INTERNATIONAL JOURNAL OF COMPUTERS COMMUNICATIONS & CONTROL
Online ISSN 1841-9844, ISSN-L 1841-9836, Volume: 16, Issue: 3, Month: June, Year: 2021
Article Number: 4233, https://doi.org/10.15837/ijccc.2021.3.4233

A Cyber Collaborative Protocol for Real-Time Communication and Control in Human-Robot-Sensor Work

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Abstract

Real-time communication and control are essential parts of the Cyber Physical System (CPS) to optimize effective performance and reliability. To gain a sustainable competitive advantage with Automation 5.0, as needed in Work-of-the-Future, this article addresses the concept of real-time communication and control in the case of an agricultural work setting, along with a newly designed Cyber Collaborative Protocol, called CCP-RTC2. The developed protocol aims to minimize information delay and maximize JIN (Just In Need) information sharing, to enable collaborative decisions among system agents. Two experiments are conducted to compare the designed protocol's performance in agricultural CPS against the current non-CPS practice. The results demonstrate that the CCP-RTC2 is superior compared with current practice in terms of information sharing in a normal operation scenario. When the system obtains an unplanned request, the CCP-RTC2 can integrate such a request to the original work plan while minimizing the system's objective function (lower is better). Hence, the system has relatively smaller information delays, as well as better timely information shared with system agents that need it.

Keywords: collaborative control theory, multi-agent systems, real-time information exchange, task administration protocols, automation 5.0.

1 Introduction

Without exception, real-time communication and control, and knowledge sharing are currently at the core of modern industry, including agriculture. As an illustration, individual agricultural agents (e.g., farmers) work with intensive, overloaded information in the way they practice in farming, the traditional agricultural work activities/methods are considered as lacking effective information flow.

Specifically, insufficient control, communication, coordination, and collaboration negatively influence timeliness and optimization of decision-making processes at work [16]. Arguably, the lack of effective information sharing process potentially leads to suboptimal agricultural work management, such as the slow process of localization and early detection of crop diseases; improper, often wasteful response and prevention; poor plant monitoring; and low crop yield [11]. Therefore, the advancement of agricultural robotics and farming equipment that improve the way farmers can work has called for effective means to communicate and connect so that the overall system reaches optimal performance. One of the emerging methods to facilitate real-time communication and control is utilizing Cyber Physical Systems (CPS), which link and can optimize the functions of physical elements by cyber connections.

Today, the term CPS has been widely adopted as one of the promising key factors leading to Automation 5.0 [23]. CPS is a rapidly evolving model that describes a system where information and communication technology is integrated into a physical process to make the entire system more efficient, reliable, and timely in the decision-making process [3, 17]. Networked manufacturing systems, intelligent transport systems, smart infrastructures, and power grids are examples of evolving CPS [17, 21, 28]. Thus, the benefits of CPS are prominent in many areas. For instance, in the manufacturing industry, the equipment used will be continuously tracked so that the equipment's performance and condition can be seen remotely and in real-time. In the service sector, CPS can prioritize and reduce service failure by sharing information with frontlines, thereby increasing customer satisfaction [14].

Recently, there has been increasing in applying CPS in agricultural work. Guo and colleagues [11] designed a CPS framework focusing on tracking, detecting, and reacting to different stress forms in an agricultural greenhouse. They found that with CPS, the system has better operation performance and error tolerance. Another useful CPS application in agricultural settings is adding human-in-the-loop, making the system more effective and responsive [2, 19]. Also, sensors and sensor networks are integrated as an essential part of CPS to enable precision control and monitoring [18, 26]. Internet and web service structure for agricultural CPS that enables wireless connection is developed and outperforms alternative systems [30]. Lastly, with synchronization among agents by task administration protocol in CPS, the monitoring process outperforms the traditional practice by reducing the operational time and increasing overall system efficiency [7]. Surprisingly, however, most of the literature has mainly focused on the agents' operations and connection structures – assuming perfect communication and control, such as information flow among agents and data exchange between systems, taken as a given prerequisite.

An essential element in CPS that enables real-time communication and control is a Cyber Collaborative Protocol (CCP). CCP is a task administration protocol that collaborates agents with cyber connections [6, 22]. The cyber connection in the CPS environment improves and enables system abilities critical for modern systems, i.e., real-time communication and control. As Herdon [12] mentioned, new and timely information processing provides a possibility for productive operation, decision-making, and adaptation to the environment. Thus, the timing of information is a critical factor, especially in short-term daily operation [5], such as patient monitoring system in a medical field [10, 15]; real-time tracking and control in operations fields [9, 24, 27]; and traffic control and safety in transportation [25, 29].

Furthermore, to gain competitive advantages with Automation 5.0, effective agricultural work management inevitably relies on this real-time communication and control (timely and comprehensive information processing, communicating, and controlling), and CCP is an essential tool to enable such advantage.

To date, there have been few researchers systematically developing a protocol for real-time communication and control that will enable collaborative decisions in CPS, especially in agriculture settings. To address this gap, in this article, we develop and validate a Cyber Collaborative Protocol for Real-Time Communication and Control, called CCP-RTC2. The designed protocol integrated with the agricultural CPS called Agriculture Robotics System (ARS). It is compared and contrasted with the current non-CPS agricultural setting.

The key contributions of the article are: 1) The introduction of a new type of CCP, which focuses on real-time communication and control, 2) The development of the CCP-RTC2, which optimizes and organizes timely and Just in Need (JIN) information flow among agents, and 3) The implemen-

Table 1: Agents and their responsibility in ARS Work

Agent	Responsibility
Human and expert system	Decision-makers; solve complex and unexpected work problems.
Robot with autonomous cart	Move into the greenhouse and approach the crop plants in the assigned direction(s).
Sensors	Collect and transmit data to the host.

tation and validation of CCP-RTC2 in CPS, compared against the current practice in terms of its performance.

The remainder of the article is structured as follows. In Section 2, the overview ARS is described, and the detailed explanation of CCP- RTC2 is presented. Next, in Section 3, two experiments are conducted to test two logic approaches. Conclusion and future work directions are discussed in Section 4.

2 Methodology

The Agricultural Robotic System (ARS) is designed to monitor and detect an abnormal status of crop plants, such as stress or disease [11]. For effective monitoring and detection, a protocol that enables smooth communication and information exchange among system agents to enable effective collaborative decisions is necessary [13]. Hence, in this section, a Cyber Collaborative Protocol for Real-Time Communication and Control, called CCP-RTC2, is established to facilitate information exchange for collaborative decisions to have better communication and informatics and, consequently, better monitoring, controlling, and detection processes in ARS.

2.1 ARS and CCP-RTC2 Designs

2.1.1 ARS overview and task description

ARS consists of a robot arm with multi-sensors mounted on an autonomous mobile cart and a human agent who serves as a decision-maker [7]. The work tasks and responsibilities of each agent in the ARS are shown in Table 1.

In every inspection round, plants are randomly selected to inspect their status. An autonomous cart is guided to visit every assigned location; then, the robot arm starts approaching the plant's leaves and stems according to the inspection procedure. Sensors capture images of the plant's parts and transmit them to the base point where a human agent with an expert system can decide whether to activate a treatment if the plant is just stressed or already infected, or move to the next location otherwise. Figure 1 presents the work system described above.

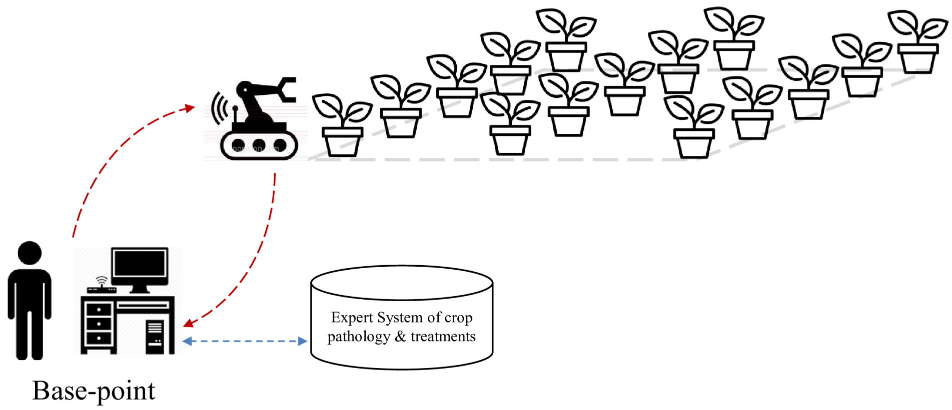


Figure 1: Agricultural Robotic System (ARS) work operations

Table 2: CCP-RTC2

Cyber Collaborative Protocol for Real-Time Communication and Control in ARS (CCP-RTC2)		
Step 1	ARS initialization	
Step 2	ARS sampling the location to visit	
Step 3	Autonomous cart is guided to visit location n	
Step 4	Robot arm approaches plant leaves and stems to capture the data	
Step 5	Sensors capture the necessary data and images	
Step 6	Sensed data are transmitted to the crop pathology expert system	
Step 7	Crop pathology expert system determines the status of the given plant	
	Step 7.1	If a plant at location n is healthy, then no action is required at location n. The expert system commands an autonomous cart to move to the next location.
	Step 7.2	If a plant at location n is unhealthy or has signs of stress that can lead to disease, then command a robot to activate specified precision treatment.

2.1.2 Cyber Collaborative Protocol for Real-Time Communication and Control in ARS (CCP-RTC2)

In ARS, multiple agents are combined as a system. Each agent connects and is responsible for a specific task regarding their strengths and weaknesses. Therefore, to optimize ARS performance, a CCP is needed to make a collaborative decision and, hence, a Cyber Collaborative Protocol for Real-Time Communication and Control in ARS (CCP-RTC2) is designed and developed. CCP-RTC2 is derived from CCP and aims to facilitate real-time information gathering and exchange, and optimize and control information flow between system agents. The objective of CCP-RTC2 is to 1) Minimize the information delay (maximize real-time communication) in the system, reacting to the emerging situation, and 2) Enable collaborative decisions and control, and information sharing, as needed and when needed. The CCP-RTC2 steps are described in Table 2. The protocol is further described by a workflow with conversion conditions (Figure 2).

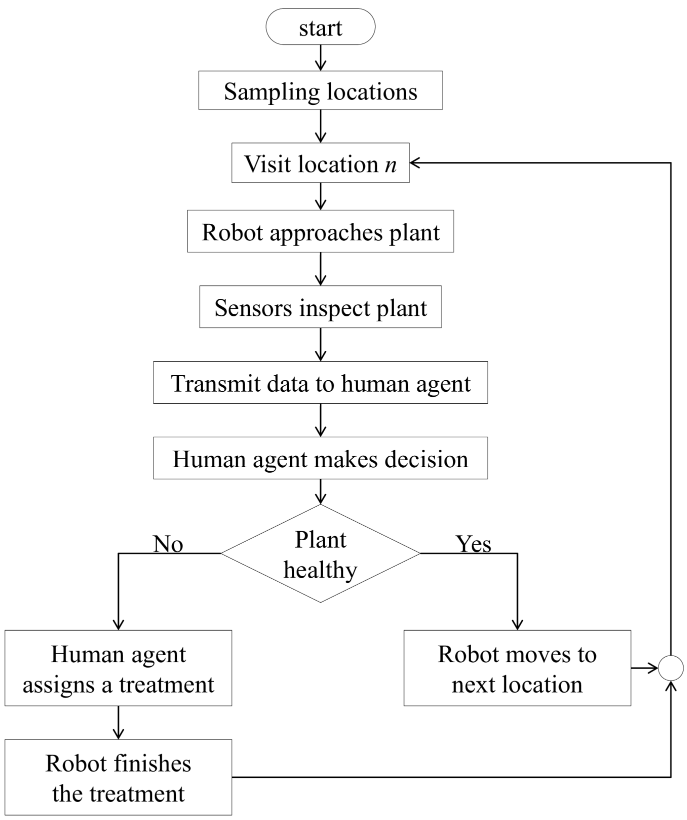


Figure 2: Agricultural Robotic System (ARS) work operations

2.1.3 Performance metrics

To capture the two objectives of CCP-RTC2, the following performance metrics are used.

- **Average Information Delay (δ)**

  δ represents the response time to the plant status. It reflects the effectiveness of information flow and timely exchange between agents. δ can be calculated as below.

$$\delta = \frac{\sum_{i=1}^{N} R_i - D_i}{N} \tag{1}$$

  Where R_i indicates timestamp that the system finishes reacting to the plant i (either stressed or healthy plant). In the case of a healthy plant, the agent should move to the next location. On the other hand, in a stressed plant, the system should indicate the treatment, such as adding fertilizer, or migrating the plant. D_i is the time stamp when the status of a plant i is found. N is the number of locations inspected.

  The system with lower δ indicates a faster response to the situation due to the high efficiency in information flow and communication among agents.

- **Average Information Sharing (μ)**

  μ represents the amount of information (e.g., plants' status) at any point in time per agent. μ indicates the collaborative decision, and also how well the system shares information among agents. μ can be calculated as follows.

$$\mu = \frac{\sum_{i=1}^{T} c_i}{T} \tag{2}$$

  Where c_i indicates the cumulative amount of information obtained until time i and T is the total time. The system with relatively higher μ means, on average, the system is able to share a higher amount of information with agents. In other words, the system has better information sharing and does not rely only on a specific agent. Hence, if certain agents fail, the remaining agents still have sufficient, timely information to continue operating without shutting down the entire system.

3 Experiments and Analysis

To evaluate the designed protocol, two computer experiments are conducted. The experiments aim to measure and compare the designed protocol against the current practice. The current practice is the common practice that farmers have used for inspecting crops. Usually, farmers scout into greenhouse fields to monitor plants themselves. If they find any stressed or diseased plants, and the treatment is commonly known, they can make an immediate decision and provide treatment for the hurting plant before moving to the next location. However, if the disease condition is vague, or the farmers are not sure about the needed treatment, they need to mark the location and return later for the proper and precise intervention.

Two experiments are defined and utilized for evaluating the system under the two alternative approaches (Table 3). Also, Table 4 summarized the experiment design parameters and their distributions.

3.1 Experiment 1: Measuring alternative performance under normal work operations

3.1.1 Experiment design

To test the two systems, computer simulations are conducted to compare δ and μ, under normal operations. The normal operation is the operation described in section 2.1.1, which is the simpler

Table 3: Experiment design

Experiment objective	Monitoring system	
	ARS	**Current practice**
Experiment 1: Objective: Compare system performances under the normal work operations. Description: The system monitors crops stress and diseases, and applies a treatment if necessary.	The robot reaches a crop for detecting diseases. Plant images that are taken by sensors are transmitted to the expert system for making a decision to move to the next location, or start proper, precise treatment.	The farmer approaches the plant to detect disease. The farmer can inspect and make a decision to move to the next location or start the treatment.
Experiment 2: Objective: Compare system performances under situations with an unplanned request. Description: The difference from Experiment 1 is an unplanned request, e.g., re-inspect the location, inspect a new location that is not in the original plan, or a new disease is found. It can randomly be assigned to the system. The system must integrate and also complete the request.	When an unplanned request is received by the system, it can recalculate robot routes, or suggest special treatment. Then, the system transmits the signal to the robot and guides the robot to integrate the given request into the work plan.	The farmer works according to a preset routine without ongoing communication with the system during the monitoring and inspection operation. Hence, the farmer can receive an unplanned request only when the farmer returns to the base point.

Table 4: Experiment design parameters

Agent action		Time cost and distribution
Movement	ARS (Autonomous mobile cart)	0.7 meters/second
	Current practice (Farmer)	1.0 meters/second
Inspection	ARS (Robot arm and sensors)	Normal distribution with mean 60 and SD 20 second ($\mathcal{N}(60, 20^2)$)
	Current practice (Farmer)	Normal distribution with mean 60 and SD 20 second ($\mathcal{N}(60, 20^2)$)
Transferring information	ARS (Sensors and computer)	Normal distribution with mean 1 and SD 0.1 second ($\mathcal{N}(1, 0.1^2)$)
	Current practice (-)	0 (No transferring information)
Making decision	ARS (Human and expert system)	Normal distribution with mean 45 and SD 15 second ($\mathcal{N}(45, 15^2)$)
	Current practice (Farmer)	Normal distribution with mean 45 and SD 15 second ($\mathcal{N}(45, 15^2)$)

scenario. With the same map and parameters, the two systems aim to visit every assigned location, N, (from $N = 5$ to $N = 20$), then inspect the locations and take the necessary actions. δ and μ of the two systems are captured, and the system with lower δ and higher μ is preferred.

3.1.2 Results and Analysis

The results of the 30 replications of simulation for every N are demonstrated in Figure 3 and are summarized in Table 5. The results indicate that δ between the ARS with CCP-RTC2 and current practice is not significantly different. The reason could be that in the current practice, the farmer who scouts into the field is also the decision-maker for the simple and unsophisticated decision, i.e., known disease. The farmer can quickly react to the situation. Hence, the time between finding the disease and the treatment is relatively short. On the other hand, in the ARS, sensors transfer information to human experts to make decisions, which are also fast because of the current cyber technology. With the two approaches, the results show that they perform with no statistically significant difference in terms of δ.

For μ, the ARS has significantly better performance than the current practice. It indicates that the ARS has a higher rate of information sharing and communicating among agents. The possible explanation is that for every event that occurs with the ARS, e.g., find a healthy plant or indicate a stressed plant, CCP-RTC2 will communicate needed information from sensors to human agents in real-time, and enable making a collaborative decision on a timely basis. Hence, agents in ARS tend to share more timely information with each other. As a result, the ARS yields higher (better) μ and is therefore preferable over the current practice.

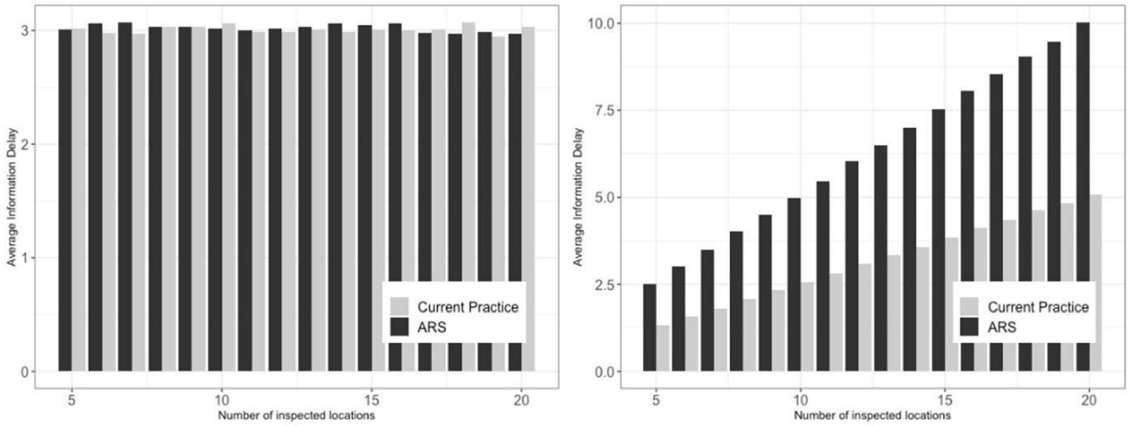


Figure 3: δ (left) and μ (right) observed from Experiment 1 for each N

Table 5: Experiment 1 results

	Average Information Delay (δ) (Second)		Average Information Sharing (μ) (Second)	
N	**ARS**	**Current Practice**	**ARS**	**Current Practice**
5	3.01 (0.17)	3.02 (0.25)	2.51*** (0.11)	1.31 (0.15)
6	3.06 (0.22)	2.98 (0.30)	3.01*** (0.15)	1.57 (0.18)
7	3.07′ (0.21)	2.97 (0.23)	3.49*** (0.14)	1.81 (0.17)
8	3.03 (0.17)	3.03 (0.26)	4.02*** (0.18)	2.08 (0.19)
9	3.01 (0.50)	3.03 (0.20)	4.49*** (0.16)	2.32 (0.17)
10	3.02 (0.16)	3.06 (0.17)	4.98*** (0.15)	2.56 (0.18)
11	3.00 (0.16)	2.99 (0.14)	5.46*** (0.17)	2.81 (0.18)
12	3.02 (0.15)	2.99 (0.16)	6.05*** (0.24)	3.09 (0.22)
13	3.03 (0.19)	3.01 (0.16)	6.50*** (0.20)	3.34 (0.19)
14	3.03 (0.15)	2.99 (0.17)	6.99*** (0.17)	3.56 (0.18)
15	3.05 (0.15)	3.01 (0.13)	7.53*** (0.20)	3.84 (0.11)
16	3.06′ (0.14)	2.99 (0.17)	8.05*** (0.22)	4.11 (0.11)
17	2.98 (0.12)	3.01 (0.12)	8.53*** (0.28)	4.35 (0.14)
18	2.97** (0.13)	3.07 (0.13)	9.05*** (0.23)	4.62 (0.10)
19	2.99 (0.11)	2.95 (0.15)	9.47*** (0.23)	4.83 (0.12)
20	2.97**(0.10)	3.03 (0.12)	10.02*** (0.26)	5.09 (0.13)

Note: H0 : The ARS with CCP-RTC2 is not statistically better than the current practice
$'p<0.1; *p<0.05; **p<0.01; ***p<0.001$; SD is shown in parentheses

3.2 Experiment 2: Operation with unplanned requests

3.2.1 Experiment Design

The second experiment aims to compare δ and μ for the two systems but in a different situation from Experiment 1. The Experiment 2 situation is when an unplanned request occurs randomly. The unplanned requests are, for example, requests to inspect a new location, re-inspect the previous location, identify an unknown disease for sensor-captured symptoms, etc. In the experiment, the same map and parameters are used. The two systems need to complete all tasks (including an unplanned request) for N=5 to N=20. δ and μ of the two alternative systems are compared to investigate their relative performance. The system with lower δ and higher μ is preferred

3.2.2 Results and Analysis

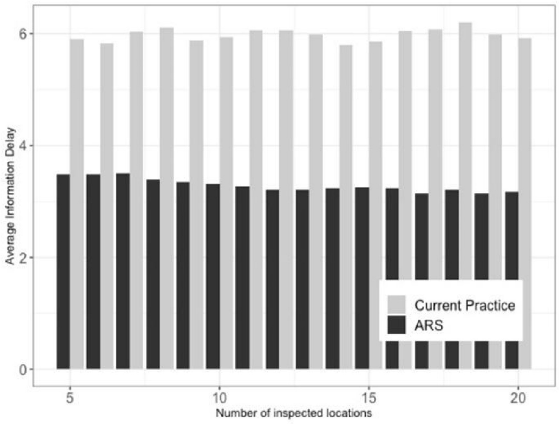
With 30 replications of simulation, the results are shown in Figure 4 and are summarized in Table 6. The average δ and μ of both systems increase when the system receives an unplanned request compared to the normal operation (Experiment 1). The reason is that when the system receives an unplanned request, they need to deviate from the original and previously optimal plan to cope with the unplanned request. The deviation can cause (and cost) an information delay and inefficiency in sharing information and communication, which subsequently increases δ and μ of the system. Hence, δ and μ in Experiment 2 are statistically higher when compared to the corresponding values observed in Experiment 1 (p-value < 0.001).

Table 6: Experiment 2 results

	Average Information Delay (δ) (Second)		Average Information Sharing (μ) (Second)	
N	**ARS**	**Current Practice**	**ARS**	**Current Practice**
5	3.48*** (0.22)	5.91 (0.40)	3.03*** (0.12)	0.99 (0.15)
6	3.49*** (0.19)	5.83 (0.57)	3.49*** (0.17)	1.20 (0.15)
7	3.51*** (0.24)	6.03 (0.68)	4.00*** (0.16)	1.41 (0.17)
8	3.40*** (0.22)	6.11 (0.62)	4.46*** (0.21)	1.62 (0.18)
9	3.35*** (0.20)	5.87 (0.54)	5.02*** (0.15)	1.85 (0.16)
10	3.31*** (0.19)	5.93 (0.60)	5.51*** (0.15)	2.08 (0.19)
11	3.27*** (0.14)	6.06 (0.58)	5.95*** (0.19)	2.30 (0.18)
12	3.21 *** (0.18)	6.06 (0.51)	6.48*** (0.23)	2.55 (0.20)
13	3.20*** (0.19)	5.99 (0.60)	6.99*** (0.20)	2.75 (0.19)
14	3.24*** (0.18)	5.79 (0.57)	7.50*** (0.21)	3.01 (0.18)
15	3.25*** (0.13)	5.86 (0.62)	8.05*** (0.24)	3.24 (0.19)
16	3.23*** (0.15)	6.04 (0.55)	8.45*** (0.21)	3.51 (0.21)
17	3.15*** (0.13)	6.08 (0.49)	8.99*** (0.30)	3.68 (0.24)
18	3.20*** (0.16)	6.20 (0.45)	9.52*** (0.26)	3.99 (0.22)
19	3.15*** (0.11)	5.99 (0.62)	9.96*** (0.30)	4.22 (0.20)
20	3.18***(0.13)	5.92 (0.58)	10.55*** (0.29)	4.42 (0.22)

Note: H0 : The ARS with CCP-RTC2 is not statistically better than the current practice
$'p<0.1; *p<0.05; **p<0.01; ***p<0.001$; SD is shown in parentheses

When δ and μ of both systems from Experiment 2 are compared, ARS indicates a significantly lower δ and significantly higher μ relative to the current practice. In ARS, the CCP-RTC2 can manage and optimize new information items by merging them to the original plan before communicating the revised plan to the autonomous cart – responding to the new, unplanned request. The benefit is the minimization of the information delay. Also, the CCP- RTC2 is significantly superior in terms of μ. The higher values of μ indicate that even if the system has an unexpected task, the CCP- RTC2 can integrate such a request into the current plan to minimize the negative impact on the overall system objectives. In contrast, the current practice is not flexible enough to deal with unexpected situations, because of the lack of timely communication, information flow, and sharing.



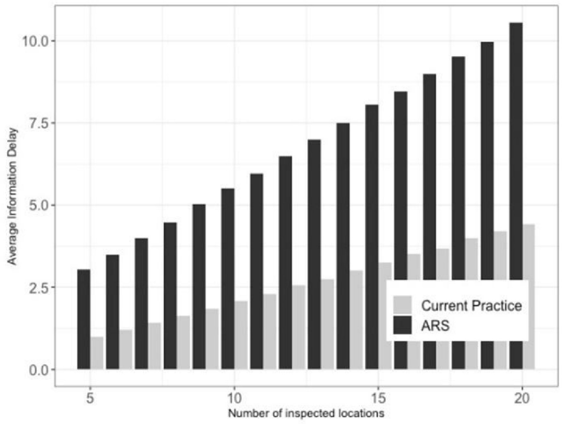


Figure 4: δ (left) and μ (right) observed from Experiment 2 for each N

4 Conclusion and Future Work

In this research, the communication, information flow, and sharing among agents in an agricultural work setting are investigated. Because the effective, cyber-based information flow is a critical element for the competitive advantages of future work systems and Automation 5.0, a Cyber Collaborative Protocol for Real-Time Communication and Control in ARS, called CCP-RTC2, is developed to facilitate timely information exchange and collaborative decision among agents. ARS is a system associated with multiple agents, i.e., human workers and expert system, autonomous robot cart, and multiple sensors. Because each agent is responsible for different work tasks, CCP-RTC2 aims to minimize information delay and effectively share information, and as a consequence, yield better collaborative decisions.

This article provides, first, an overview of the cyber physical ARS. Then, an original CCP-RTC2 is developed with a detailed explanation of how CCP-RTC2 works in ARS once it is integrated with it. Finally, the ARS with CCP-RTC2 is validated by simulation against the current practice. (Earlier, ARS with other versions of collaborative task administration protocols were tested experimentally in the field, in addition to computer simulations [1, 8, 20].)

The protocol validation is performed through computer simulation experiments in two scenarios: 1) Normal operation; and 2) Operation with an unplanned request. From the observation and analysis, results indicate that, in normal operation, CCP-RTC2 shows a statistically significant advantage in terms of information sharing while information delay shows no significant difference compared with the current practice. When the system receives an unexpected request, however, such as inspecting a new location, re-inspecting a previous location, or identifying the symptoms of a new disease, CCP-RTC2 outperforms the current practice in terms of significantly lower information delay and higher information sharing.

For future progress, researchers are challenged to continue by addressing three interesting real-time communication and control directions in the context of cyber physical work:

1. Research on algorithms and protocols that can prevent conflicts in the information exchange process and resolve imperfect information and communication from sensors.

2. Expand the CCP for situations where one, or more agents in the ARS have failed, e.g., human agents or sensors are temporarily unavailable, or an autonomous robot cart cannot access an assigned crop plant location due to unknown constraints.

3. Explore the situation where additional agents may be needed, i.e., an inspection or treatment task for the given robot might be beyond its work skills, and require robots with augmented inspection or treatment skills.

Acknowledgments

The research presented here is supported by PRISM Center for Production, Robotics, and Integration Software for Manufacturing and Management at Purdue University. In addition, the research on Agricultural Robotic System is supported by BARD project Grant# IS-4886-16R, *Development of a Robotic Inspection System for Early Identification and Locating of Biotic and Abiotic Stresses in Greenhouse Crops*; and NSF project Grant# 1839971, *FW-HTF: Collaborative Research: Pre-Skilling Workers, Understanding Labor Force Implications and Designing Future Factory Human-Robot Workflows Using a Physical Simulation Platform.*

Conflict of interest

The authors declare no conflict of interest.

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Cite this paper as:

Dusadeerungsikul, P. O., Nof, S. Y. (2021). A Cyber Collaborative Protocol for Real-Time Communication and Control in Human-Robot-Sensor Work, *International Journal of Computers Communications & Control*, 16(3), 4233, 2021.
https://doi.org/10.15837/ijccc.2021.3.4233