j}-x_{2i}\right) + \left(y_{1j}-y_{1i}\right)\left(y_{2j}-y_{2i}\right)\right]s \\ &+\left[\left(x_{2j}-x_{2i}\right)^2 + \left(y_{2j}-y_{2i}\right)^2\right]t \\ &=\left(x_{1i}-x_{2i}\right)\left(x_{2j}-x_{2i}\right) + \left(y_{1i}-y_{2i}\right)\left(y_{2j}-y_{2i}\right) \end{aligned} \tag{11}$$

$$\overline{MN} = min p_{1i} \to L_{2k}; p_{1j} \to L_{2k} \ \ \mathrm{i}, j, k \in \{1,2,3,4\} \tag{12}$$

The minimum distance between two rectangular zones is used to judge whether it is safe for robots to continue work. For instance, by setting a limited value, e.g., 0.5 m, if the distance is less than 0.5 m, RT2 needs to stop work and wait until RT1 goes away.

Formation control in a work operation

Formation control is mainly used in the leader-follower pattern. Each robot tractor's path is already known, and the lateral distance between two robots is limited to the desired path. The longitudinal distance is used for formation control. The velocities of the robots are changed according to the longitudinal distance between the two robots. Figure 3 shows the control parameters used in velocity control. $\left(x_0, y_0\right)$ and $\left(x_0^{'}, y_0^{'}\right)$ are the start and end points of the current path of RT1, respectively. $RT_1.x$, $RT_1.y$ and $RT_2.x$, $RT_2.y$ are the positions of the robot tractors. *l* is the lateral displacement between the two robots, *d* is longitudinal displacement between the two robots, L_1 is the distance from RT1 to the current path, L_2 is the distance from RT2 to the current path, d_1 is RT1's distance to the end point of the current path, d_2 is RT2's distance to the end point of the current path, and d_3 is the length of the current path. *L*, d_1, d_2 *and d* are used for velocity control. L, d, d_1, d_2, d_3, L_1, L_2 can be calculated by Eq. (13).

$$L_1 = \frac{\left|\left(y_0^{'}-y_0\right)RT_1.x + \left(x_0 - x_0^{'}\right)RT_1.y + \left(x_0^{'}y_0 - x_0 y_0^{'}\right)\right|}{\sqrt{\left(x_0^{'}-x_0\right)^2 + \left(y_0^{'}-y_0\right)^2}}$$

$$L_2 = \frac{\left|\left(y_0^{'}-y_0\right)RT_2.x + \left(x_0 - x_0^{'}\right)RT_2.y + \left(x_0^{'}y_0 - x_0 y_0^{'}\right)\right|}{\sqrt{\left(x_0^{'}-x_0\right)^2 + \left(y_0^{'}-y_0\right)^2}}$$

$$l = L_1 - L_2$$

$$d = \sqrt{\left(RT_1.x - RT_2.x\right)^2 + \left(RT_1.y - RT_2.y\right)^2 - l^2}$$

$$d_1 = \sqrt{\left(RT_1.x - x_0^{'}\right)^2 + \left(RT_1.y - y_0^{'}\right)^{2-} L_1^2}$$

$$d_2 = \sqrt{\left(RT_2.x - x_0^{'}\right)^2 + \left(RT_2.y - y_0^{'}\right)^{2-} L_2^2}$$

$$d_3 = \sqrt{\left(x_0^{'} - x_0\right)^2 + \left(y_0^{'} - y_0\right)^2} \tag{13}$$

Eq. (14) shows the equations of the velocity controller, where k, a and b are control gains. In this system, the change value, *temp*, is departed by two parts, for one robot is speed up, for the other one is speed down. Also, maximum velocity is set to ensure safety. In some conditions, the velocity of the tractor cannot increase much since the power of the tractor is not sufficient for the work. In that case, the maximum velocity is used to limit the velocity of the tractor.

$$\begin{cases} temp = kd + a\int dd_t + b\dfrac{d_d}{d_t} \\ \quad V_1 = V_{set} + 0.5temp \\ \quad V_2 = V_{set} - 0.5temp \\ V_1 \in \left[0, v_{max}\right], V_2 \in \left[0, v_{max}\right] \end{cases} \tag{14}$$

Path planning and skip path method

A U-turning method has been proposed for headland turn. Figure 4 shows the U-turning method. A flag is added to record the current turning status of the robot, simplified as T_F, and T_F is used in the turning cooperation. The turning procedure is composed of nine steps. The steps of the turning are as follows.

Step 1: The robot went straight forward from A to B (T_F=1) and then turned at the maximum steering angle to point C (T_F=2).

Step 2: The robot calculated the distance between the current path and the next path, which is *w*, and then decided the distance between point C and point D, which is *w-2r*, where *r* is the minimum turning radius of the robot tractor. If *w* was less than *2r*, the robot would go

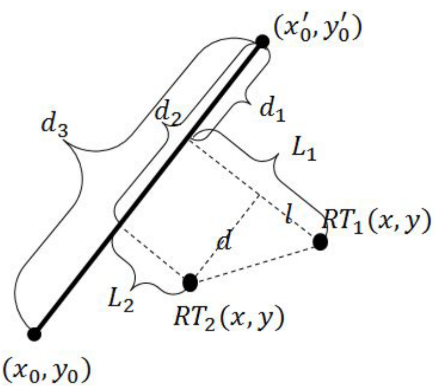


Figure 3: Control parameters of velocity control.

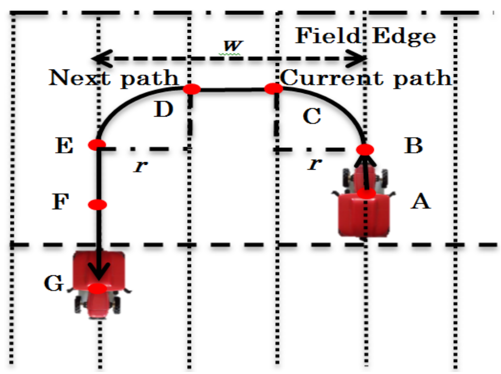


Figure 4: U-turning method.

backward to ensure a turning radius (T_F=3); otherwise, the robot went forward from point C to point D (T_F=4).

Step 3: The tractor turned to the next path from point D (T_F=5) and went straight forward to point F (T_F=6) and then went back to point E (T_F=7).

Step 4: The tractor restarted initialization from point E to point G (T_F=8), and the turning was completed at point G (T_F=9).

In general, similar to the human driver's usual practice, the robot turns to the next path adjacent to the current path. However, in this case, the robot goes backward during point C to point D since the turn radius of robot is larger than the path width.

When the robot goes backward, whatever condition it is in, it is a danger to the other robot. If the robot always goes forward to enter the next path, the width between the current path and next path should be more than 8 m, which means the robot should skip at least one path from the current path to next path. Then the path number should satisfy Eq. (15). Each set includes *m* paths, and Eq. (16) shows the sequence of paths. Taking (m=5, n=2) as an example, the total number of paths should be 11. Suppose the path order starts from path 1, according to Eq. (16), the path sequence should be 1->4->2->5->3->6->9->7->10->8->11.

$$\text{Path number} = \text{mn}+1; \quad \text{n} \in \text{N},\ \text{m} \in \{m | m = 2x+1, x > 1\, and\, x \in N\} \tag{15}$$

$$a_{mn+i} = \begin{cases} a_{mn+i-1} + \left[\dfrac{m}{2}\right], i \in even\ And\ i \in [2, m+1] \\ a_{mn+i-1} - \left[\dfrac{m}{2}\right], i \in odd\ And\ i \in [2, m+1] \end{cases} \tag{16}$$

Turning cooperation

The turning cooperation of RT1 and RT2 can be divided into four steps.

Step 1: RT1 starts turning and RT2 continues working if it is safe. If RT2 reaches a given position, which means d_2 is less than a given limited value, and RT1 is still turning from the current path, which means T_F is less than 4, RT2 will stop and wait.

Step 2: RT1 continues turning and begins to turn to the next path. RT2 continues working and starts turning. RT1 and RT2 will turn together. If it is in a dangerous situation, RT2 will stop and wait until it is safe. If RT2 has already stopped, and T_F of RT1 equals 7 and the distance between two safety zones is less than the limited value, then RT1 will stop the current operation and skip to the next operation, which means RT1 will stop going backward and will go forward to continue the turning operation.

Step 3: RT1 finishes turning and RT2 continues turning. RT1 will stop and wait at a given position, which means d_3-d_1 is larger than a given limited value.

Step 4: RT2 finishes turning, and RT1 and RT2 will work together. Formation control will be used to ensure the two robots keep a certain shape.

Step 1 and 2 are also used to avoid deadlock. In general, the deadlock may happen when T_F of RT1 equals 3 or 7. According to step 1, RT2 stops at a given position until RT1 finishes status 3. Thus it is safe for both robots. As mentioned in step 2, when it comes to a dangerous situation and RT2 already stopped, RT1 will stop current operation (T_F=7) and move to next operation (T_F=8) to avoid deadlock. In addition, before the field test, simulation is needed to check whether it is a safe situation.

Simulation Results

Simulation was needed to help us check the cooperation status of the two robots and also to determine appropriate control gains. For the robot tractors used in this study, $RT_1.l_{width}$, $RT_1.l_{front}$ and $RT_1.l_{rear}$ are 2.3 m, 3 m and 2.7 m, respectively, and the $RT_2.l_{width}$, $RT_2.l_{front}$ and $RT_2.l_{rear}$ are 2.3 m, 3.3 m and 2.4 m, respectively. According to practical experience, the velocity of a robot tractor is 3.0 km/h when conducting rotary tillage. As mentioned in formation control, the maximum velocity of a robot tractor is 3.5 km/h. The longitudinal distance between the two robots is 12 m, which is calculated by Eq. (17).

$$d_{RT1betRT2} = RT1.l_{rear} + RT2.l_{front} + \frac{1}{2} * v_{set} * t_{Em\_stop} \tag{17}$$

Where, $d_{RT1betRT2}$ is the set longitudinal distance between two robots, and t_{EM_stop} is the stopping time of the robots. In this study, v_{set} was replaced by v_{max} of tractor (not v_{max} of robot), which is 15 km/h, t_{EM_stop} was 2.5 s. That is how 12 m was calculated. In addition, the minimum longitudinal distance between two robots was 8 m (2.7m + 3.3m + 0.5*1m/s*2.5s). Thus, the longitudinal distance between two robots should be more than 8 m.

As for the turning cooperation, the limited value of RT1 is the same as the longitudinal distance, and the limited value of RT2 is 2 m. For simulation, taking into account overlap, the path width is 2.2 m and the path length is 100 m.

Each robot starts from the related start point, and changes velocity according to the longitudinal distance between two robots. During headland turn operation, the simulation software simulates the trajectory of the robot based on the distance between current path and next path (in this case, the distance is 4.4 m) and the robot followed the trajectory. If the distance between two robots or the distance between two safety zones was less than a given limited value, the RT2 would stop and wait until it was safe.

Turning to an adjacent path

A navigation map with six paths was made for the simulation, and the path order was 1→2→3→4→5→6. A circular model was first used in the simulation.

Figure 5 shows the routine of the two robots. The two robots turn to adjacent path. The red line indicates RT1 and blue line indicates RT2. The first figure of Figure 6a shows the work status of two robots.

0 means headland turn and 1 means working. The minimum distance between two robots is 6.6 m. The longitudinal distance between the two robots is zero and the lateral distance between the two robots is 6.6 m, which means that the two robots are parallel to the path direction but moving in different directions, as shown in Figure 6b.

Figure 7 shows the velocity data of two robots. The waiting time of RT1 is 40.8 s and that of RT2 is 38.3 s during each headland turn.

To reduce the waiting time of two robots, rectangular model is used to retake the simulation. Figure 8a shows the distance between two robots and the distance between two rectangular zones. The minimum distance between two robots is 5.18 m, and the distance between two rectangular zones is 1.24 m. The minimum distance between two rectangular zones is 0.76 m, and the distance between two robots is 5.2 m, as shown in Figure 8b.

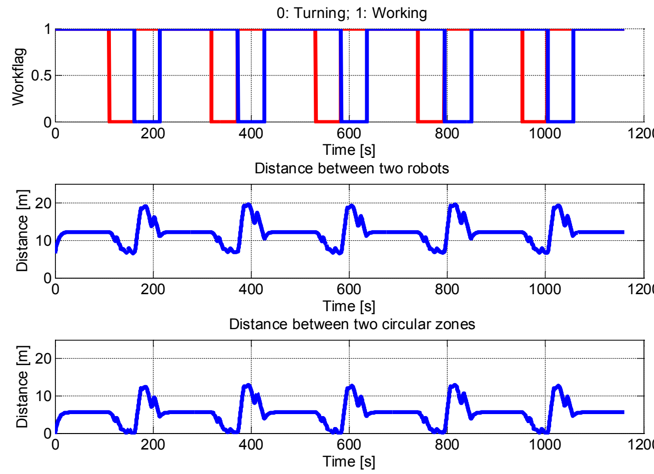
Figure 9 shows the velocity data of the two robots. RT1 stops and waits 25.5 s, and RT2 stops and waits 24.4 s during each headland turn.

The minimum distance between the two robots when using a rectangular model is 5.18 m, 1.42 m less than that when using a circular model. Also, compared with using a circular model, the waiting time of RT1 is reduced by 15.3 s by using a rectangular model. The advantages of a circular model are that it is easy to realize and has less calculation, but a circular model is less effective than a rectangular model for space utilization, which increased the waiting time of the two robots and decreased the work efficiency.

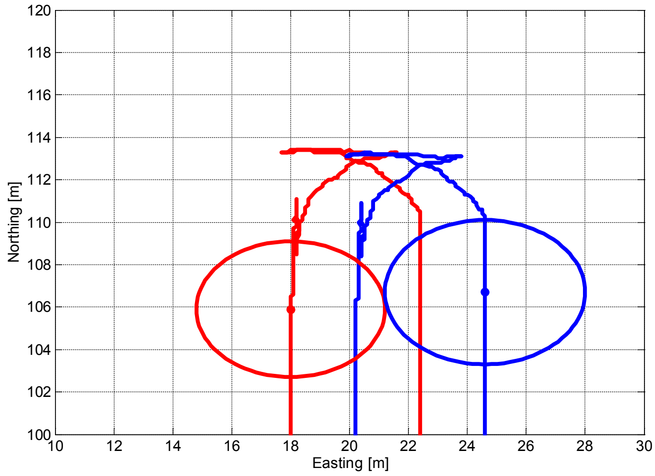
Skip path turn simulation

The comparison of the circle model and the rectangle model was discussed, and the rectangle model was effective on space utilization, thus the rectangle model was used in the following simulation. Skip path turn method is used to retake the simulation, as shown in Figure 10. The robot always turns left and skips 1 or 2 paths to enter the next path. Thus, the robot does not go backward to enter the next path during headland turn.

Figure 11a shows the distance between two robots and the distance between two rectangular zones when the robots skip 2 paths. The minimum distance between the two robots is 7.8 m, and the distance between the two rectangular zones is 1.88 m. The minimum distance between the two rectangular zones is 1.62 m, and the distance between



(a) Distance between two robots and two circular zones



(b) Robots' status at the minimum distance between two robots

Figure 6: Performance of distance using circular model.

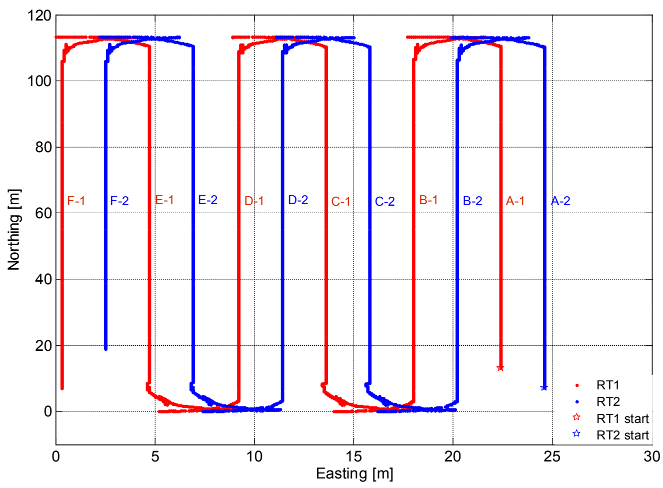


Figure 5: Simulation of routine of two robots when they turn to adjacent path.

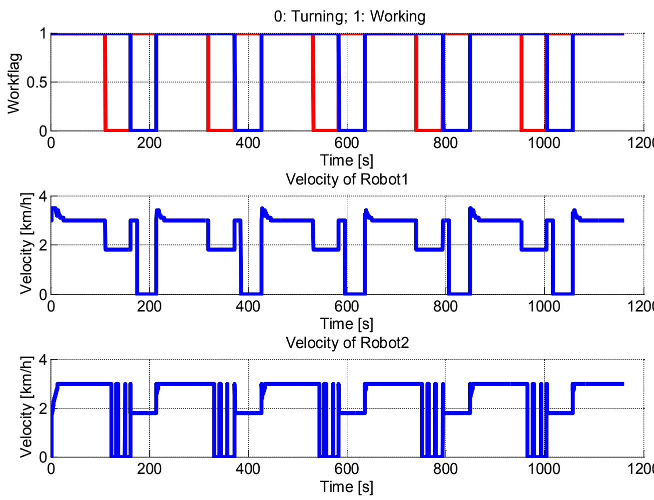


Figure 7: Velocity data of two robots using circular model.

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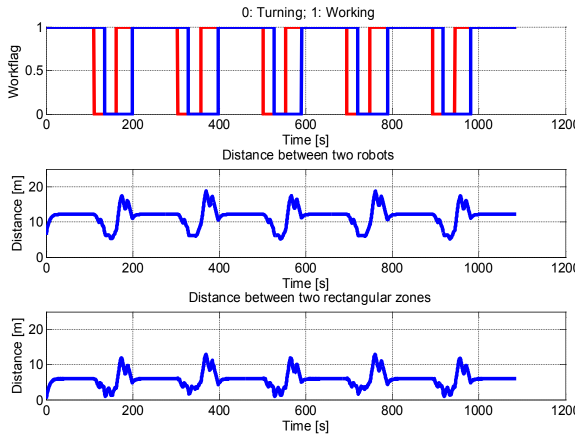
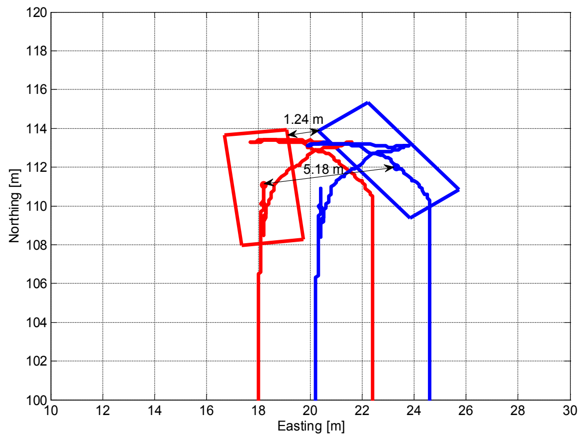


(a) Distance between two robots and two rectangular zones



(b) Robots' status at the minimum distance between two rectangular zones

Figure 8: Performance of distance using rectangular model.

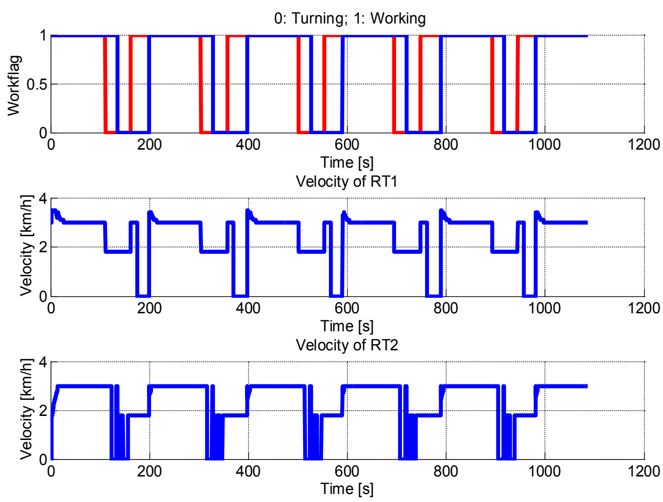


Figure 9: Velocity data of two robots using rectangular model.

the two robots is 7.9 m, as shown in Figure 11b.

Figure 12 shows the distance between two robots and the distance between two rectangular zones when the robots skip 1 path to enter the next path. The minimum distance between the two robots is 5.2 m, and the distance between two rectangular zones is 0.76 m, as shown in Figure 12b. This is a slightly closer situation than that when 2 paths are

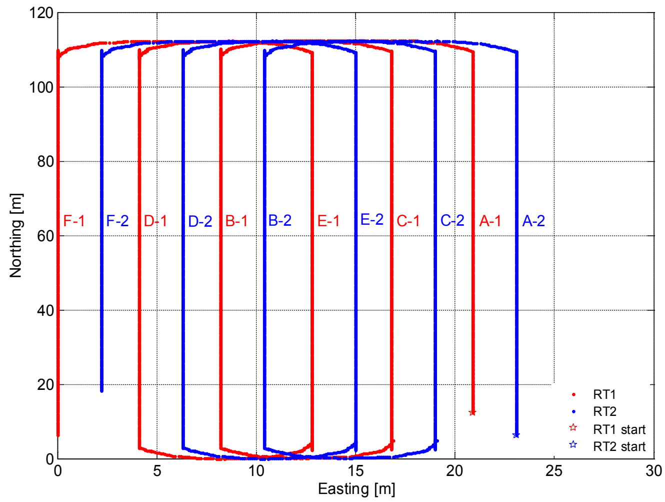
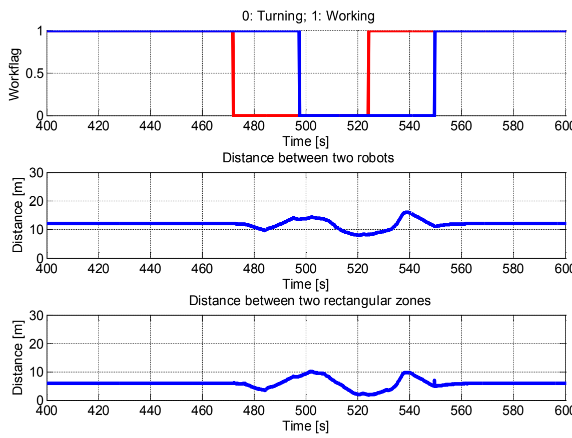
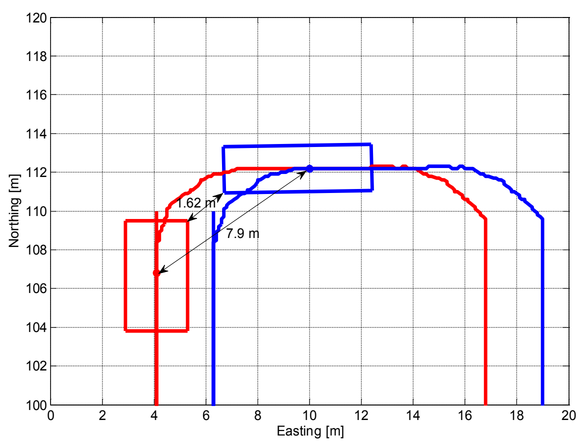


Figure 10: Simulation of routine of two robots using skip path turn method.



(a) Distance between two robots and two rectangular zones



(b) Robots' status at the minimum distance between two rectangular zones

Figure 11: Performance of distance when robots skip 2 paths.

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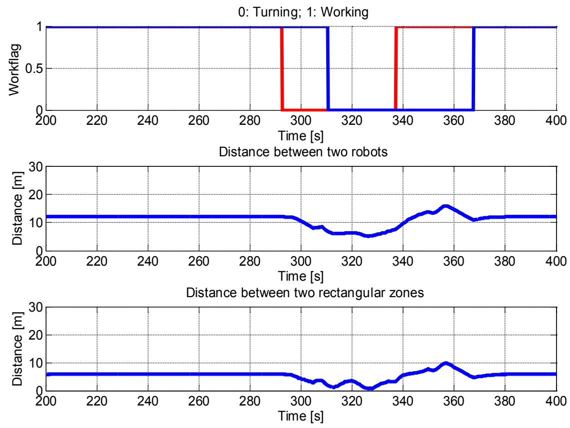
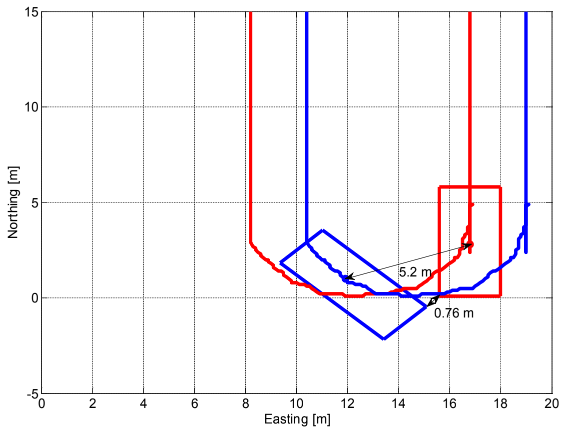


(a) Distance between two robots and two rectangular zones



(b) Robots' status at the minimum distance between two rectangular zones

Figure 12: Performance of distance when robots skip 1 path.

skipped, but it is also an acceptable value.

Figure 13a and 13b show the velocity data of two robots when they skip 2 paths and 1 path to enter the next path, respectively. If the robots skip 2 paths, the waiting time of RT1 is 12.4 s and waiting time of RT2 is 11.2 s. If the robots skip 1 path, the waiting time of RT1 is 17.6 s and waiting time of RT2 is 16.2 s.

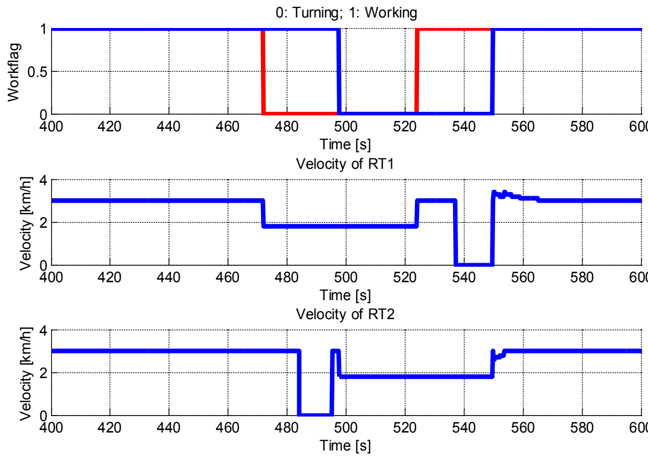
Work efficiency

The waiting times of RT1 and RT2 using different methods are shown in Table 1. By skipping 2 paths, the waiting time of RT1 was reduced by 7.9 s compared with that when turning to the adjacent path and was reduced by 5.4 s compared with that when skipping 1 path. In conclusion, the rectangle model is more effective than the circle model on waiting time, and skipping a path is more effective than turning to the adjacent method.

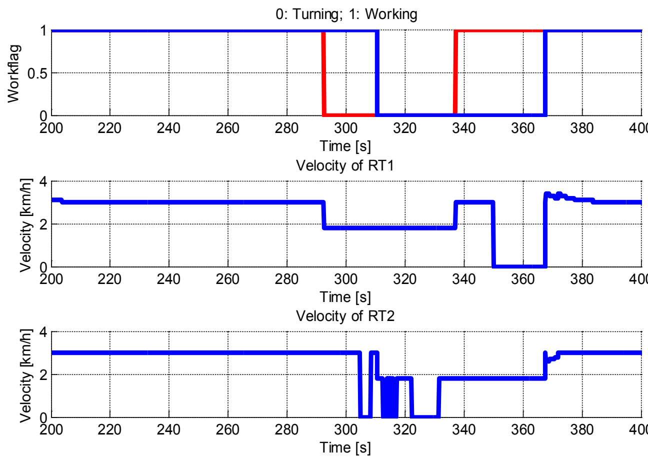
Take turning to an adjacent path as example. The setting longitudinal distance between the two robots is 12 m and turning time of RT1 is 52.3 s. It takes two robots 19.8 min to finish the work and it takes one robot 34.5 min to finish the same work, which is an improvement in efficiency of 74.2 percent. To improve the work efficiency, we need to reduce the waiting time of RT1. Increase the longitudinal distance between two robots can reduce the waiting time. Take the longitudinal distance as 34 m as an example and do the simulation. The velocity data is shown in Figure 14 Both of the robots continue working without stopping during the whole operation. In this simulation, it will take two robots 17.23 min to finish the work, an improvement in efficiency of almost 100 percent compared with that using one robot. Generally, the distance between two robots has a positive effect on waiting time of the two robots, and waiting time has a negative effect on work efficiency.

Results of field test

Figure 15 shows the trajectory of two robots of the experiment. The experiment was taken in a farm in Hokkaido University. The length of the path was 100.8 m, and the width of the each robot's path was 2.2 m. The velocity of two robots was 3.0 km/h and the maximum velocity of two robots was 3.5 km/h. The longitudinal distance between two robots



(a) Velocity data of two robots when skip 2 paths



(b) Velocity data of two robots when skip 1 path

Figure 13: Velocity data of two robots using skip path turn method.

	Waiting time of RT1	Waiting time of RT2	Total waiting time (each turn)
Skip 0 path	25.5 s	24.4 s	25.5 s
Skip 1 path	17.6 s	16.2 s	17.6 s
Skip 2 path	12.4 s	11.2 s	12.4 s
Skip 0 path (Circle model)	40.8 s	38.3 s	40.8 s

Table 1: Waiting time of two robots.

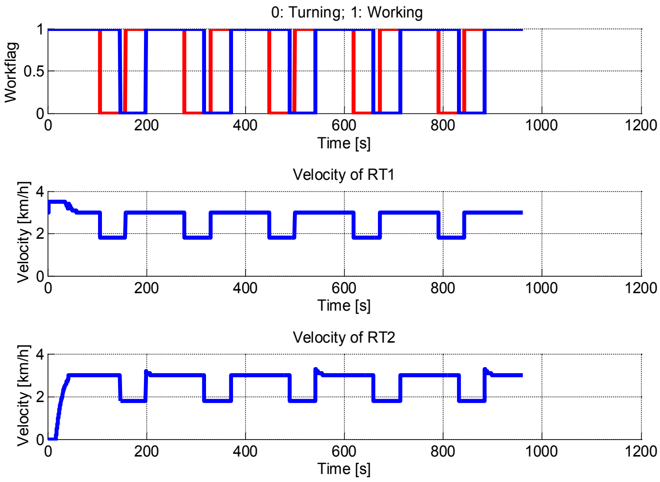
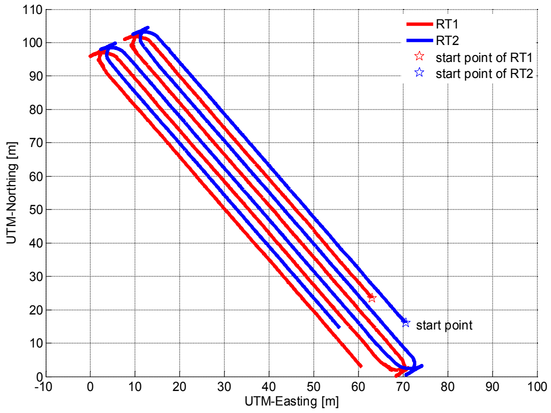


Figure 14: Velocity data of two robots when waiting time of RT1 is zero.



(a) Trajectory

(b) Photo of two robots

Figure 15: Trajectory of two robots.

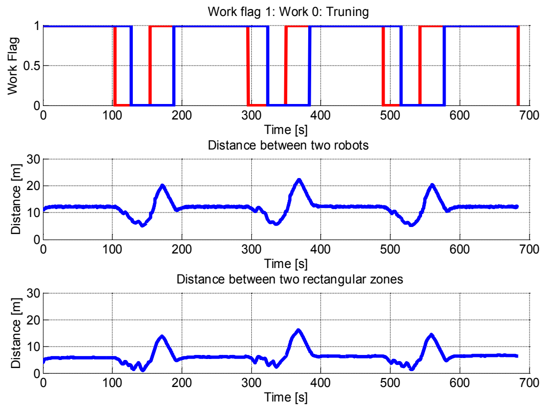
was 12 m.

Figure 16 shows the performance of distance of two robots. The minimum distance between two robots was 5.12 m, and the distance between two rectangles was 1.02 m. This distance is 0.39 m larger than that of simulation. The minimum distance between two rectangles was 0.85 m, which is safe for two robots to work. The average error of distance between two robots when they were working on the path is 0.19 m, and the RMS of the distance is 0.22 m. The average error of distance between two rectangles when two robots were working on the path is 0.13 m, and the RMS of this distance is 0.34 m.

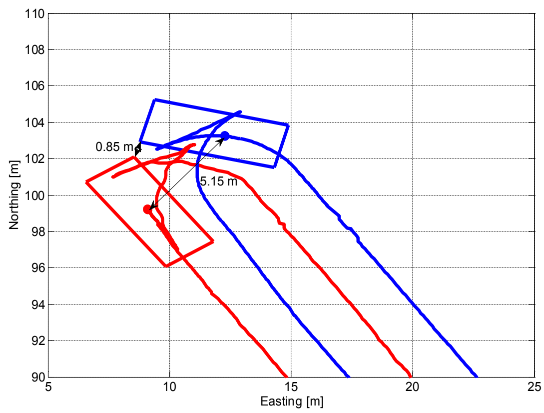
Figure 17 shows the performance of velocity of two robots. According to the experiment results, RT1 stopped and waited 18 s during each turning, 7.5 s shorter than simulation. RT2 stopped and waited 18.4 s during each turning, 6 s shorter than simulation. The main reason of this is that the real velocity of the robot tractor is always changing, and delay exists between command and response. The delay is about 1.8 s.

Figure 18 shows the accuracy of each robot. Lateral error is used to evaluate the robot's performance. Lateral error is the distance error between robot's position and pre-determined path. The average lateral error of RT1 is -0.03 m, and RMS of lateral error of RT1 is 0.05 m. The average lateral error of RT2 is -0.02 m, 0.01 m less than RT1. And RMS of lateral error of RT2 is 0.03 m.

The total work time of the experiment is 11.3 min, improved 79.6% work efficiency compared with using one robot, which takes 20.3 min to finish the work.



(a) Experiment of distance between two robots and two rectangular zones



(b) Experiment of robots' status at the minimum distance between two robots

Figure 16: Performance of distance between two robots.

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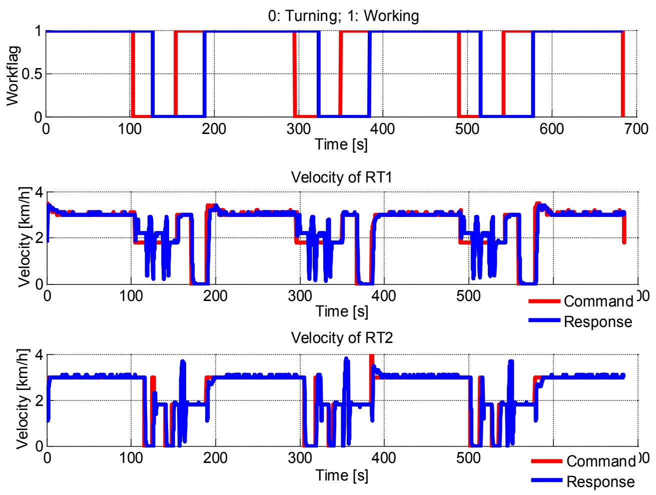

Figure 17: Experiment of velocity data of two robots.

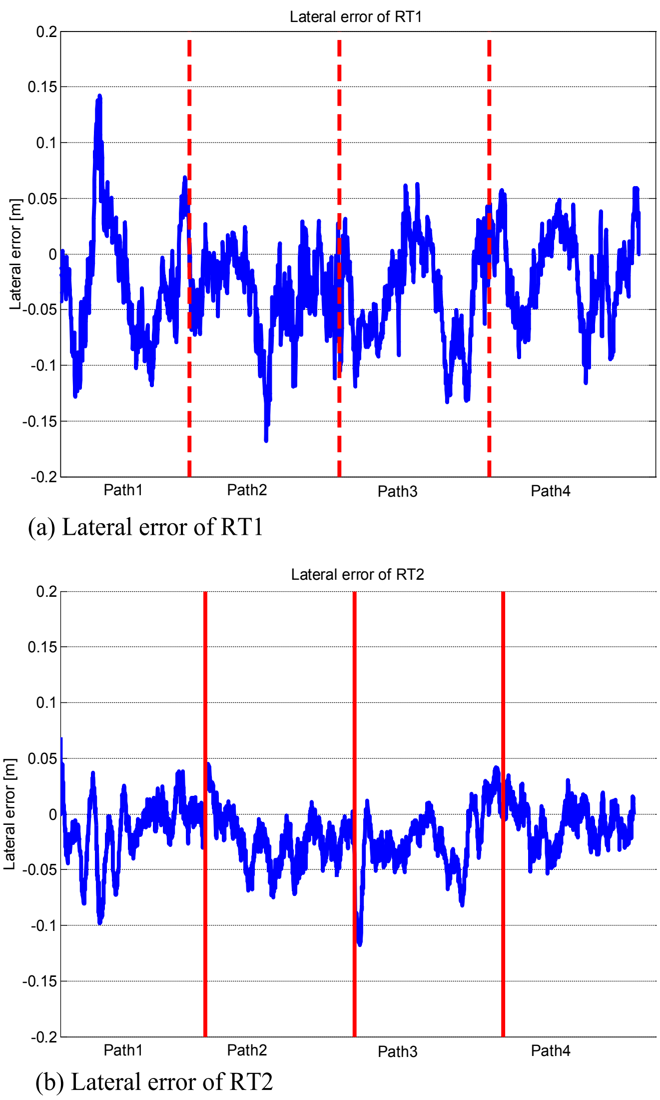

Figure 18: Lateral error of two robots.

Conclusion

Cooperation of two robot tractors was proposed in this article. Each robot individually tracks its desired path and maintains a certain shape during the work operation. To ensure the safety of robot tractors, a rectangle model and a circle model were proposed. Path planning and turning cooperation were used to improve the efficiency of this system.

The results of simulation showed that the rectangle model reduced waiting time by 15.3 s compared with that using the circle model when the robots turn to adjacent paths. By skipping 2 paths to turn to the next path, the waiting times of RT1 and RT2 were reduced by 5.2 s and 5 s, respectively, compared with that when skipping 1 path. If the robots turn to adjacent paths, the waiting times of RT1 and RT2 would be 25.5 s and 24.4 s, respectively. The work efficiency was limited by the length of field, set velocity of robots and waiting time of RT1. If the length is 100 m, set velocity is 3.0 km/h, and set distance between the two robots is 12 m, the efficiency will be improved by 74.2 percent compared with that using one robot. However, if the length of the field is increased to 500 m, the efficiency improves by 92.5 percent. If the set distance is increased to 34 m, the efficiency improves almost 100 percent compared to that using one robot. In addition, the improved work efficiency have a positive effect on the energy consumption ($E_{con}=2/(1+E_w)$), where, E_{con} is the efficiency of energy consumption, E_w is the improved work efficiency. If E_w increases, then E_{con} decreases; the smallest E_{con} possible is optimal. For instance, if the E_w increase from 60 percent to 100 percent, the E_{con} will decrease from 1.25 to 1.

In conclusion, cooperation of two robot tractors can reduce work time and work strength. Work efficiency is based on the setting parameters and the system can be improved close to 100 percent efficiency compared with using one robot.

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