学 位 論 文 内 容 の 要 約

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学 位 論 文 題 名

Development of a Multi-robot Tractor System for Farm Work
(マルチロボットトラクタによる協調作業システムの開発)

I Introduction

Labor shortage damages farmer revenue, yield and durability. Some of the farm work can cause musculoskeletal disorder risks and chronic health issues to workers. In this research, an autonomous robot tractor was developed using multiple navigation sensors. Furthermore, a multi-robot tractor system was developed to reduce work time and improve work efficiency. To deal with external disturbances in the agriculture field, safety system using laser scanner was developed, and to deal with internal disturbances in the agriculture field, fault tolerant method were developed. Three simulation and three field experiment were conducted to testify the effectiveness of the multi-robot tractor system.

The research platform of single robot tractor was a commercial tractor called EG453. Necessary modifications were made to reform the original manually-operated tractor into an autonomous tractor. An RTK-GPS and an IMU were integrated using a fusion algorithm to calculate current position and absolute heading of the robot tractor under UTM coordinate system. Based on map navigation method, the robot tractor could conduct field work, such as tillage, fertilizing, spraying, weeding and so on. Coordination of multiple robot tractors allows for the execution of complex tasks. In addition, the total work time can be reduced, the work efficiency can be increased and the human labor can be saved.

The objective of this research is to develop a multi-robot tractor system for farm work. Availability, safety and efficiency are the three key points of this research. In this research, (a) a high accuracy robot tractor was developed, (b) improved U-turn method and skip path turn method were proposed to improve accuracy and efficiency of single robot tractor, (c) a multi-robot tractor system was developed, (d) formation control method and headland turn control method were proposed, (e) circular zone and rectangular zone were proposed to ensure safety of the system, (f) work efficiency evaluation method were proposed, (g) safety system including laser scanner safety system and fault tolerant system were developed.

II Single robot tractor

In this chapter, equipment for single *RT* and algorithm of automatic control of single *RT* were discussed. A commercial tractor was modified into a robot tractor for farm work. An RTK-GPS, an IMU, a laser scanner, a remote switch and a control PC were mounted on the robot tractor, as shown in Fig. 1. The control PC can get information from sensors and messages from Tractor's ECU (TECU) as well as calculate control parameters of *RT*. The TECU can receive the control parameters, control the tractor based on these parameters, and feedback the status of tractor to the control PC through a CAN BUS using ISO protocol. Thus the PC can control the steer, forward/backward movements, easy-change transmission, brake, power take off (PTO), hitch functions and engine speed set of the tractor. The control PC receives the RTK-GPS data via RS-232 transducer and receives the IMU data via another RS-232 transducer at 10 Hz. The laser scanner was used to detect objects out of the system, such as human or other vehicles in the field. The remote switch was used for human operator to shut down the tractor under certain emergences, i.e. the system failed to detect other objects and about to collide with them.

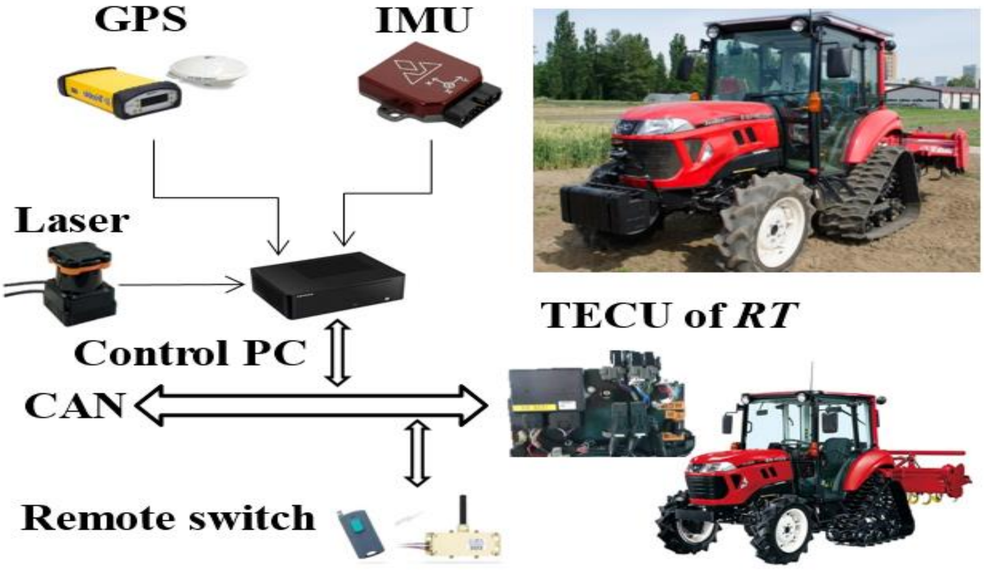


Fig. 1. Platform of single *RT*

Firstly, a work area was segmented by a grid map to cover the surface of the field, called navigation map. The absolute position and work condition of the *RT* was included in the navigation map.

Secondly, a navigator, developed software for navigation, read the navigation map and obtained RTK-GPS data and IMU data to get the absolute location and orientation of the *RT*. Based on the current location, the navigator can get the next operation-work process or headland turn process.

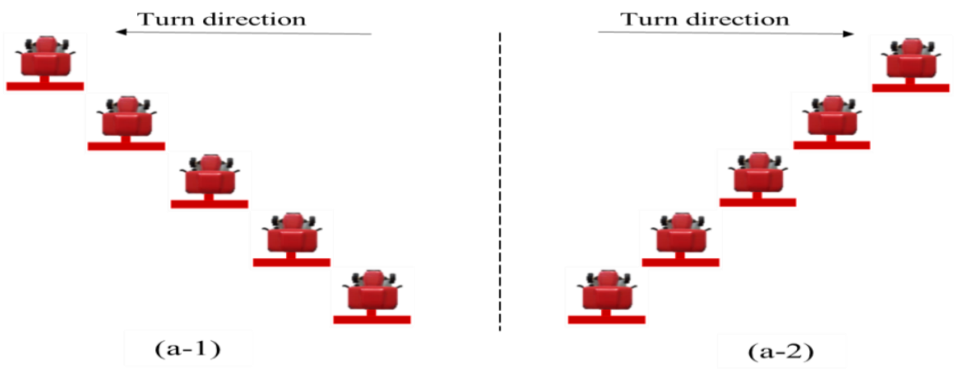
Thirdly, if the *RT* was in work process, the navigator calculated the lateral error and heading error from the real time position, heading angle of the tractor, and the navigation map. Steering angle was calculated by using a PI controller.

In addition, if the *RT* was in headland turn process, the navigator controlled the steering angle and velocity according to improved U-turn method. Skip path turn method was used to reduce backward distance to reduce headland turn time.

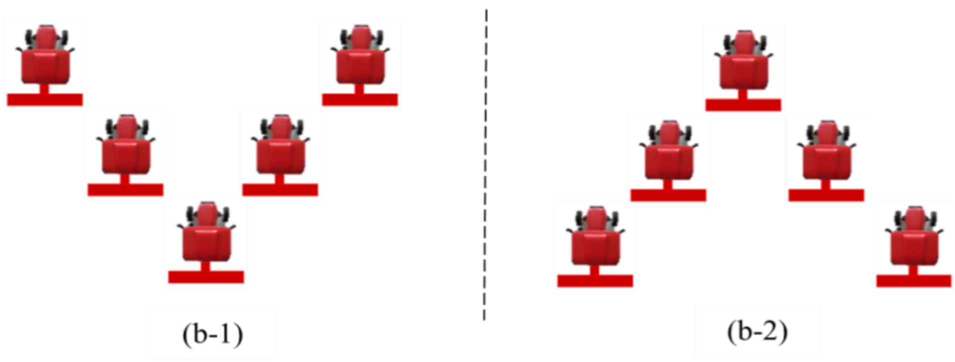
Simulation and experiment were conducted to check the performance of the *RT*. The accuracy of the robot tractor is 0.05 m, which is high enough to conduct agricultural farm work. The total work time is 10.78 min, almost the same as simulation, which is 10.80 min. In conclusion, the single robot tractor can be used in real agricultural field. Furthermore, the agriculture multi-robot tractor system can be developed based on the single robot tractor.

III Method and materials of multi-robot system

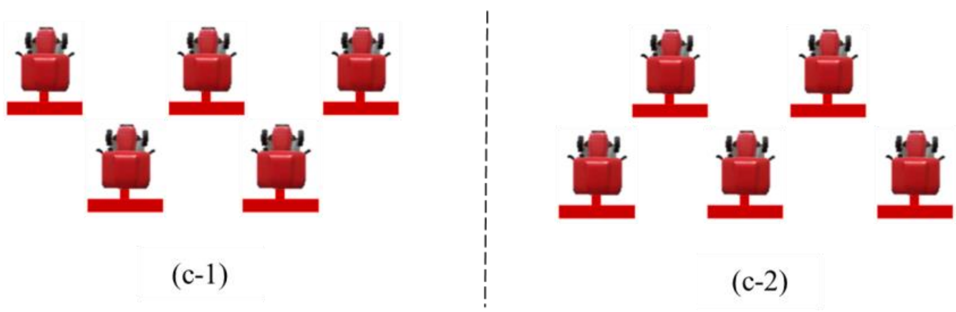
In this chapter, the theory of the multi-robot system was discussed. It is a distributed system that each *RT* in the multi-robot system can work independently, they can also work together to keep a formation pattern during work process. *I*- pattern, *V*- pattern and *W*- pattern were used in this system, as shown in Fig. 2.



(a) *I*- pattern



(b) *V*- pattern



(c) *W*- pattern

Fig. 2. *I*- pattern, *V*- pattern and *W*- pattern for the multi-robot system

A server application was developed to receive messages from clients and monitor, and send related messages to clients and monitor for cooperation and coordination. The server can also group the *RTs* to several groups to reduce calculation. Each *RT* in a group has a priority. A *RT's* priority is based on the formation pattern and the position of the *RT* in the formation pattern. A monitor application was developed for human operator to monitor all the *RTs*. A client application was developed to do the cooperation and coordination process. The client mainly has three functions: work process control, headland turn process control and safety control. During work process, the client adjusts its velocity according to the closest higher priority *RT* to keep the formation pattern. During headland turn process, to reduce the total headland space, the *RTs* do not need to keep the formation pattern. Safety zone was proposed to avoid collision of *RTs*. Circular zone and rectangular zone were used as safety zone in safety control. The circular zone uses less calculation than rectangular zone. However, the rectangular zone is more effective than circular zone since it is more compact than circular zone. Space distance, distance between two safety zones, was used to check whether two *RTs* are safe or not.

Two methods were used to describe the efficiency of the multi-robot system. One is use the total time of the multi-robot system compare with the total time of the single robot system, the other one is use the running time of the multi-robot system compare with the total time of the multi-robot system. Both methods are relying on the field conditions and work conditions of the task, and different settings lead to different results. In general, the multi-robot system is more useful in large sized field.

IV Safety system

Aimed at developing an effective safety system for multi-robot tractor system to ensure safe operations in the agriculture field, this chapter investigated the basic technology of laser scanner based object detection and dead reckoning based fault tolerance for robot tractors.

A laser scanner was used to detect object in the field. The output data of laser scanner is in P-coordinates system. In order to use the data in multi-robot tractor system, coordinate transformation has to be done three times: (1) Polar to Vertical coordinates, (2) Vertical to RT-Vertical coordinates, and (3) RT-Vertical to World coordinates. Wavelet transform method was used to detect objects, and the input signal passed through a high pass filter and a low pass filter twice to get the results. Two robot tractors were used to do the experiment. According to the field results, *RT1* detected one object and *RT2* detected two objects successfully. The reason *RT1* only detected one object is that the second object was out of *RT1*'s detection zone. It took two *RTs* 2.2 s to fully stop after they detected the objects, which is acceptable value.

The fault tolerant system was developed to solve GPS error, IMU error, transmission delay and uneven ground. The fault tolerant method was based on dead reckoning, which means it is effective on a short time period. However, the accumulated error increased on a long time period. In order to solve this issue, frequent recalibration was used to diminish the accumulated error. Four robot tractors were used to do the experiment. According to the experiment results, the distance between each RT was not influenced by the GPS error. And the filtered yaw angles of 4*RTs* were in the same direction. The filtered RMS of yaw angle of 4*RTs* is 1.05, and the original RMS of yaw angle of 4*RTs* is 1.56.

In conclusion, the developed safety system is capable of detecting objects in the field and tolerant disturbances inside of the system.

V Computer simulation of multi-robot system

Three simulations were taken to testify the availability of the system: 3*RTs* system, 5*RTs* system and 7*RTs* system. Our focus is (a) the distance between *RTs*, (b) the space distance between *RTs*, (c) the velocity of *RTs* and (d) work efficiency of the system. Among these four factors, the most important ones are the minimum space distance between *RTs* and work efficiency of the system.

The length and width of the path is 100 m and 2.0 m; each RT has four paths.

In 3*RTs* system, the three *RTs* using I- pattern. *RT1* and *RT2*, *RT2* and *RT3* share the same formation pattern, as shown in Fig. 2 (a). Due to that reason, the minimum space distance between *RT1* and *RT2*, *RT2* and *RT3* are the same, which are 0.72 m. In 5*RTs* system, the five *RTs* keep a V- pattern during work process. The minimum space distances between *RTs* are different. The minimum space distance between *RT1* and *RT2* is 5.02 m. However, the minimum space distance between *RT3* and *RT4* is 0.63 m, much smaller than the former value. The reason is the distances between two *RTs* are different. In this test, the distance between *RT1* and *RT2* is 8.0 m and the distance between *RT3* and *RT4* is 4.0m. For this reason, the minimum space distance between *RT2* and *RT3* (1.41 m) differs from the minimum space distance between *RT4* and *RT5* (0.58 m) even though they seem to share the same formation. In 7*RTs* system, the seven RTs keep W- pattern during the work process, and most formations of two *RTs* share the same formation pattern, as shown in Fig. 2 (c). As a result, the minimum space distance between two adjacent *RTs* except *RT4* and *RT5* are the same, which are 0.62 m. The minimum space distance between *RT4* and *RT5* is 0.84 m, 0.22 m larger than others' value.

With the path length increased from 100 m to 1000 m, the Eff_{c_s} of the 3*RTs* system is 295.2 percent, improved by 26.8 percent, the Eff_{c_s} of the 5*RTs* system is 475.5 percent, improved by 109.9 percent, and the Eff_{c_s} of the 7*RTs* system is 645.6 percent, improved by 207.8 percent. It can be predicted that with the path length continue increasing, the Eff_{c_s} of a system will be close to the number of *RTs* of the system.

With the increasing path length, the difference between efficiency of three systems decreased. The efficiency of the 7*RTs* system is 84.9 percent at the path length of 500 m, improved 25 percent compare with the efficiency at the path length of 100 m. In conclusion, the multi-robot tractor system is more effective in large sized field.

VI Field experiment of multi-robot system

Three experiments were taken to testify the multi-robot system: 2*RTs* system, 3*RTs* system and 4*RTs* system. 2*RTs* system using *I*- pattern, 3*RTs* system using *V*- pattern and 4*RTs* system using *W*- pattern, respectively. The experiments were taken in a farm in Hokkaido University, Sapporo, Japan. According to the experiment results, the average accuracy of *RTs* is 0.04 m, which is high enough to do the work. In 2*RTs* system, the minimum space distance between *RTs* is 0.8 m. The minimum space distance between *RTs* of 3*RTs* system is 0.78 m, and the minimum space distance between *RTs* of 4*RTs* system is 0.82 m. Thus we can conclude that the multi-robot system can work safely in these experiments.

The efficiency of 2*RTs* system is 88.6 percent, the efficiency of 3*RTs* system is 80.0 percent, and the efficiency of 4*RTs* system is 82.1 percent at the path length at 100 m. It is easy to understand that the 2*RTs* system is more effective than the 3*RTs* system. The wait time of 2*RTs* system is 33.8 s shorter than 3*RTs* system, and the efficiency of 2*RTs* system is 8.6 percent higher than that of 3*RTs* system. However, it is difficult to understand that efficiency of 4*RTs* system is higher than that of 3*RTs* system. The headlands turn time of each *RT* in 4*RTs* system is 6.9 s shorter than that of in 3*RTs* system. In addition, the waiting time of 4*RTs* system is 9.0 s shorter than that of 3*RTs* system. That is the reason the 4*RTs* system (82.1 %) have a higher efficiency than 3*RTs* system (80.0 %).

In conclusion, the developed multi-robot tractor system can reduce work time and improve work efficiency.

VII Conclusion

In this research, an autonomous robot tractor was developed using multiple navigation sensors. Furthermore, a multi-robot tractor system was developed to reduce work time and improve work efficiency. To deal with external disturbances in the agriculture field, safety system using a laser scanner was developed, and to deal with internal disturbances in the agriculture field, fault tolerant method were developed. Three simulations and three field experiments were conducted to testify the effectiveness of the multi-robot tractor system. According to the simulation and experiment results, the developed multi-robot tractor system can dramatically reduce work time and improve work efficiency.