Computers and Electronics in Agriculture 142 (2017) 79–90

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Development of a multi-robot tractor system for agriculture field work

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ARTICLE INFO

Article history:
Received 14 March 2017
Received in revised form 15 August 2017
Accepted 17 August 2017
Available online 1 September 2017

Keywords:
Formation control
Safety zone
Work efficiency
Headland turn coordination

ABSTRACT

A multi-robot tractor system for conducting agriculture field work was developed in order to reduce total work time and to improve work efficiency. The robot tractors can form a spatial pattern, *I*-pattern, *V*-pattern or *W*-pattern, during the work process. The safety zones of each robot were defined as a circle and a rectangle. The robots can coordinate to turn to the next lands without collision or deadlock. The efficiency of the system depends on the number of robots, the spatial pattern, the setting distance between each robot, and the field length. Three simulations were carried out to determine the usefulness of the system. The simulation results showed that the efficiency range of three robots using the *I*-pattern is from 83.2% to 89.8% at a field length of 100 m. The efficiency range of seven robots using the *W*-pattern is from 59.4% to 65.8% at a field length of 100 m. However, the minimum efficiency of seven robots using the *W*-pattern is 84.9% at a field length of 500 m. The efficiency would be higher than 85% if the field length was larger than 500 m. Thus, the newly developed multi-robot tractor system is more effective in a large field.

1. Introduction

Various multi-robot systems have been developed in the past two decades. The coordination of a group of robots enables the execution of complex tasks. In many multi-robot systems, the robots are required to move in a desired spatial pattern, which is called formation control. To coordinate a group of robots, some researchers have developed a leader-follower system in which the follower robots adjust their velocity and heading based on the leader's behavior. For example, Nascimento et al. (2013) developed a multi-robot system for target tracking. A team of robots maintains a desired formation following a target while the target is moving or follows a leader in the case of no target. They used a nonlinear model predictive formation controller for target perception. Peng et al. (2013) developed a leader-follower system for nonholonomic mobile robots. They used a bioinspired neurodynamics-based approach according to the back-stepping technique to control the formation of the robots in order to solve the impractical velocity jumps problem. Yu et al. (2015) developed leader-following consensus of a fractional-order multi-agent system. The motion of the leader is independent of all other agents and is followed by all other ones. They used the stability theory of the fractional-order differential system and Lyapunov method to make the robots under that fixed topology. On the other hand, some researchers have focused on a multi-robot system that is leaderless or temp-leader. Cifuentes et al. (2015) proposed a multi-robot system based on virtual fields, situation awareness and basic behavior blending. The robots are anonymous, which means they do not know the existence of each other, and the navigation system is fully decentralized. Their system does not need a leader or a specific coordination protocol. The robots can simply navigate holding the cohesion of the group or they can navigate building up to keep a certain pattern. Savkin et al. (2016) proposed decentralized motion coordination control algorithms for groups of robots. The robots collectively move in a desired geometric pattern from any initial position with no predefined leaders in the group.

The formation of a multi-robot system has widely applications. Sabattini et al. (2011) proposed a decentralized control strategy to realize the formation of mobile robots for cleaning. They used three robot vacuum cleaners to keep a regular polygon shape. There was no centralized controller; thus, even if the total number of robots was increased, the amount of information needed by each agent did not change. Vougioukas (2012) developed a multi-robot system for agriculture work. Two or three robot tractors were used to conduct field work. The system supported two modes: master-slave mode and peer-to-peer mode. Jia and Wang (2014) developed a multiple robotic fish system. The robotic fish swim on the water surface and communicate with each other under switching topologies with an undirected information flow

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http://dx.doi.org/10.1016/j.compag.2017.08.017
0168-1699/

based on nearest-neighbor interaction. Karma et al. (2015) used multi-vehicles in search and rescue in forest fires.

For agriculture, researchers have developed robot tractors (or vehicles) to solve the problem of labor shortage and to reduce work requirement (Larsen et al., 1994; Billingsley and Schoenfisch, 1997; Elkaim et al., 1997; Bak and Jakobsen, 2004; Nagasaka et al., 2004; Nørremark et al., 2008). Master-slave robot tractor systems have also been developed to improve work efficiency (Noguchi et al., 2004; Zhang et al., 2010, 2016a; Vougioukas, 2012). Johnson et al. (2009) developed a team of robotic tractors for peat moss harvesting. In their system, three robot tractors worked in three different fields and a human operator remotely commanded and monitored the robots. An agriculture multi-robot system is similar to the sweep coverage robot system (Hazon and Kaminka, 2008; Cheng et al., 2011a,b; Ni et al., 2013; Zhai and Hong, 2013), both of which need to cover a large area in minimum time.

The objective of this study was to develop a multi-robot tractor system for agricultural field work. In some situations, such as planting or harvesting before rain, field work needs to be done in a limited time. By coordination of a team of robot tractors, the total work time can be reduced and the work efficiency compared with that with a single robot can be increased. A significant reduction in human labor can also be achieved.

The two key points of this research are the usefulness and efficiency of the system. Multiple robots can generally work by two methods: working together and working separately. If multiple robots work separately, there is no risk of collision between the robots. However, more human monitors are needed to monitor the operations of the robots based on current conditions (Noguchi and Reid, 2000). In contrast, if multiple robots work together, one human monitor is sufficient to monitor all of the robots and thus human labor can be saved. In addition, in some cases the multiple robots have to work together. For example, a robotic harvester harvesting in a field, an on-the-go unloading system with a robotic trailer that moves the harvested products to collection positions helps improve harvesting efficiency since the harvester does not need to stop.

This system is a decentralized system in which each robot tractor can work alone or they can work together to form a spatial pattern during the work process. One difference between the agriculture robot tractors and sweep coverage robots is that robot tractors need to cover each place only one time. Another difference is that robot tractors cannot maintain the spatial pattern during a headland turn process in order to make best use of the headland. These are the main reasons that the efficiency of the multi-robot tractor system cannot reach 100 percent. If the robot tractors continue to maintain the spatial pattern, the headland space would have to be larger than normal, which is not acceptable for farmers. In addition, a robot tractor cannot work with a large steering angle because the machinery it is towing might be damaged. Therefore, a formation control algorithm is used in the work process and a turning coordination algorithm is used in the headland turn process. In addition, a safety zone of the robot tractor is proposed to ensure safety of the system.

In the previous studies (Zhang et al., 2010; Cheng et al., 2011b; Vougioukas, 2012), researchers focused on formation control by which robot tractors can maintain the spatial pattern even when they conduct the turn process. Thus, work efficiency was not a relevant factor since the robots did not stop. However, in the newly developed system, the robot needs to coordinate with other robots and sometimes needs to stop to avoid deadlock and ensure safety. The formation and number of multi-robot tractors can be in several combinations, and each of them has a different efficiency than that of a single robot tractor. For example, in the same field, the efficiency of using three robots differs from that of using five robots. In addition, using the same three robots, the efficiency of three robots conduct 100 m work differs from the efficiency of three robots conduct 500 m work. In this study, the field was a regular rectangular field and the formation patterns of robots included an *I*-pattern, a *V*-pattern and a *W*-pattern. The results of simulations of the three typical formations and the results of experiments using two formations (*V*-pattern and *W*-pattern) are presented in this article and the efficiency of the system is discussed.

The rest of this article is organized as follows. The methods used in the system, including formation control, headland turn coordination, safety and work efficiency evaluation, are presented in Section 2. The results of simulations and experiments are presented in Section 3. The usefulness and efficiency of the system are discussed in Section 4. Conclusions are given in Section 5.

2. Methods

The factors involved in a multi-robot system include (1) formation pattern and priority assignment, (2) control during the work process, (3) control during the headland turn process, (4) safety evaluation and (5) work efficiency evaluation.

2.1. Formation pattern and priority assignment

Robot tractors (abbreviated as *RTs*) traveling in a field can be coordinated in several ways. In this study, the *I*-pattern, *V*-pattern and *W*-pattern were used in the multi-robot system, as shown in Fig. 1. Each *RT* can be schematized as a rectangular brush, the purpose of the use brushes being to cover the whole field and to brush each place only one time.

Each *RT* in the same group was assigned a priority ID, $RT_i.p$, as shown in Fig. 2. When a conflict is found, the lower priority *RT* adjusts itself to ensure the higher priority *RT*'s operation. The rules of priority assignment of the multi-robot system are defined as follows:

①When traveling forwards, priority is given to the order of positions from the front to the rear; an *RT* in the front has higher priority than an *RT* in the back.
②When turning to the right, priority is given to the order of positions from right to left; an *RT* on the right has higher priority than an *RT* on the left.

2.2. Control during the work process

Once the formation pattern has been defined, the lateral distance (l_{lat}) and longitudinal distance (l_{lon}) between *RTs* are determined. The longitudinal distance between two *RTs* is the distance between the two *RTs* in the lands direction, and the lateral distance between two *RTs* is the distance between the two *RTs* perpendicular to the lands direction. $RT_i.l_{lat\_set}$ is defined as the setting for the lateral distance between RT_i and RT_j , where RT_j is the closest higher priority *RT* relative to RT_j, and $RT_i.l_{lon\_set}$ is defined as the setting for the longitudinal distance between RT_i and RT_j.

2.2.1. Lateral distance control

The lateral distance between RT_i and RT_j, namely $RT_i.l_{lat}$, is limited by the lands of the two *RTs*. If the two *RTs* are each working on their own lands, $RT_i.l_{lat}$ is equal to the width between the two lands. If any *RT* off-tracks its lands, it starts to track its own lands again. The algorithm of lands tracking was discussed in Yang et al. (2016).

$$\Psi = k_{\varphi}\Delta\varphi + k_d d \tag{1}$$

where Ψ is the steering angle, $\Delta\varphi$ is the heading error, d is the lateral error and k_{φ}, k_d are the control gains. The lateral error d is the