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Multi-Robot System Control Architecture (MRSCA) for Agricultural Production

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Multi-Robot System Control Architecture (MRSCA) for Agricultural Production

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Abstract. *Coordinating multiple autonomous robots for achieving an assigned collective task presents a complex engineering challenge. In this paper multi robot system control architecture (MRSCA) for the coordination of multiple agricultural robots is developed. The two important aspects of MRSCA; coordination strategy and inter-robot communication were discussed with typical agricultural tasks as examples. Classification of MRS into homogeneous and heterogeneous robots was done to identify appropriate form of cooperative behavior and inter-robot communication. The framework developed, proposes that inter-robot communication is not always required for a MRS. Three types of cooperative behaviors; No-cooperation, modest cooperation and absolute cooperation for a MRS were devised for accomplishing a variety of coordinated operations in agricultural production.*

Keywords. *Multi-robot system, control architecture, inter-robot communication, coordination strategy*

Introduction

The demand for application of computers and electronics for the automation of agricultural field machinery has seen tremendous growth in the recent years. The primary objective of automating field machinery is to increase productivity. Although, electronics are extensively used in contemporary agriculture to assist machine operators, the continual increase in the size of farm equipment is creating problems with the metering and placement of crop production inputs. Autonomous operation of agricultural machines may be able to mitigate the sources of errors caused by human intervention. Typically, multiple machines are used for agricultural production where one operator is required for each machine. Usage of multiple machines is common on most of the large scale farms. Hence, there is a one to one ratio of human operators to number of machines. The capability of one human to manage and monitor multiple unmanned agricultural machines/robots may prove to be the most efficient way of utilizing technology to improve farm productivity. Taking agricultural robots a step further, deployment of multiple robots which are efficient, profitable and scale neutral will result in a situation where the farm operators monitor field operations and responds to machine errors/failures. Goal oriented multiple agricultural robots which work in coordination to achieve a common goal can greatly increase the productivity of agricultural farms. A system consisting of multiple, simpler robots will most likely be more cost-effective and robust than having a single complex unmanned vehicle (Parker, 2002.). Multiple cooperating robots can complete a given task faster with greater reliability because of the distributive nature of work of the multi-robot system (MRS). In a MRS if one robot fails the remaining robots continue to work to finish the given task making it more reliable than a single complex robot. Although, MRS is desirable for increasing the efficiency of agricultural production, it is a big challenge to coordinate the activities of multiple robots to accomplish an assigned task. Effective inter-robot communication is a major aspect of MRS to be resolved to garner the benefits of a team of working robots.

It is important to identify the specific advantages of deploying inter-robot communication because the cost increases with the complexity of communication among the robots. Three types of inter-robot communication were explored by Balch et al. (1994). They found that communication can significantly improve performance in some cases but for others, inter-agent communication is unnecessary. In cases where communication helps, the lowest level of communication is almost as effective as the more complex type. Rude et al. (1997) developed a wireless inter robot communication network called IRoN. The two important concepts of the network were; implicit communication and explicit communication. A modest cooperation between robots is realized using implicit communication and a dynamic cooperation is achieved by using explicit communication. The authors utilized two robots to implement IRoN and were able to identify the changes which reduced the motion delay time ranges from 1000 ms to 50 ms. Wilke and Braunl (2001) developed flexible wireless communication network for mobile robot agents. The communication network was an explicit communication method which was applied to team members of a RoboCup team playing soccer. The communication network allowed broadcasting, transmission of messages between individuals and communication with a remote computer workstation.

To identify the type of inter-robot communication required for multiple robots in an agricultural production environment, a good understanding of the cooperative behaviors of agricultural robots is required. Thus, the current work is focused on developing multi-robot system control architecture (MRSCA) that would provide a coordination strategy for the working of multiple agricultural robots and a framework to develop inter-robot communication. The concepts of Implicit, explicit communication and the internal control structure of an individual robot in a MRS are critical for the realization of a robust MRSCA. A Behavior-Based control architecture consisting of reactive and deliberative behaviors of an autonomous agricultural robot developed by Pitla et al. (2009) will be considered as a building block in the development of the MRSCA. This architecture will be discussed briefly in the following sections.

Objectives

- To develop MRSCA for agricultural production that comprises of two principal components; coordination strategy and Inter-robot communication.
- Evaluate the relevance of the proposed architecture to typical agricultural operations.

Coordination strategy and Inter-robot communication

When multiple robots are working together to accomplish a task the foremost question to be resolved is the type of inter-robot communication required. Intuitively, the coordination strategy that multiple robots pursue affects the way the robots communicate with each other. The coordination strategy of a MRS is different for homogeneous robots and heterogeneous robots. Homogeneous MRS is a group of functionally equivalent robots which perform similar actions utilizing the same levels of sensing and control capabilities whereas, heterogeneous robots are functionally different. Thus, the homogeneity and heterogeneity of the robots in a MRS affect the coordination strategies and are crucial to determine the type of inter-robot communication to be deployed.

Two forms of inter-robot communication; implicit and explicit communication are considered to aid the process of identifying a communication framework for homogeneous and non-homogeneous robots. Implicit communication is the unintentional communication between wireless entities. Important data representing the state of the robot like the position (x, y, θ) and velocity (v) variables of robots are broadcasted over the wireless channel. Intentional communication specifically directed at a unique wireless entity constitutes explicit communication. Explicit communication can be of type point to point or point to multi-point communication. In comparison to implicit communication, explicit communication is intricate as it has to acquire the address of a specific robot before it can transmit the data. While some tasks require just implicit communication, a combination of implicit and explicit communication is mandatory for some specific tasks. Rude et al. (1997) defined implicit communication as unintentional inter-robot communication and explicit communication as intentional inter-robot communication. In this paper the definition for implicit communication will be modified to reduce the communication overhead on each robot. Implicit communication in this paper is the unintentional communication between the individual robot and the central monitoring station (CMS) as opposed to unintentional communication among robots of a MRS. A new form of communication called the default communication will be defined for a MRS. The default communication is nothing but the implicit communication which will enable all the robots in a MRS to broadcast their states to the CMS. The CMS is a workstation considered to possess high processing power which can receive and store the statuses of all the robots of a MRS. When the robots in a MRS need to communicate with each other they will initiate explicit communication.

Homogeneous robots

Although the notion of MRS compels us to think that some form of communication between robots is necessary, in reality, in some cases, no-communication between homogeneous robots is as good as when there is some form of communication among robots. But, a major requirement for a homogeneous MRS with no inter-robot communication to be robust is that the individual robot of the MRS has to be intelligent. A robust internal control structure within each robot is required for an individual robot to be intelligent. A Behavior-Based control architecture (IRCA) consisting of reactive and deliberative behaviors for an autonomous agricultural robot was developed by Pitla et al. (2009a, 2009b). Hence, each robot of the MRS with an IRCA will be assumed to be intelligent. IRCA (fig.1) provides intelligence to an individual robot where it reacts to the obstacles and continues to move towards achieving its assigned goal. Thus, for a homogeneous MRS as long as individual robots are intelligent, cooperation is not required and inter-robot communication can be assumed to be trivial.

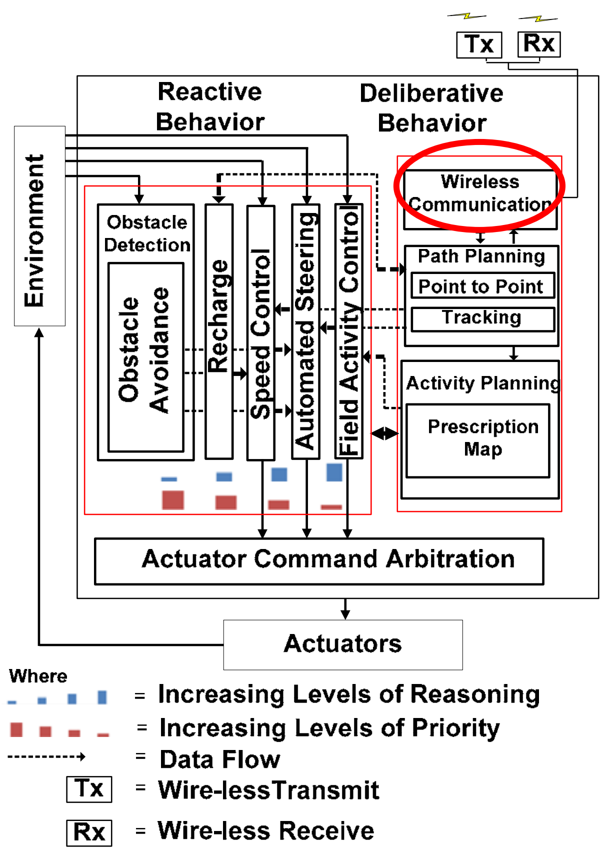


Figure 1. IRCA for an agricultural robot (Pitla et. al 2009a)

The homogeneous robots will divide the task into multiple working zones (WZ) and operate in their respective unique zones without interfering in each other's tasks. The robots are always in their default communication state (Implicit communication) and broadcast their states on the wireless channel. The CMS receives the states of all robots and stores them with their unique IDs. The wireless communication module (WCM) within the deliberative component (Fig.1) of the robot is responsible for establishing communication with the CMS. WCM consists of wireless modems with the capabilities of broadcasting, point to point and point to multi-point communication.

Heterogeneous robots

A MRS involving heterogeneous robots requires some form of inter-robot communication unlike a homogeneous MRS where, inter-robot communication is not mandatory. In a heterogeneous MRS each robot performs a different function and so it is necessary for the robots to coordinate their actions to accomplish a collective task. The extent to which the robots cooperate with each other varies for different tasks and hence two forms of cooperation are defined; modest cooperation and absolute cooperation. In *modest cooperation*, the robots do not interfere with each other's work but short-term cooperation is established at the instant when robots have to work together. *Explicit momentary* communication is established for moderate cooperation enabling one robot to establish a point to point communication with another robot. Typically, in this form of communication one robot provides an instruction to the other robot to work on a specific task. The robot which receives the instruction acknowledges the reception of the message which allows the other robot to resume its default function. On the other hand, absolute cooperation involves continuous cooperation of two robots at all times and *explicit continuous* communication is established between the two robots to finish an assigned task. In addition to momentary explicit communication for modest cooperation, and continuous explicit communication for absolute cooperation, the default implicit communication is used to enable the robots to broadcast their states to CMS. Classification of MRS on the basis of homogeneity and heterogeneity is provided in figure 2. The fusion of coordination strategy and Inter-robot communication (Fig.2) with IRCA (Fig.1) constitutes the MRSCA.

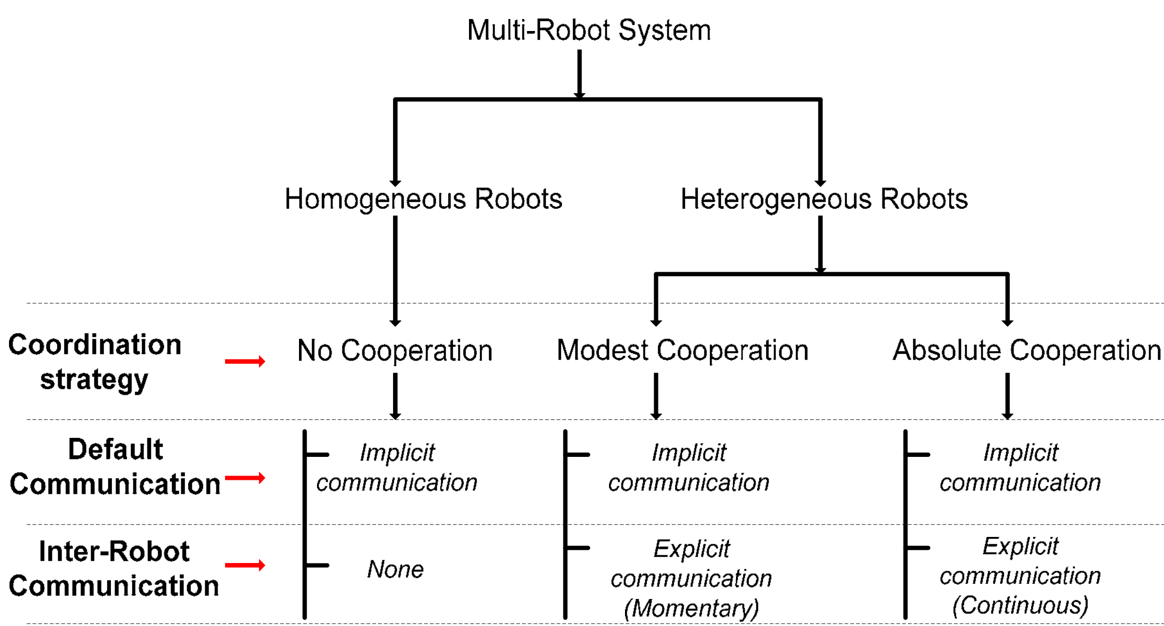


Figure 2. Coordination strategy and inter-robot communication chart for a MRS

Proposed MRSCA applied to typical agricultural operations

Homogeneous robots (No Cooperation):

MRS with homogeneous robots can be used for spraying, planting and fertilizer application. For these agricultural operations all the robots are functionally equivalent where each robot performs a similar function of covering a given field area to apply plant material (chemicals, seed and fertilizer). To illustrate the relevance of the proposed MRSCA, the MRS considered is a team of robotic sprayers. In this case, the sprayers divide the total coverage area in to multiple equal WZ and apply chemicals in their respective WZs. Each robot is assumed to have an onboard GPS which aids the robots to work within its assigned WZ. Four robotic sprayers (I, II, III, and IV) can be seen spraying in their respective WZs in figure 3. No cooperation between robots is required as the robots do not interfere with each other's work. Since there is no cooperation, there is no inter-robot communication. The only form of communication the robotic sprayers use is the default communication (*implicit communication*) using which each robot broadcasts its states to the CMS at a regular time interval. If two robots are threateningly close to each other, the IRCA within each robot switches the robot to reactive mode and provides the robot, the intelligence to avoid obstacles. Once the obstacle is avoided the robot resumes its function of spraying.

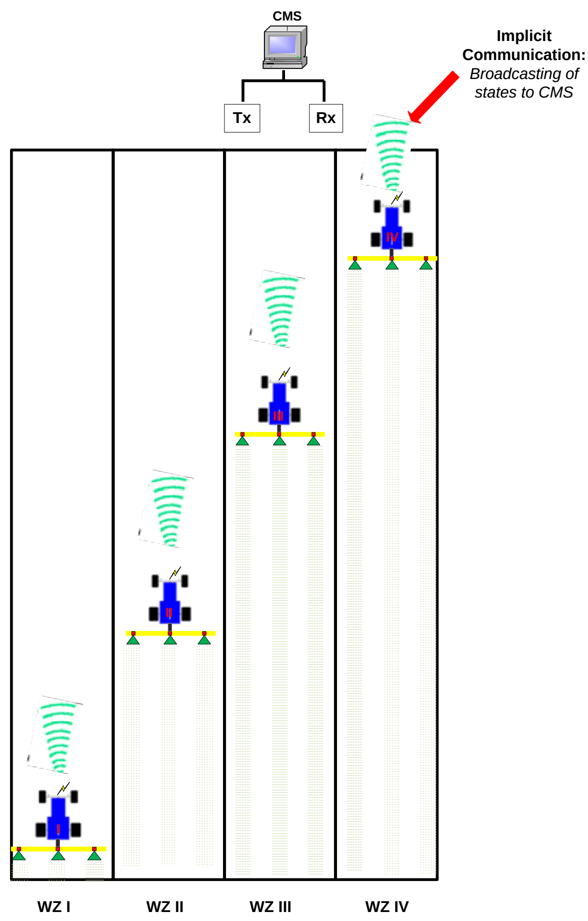
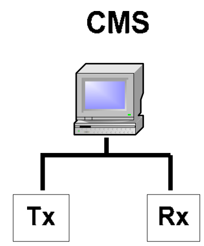


Figure 3. Homogeneous MRS (multiple robotic sprayers)

The broadcasted message structure of each robot is shown in figure 4. The robotic sprayers working in the field broadcasts messages with information containing their unique IDs, states, time stamp and the status of the assigned work. Each robot is assigned a unique ID of data type integer (Eg: Unique ID: 1) instead of names to reduce the size of data sent on the wireless channel. The status of work in this case would be the percent of area covered by the robot. The CMS receives the data and stores all the data in its database for monitoring and post processing.



Message Frame

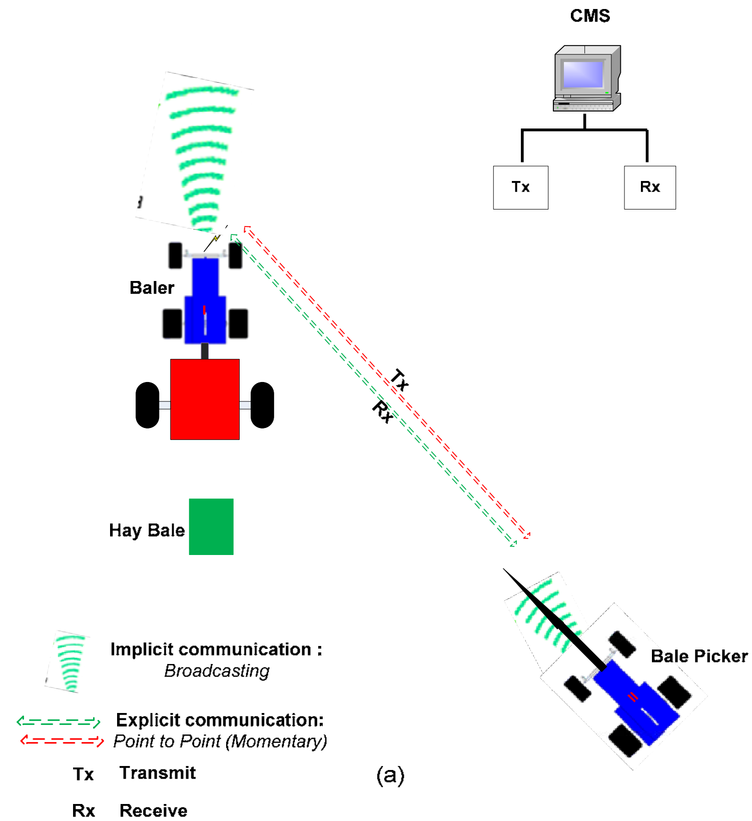
Unique ID	States	Status	Time stamp
i	x_i,y_i,θ_i,v_i	% (a_i) area covered	t_i

		CMS database	
Unique ID	**States**	**Status**	**Time stamp**
1	x_1,y_1,θ_1,v_1	% (a_1) area covered	t_1
2	x_2,y_2,θ_2,v_2	% (a_2) area covered	t_2
3	x_3,y_3,θ_3,v_3	% (a_3) area covered	t_3
4	x_4,y_4,θ_4,v_4	% (a_4) area covered	t_4

Figure 4. Message structure for implicit communication of Homogeneous robots

Heterogeneous robots (Modest Cooperation):

One of the typical agricultural operations found on US farms is hay baling. The baler performs the function of baling and the bale picker does the job of picking the bale to transfer it to a desired location outside the field. To automate the baling-picking operation, heterogeneous robots which perform different functions are required. Momentary cooperation is required for the baling-picking operation as the baler needs to communicate with the bale picker only when the bale is ready to be picked. The baling-picking robots require a coordination strategy of type modest cooperation and the inter-robot communication required is of type *explicit-momentary***.** Using explicit communication the baler robot sends a message to the picker stating that the bale is ready to be picked up (figure 5.). The baler sends the location where it dropped the hay bale to aid the picker in path planning. Hence, in this kind of operation intermittent communication is required where the robots communicate momentarily and then continue to do their principal functions. During the whole process the states of the two robots are broadcasted to CMS using implicit communication. The message structure required for this inter-robot communication is provided in figure 5. The baler and the picker robot each have three types of message frames to communicate the status of the bale and the location of the bale. When the baler finishes a bale it sets the ACK and Status bit in its Rx-message frame to 0 indicating that the bale is ready to be picked. Once the status bit is 0, the baler stops working and transmits the location and timestamp through the Tx-message frame to the picker using the destination ID of the picker. The information about the bale is transmitted to the picker and the picker acknowledges the reception by transmitting Tx-message frame with an ACK and Status bits of value 1. A value of 1 in the status bit of the Rx-message frame triggers the baler to baling to produce another bale.



Baler (Robot I)

Rx-message frame

ACK	Status
0	0

Tx-Message frame

Unique ID	Destination ID	States	Time stamp
1	2	x_1,y_1,θ_1,v_1	t_1

Onboard-message frame (Broadcast)

Unique ID	Location	Status	Time stamp
1	x_1,y_1,θ_1,v_1	0	t_1

Picker (Robot II)

Rx-message frame

Unique ID	Source ID	States	Time stamp
2	1	x_1,y_1,θ_1,v_1	t_1

Onboard-message frame (Broadcast)

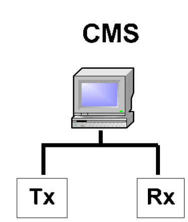
Unique ID	Location	Status	Time stamp
2	x_2,y_2,θ_2,v_2	1	t_2

Tx-Message frame

ACK	Status
1	1

CMS database

Unique ID	States	Status	Time stamp
1	x_1,y_1,θ_1,v_1	0	t_1
2	x_2,y_2,θ_2,v_2	1	t_2



(b)

Figure 5. Heterogeneous multi-robot system (a), Message structure of explicit -momentary and implicit inter-robot communication (b)

Heterogeneous robots (Absolute Cooperation):

Another typical example where heterogeneous machines are used for agricultural production is grain harvesting operation. One grain harvester and multiple grain wagons are typical on large US farms. A heterogeneous MRS with one grain harvester robot (GHR) and two grain wagon robots (GWRs) performing grain harvesting operation is depicted in figure 6. This type of operation requires a coordination strategy of type *absolute cooperation* as the GHR and grain GWRs should cooperate with each other throughout the harvesting operation.

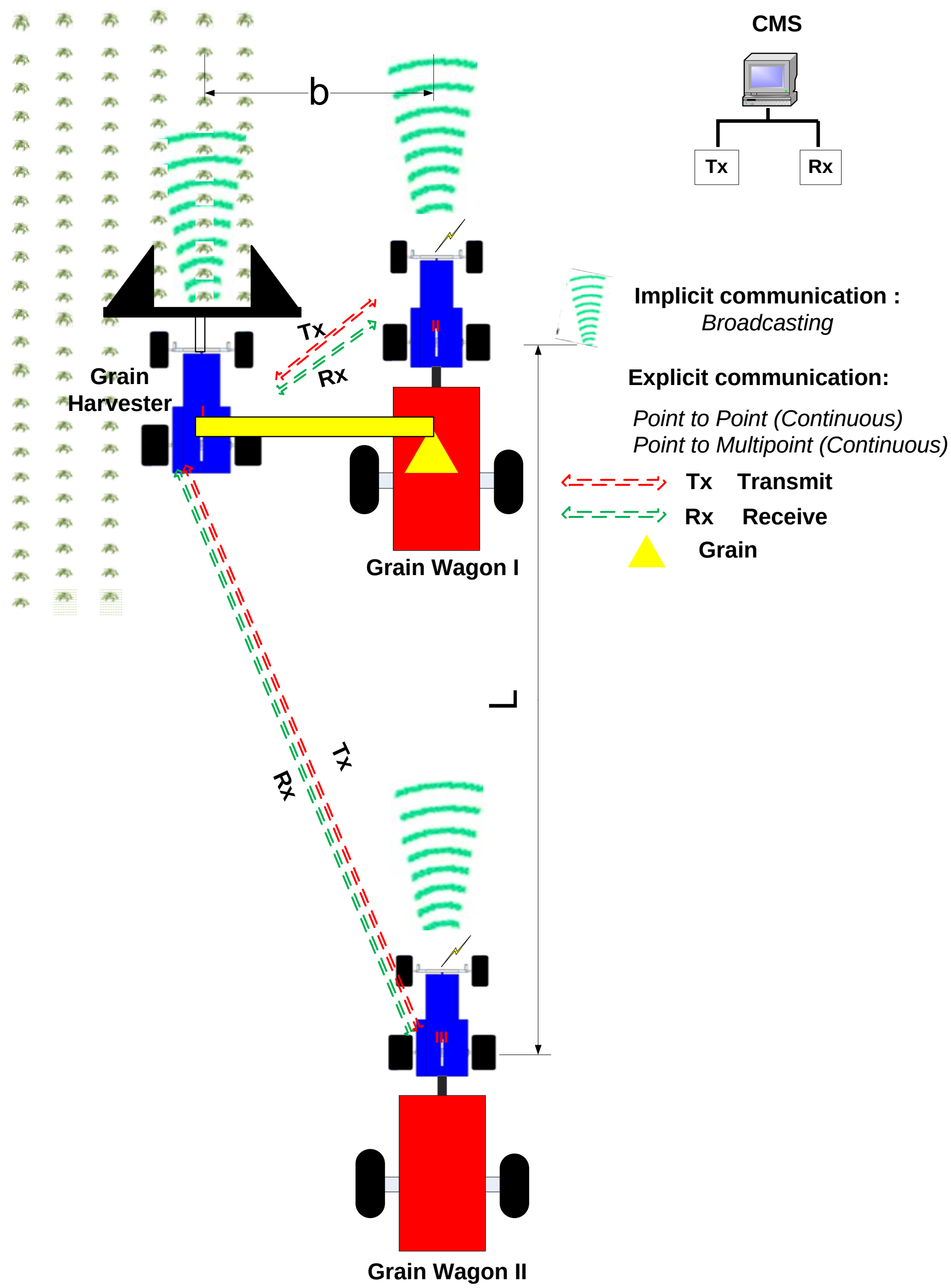


Figure 6. Heterogeneous multi-robot system (Harvester and grain wagon robots)

To maintain absolute cooperation, *explicit-continuous* inter-robot communication is required. Unlike baling-picking operation, the harvesting operation is complex and uninterrupted cooperation is needed between the GHR and the GWR. At the beginning of the operation, the GWR establishes continuous point to point communication with GWR I. The two robots maintain close proximity to transfer the grain. In the case where there are two GWRs the GHR requires continuous point to multipoint communication to plan the logistics. GWR II should be prepared to take the position of GWR I when GWR I is full. This form of inter-robot cooperation is by far the complex form of coordination discussed in this paper. The complexity of the inter-robot communication increases with increase in number of robots in a heterogeneous MRS. The message structure required is presented in figure 7. In this example, GHR continuously transmits its Tx-message frame at regular intervals of time to GWRs. The Tx-message frame contains the destination IDs, the target states for GWR I and GWR II to maintain, timestamp and the required statuses of GWR I and GWR II. In this example the Tx-message frame sends status 1, 0 to GWR I and GWR II respectively. This indicates that GHR wants GWR I to assist in harvesting by requesting it to maintain a position on one side of it. Hence, status bit 1 in the Rx-message frame of GWR I indicates that it is currently assisting robot I during harvest and status bit 0 in Rx-message frame of GWR II indicates that it is not assisting robot I. GWR I maintains a state of (x_1+b, y_1, θ_1, v_1) and GWR II maintains a state of (x_1+b, y_1-L, θ_1, v_1) to follow the GHR.

Grain Harvester Robot (GHR)

Tx-Message frame

Unique ID	Destination ID	States	Time stamp	Status
1	2,3	(x_1+b,y_1,θ_1,v_1),(x_1+b,y_1-L,θ_1,v_1)	t_1	1,0

Onboard-message frame (Broadcast)

Unique ID	States	Status	Time stamp
2	x_1,y_1,θ_1,v_1	1	t_1

Grain Wagon Robot I (GWR I)

Rx-message frame

Unique ID	Source ID	States	Time stamp	Status
2	1	(x_1+b,y_1,θ_1,v_1)	t_1	1

Onboard-message frame (Broadcast)

Unique ID	States	Status	Time stamp
2	x_2,y_2,θ_2,v_2	1	t_2

Grain Wagon Robot II (GWR II)

Rx-message frame

Unique ID	Source ID	States	Time stamp	Status
3	1	(x_1+b,y_1-L,θ_1,v_1)	t_1	0

Onboard-message frame (Broadcast)

Unique ID	States	Status	Time stamp
3	x_3,y_3,θ_3,v_3	1	t_3

CMS database

Unique ID	States	Status	Time stamp
1	x_1,y_1,θ_1,v_1	1	t_1
2	x_2,y_2,θ_2,v_2	1	t_2
3	x_3,y_3,θ_3,v_3	1	t_3

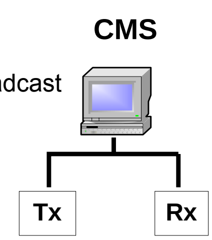


Figure 7. Message structure of explicit-continuous and implicit communication for Heterogeneous robots

Conclusions

With no pertinent literature available for inter-robot communication of a MRS for agricultural production, this paper serves as a good starting point to develop communication protocols for a group of agricultural robots. The application of implicit and explicit communication for different types of agricultural operations involving multiple robots in this paper highlights the fact that inter-robot communication in a MRS is not always required. No-cooperation, modest cooperation and absolute cooperation are some of the important features of MRSCA which support different tasks and allow efficient utilization of communication resources. Although no specific hardware and software requirements for inter-robot communication are listed, the concepts of homogeneous MRS, heterogeneous MRS and the message structure for different forms of inter-robot communication discussed aid the programmers in developing efficient communication protocols.

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