Automation, Collaboration,
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Cyber-Collaborative Algorithms and Protocols

Optimizing Agricultural Robotics

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To my wife, Crystal

—Puwadol Oak Dusadeerungsikul

To my wife, Nava

—Shimon Y. Nof

…and to all our Purdue PRISM Center and PGRN, PRISM Global Research Network scholars who contributed to this knowledge.

Foreword

When I was invited to write a foreword for this book, I was deeply excited. With experience of several decades in agricultural engineering and agricultural robotics, I am grateful for the opportunity to express my insights on the visionary and yet necessary topic of this book: *Cyber-Collaborative Algorithms and Protocols: Optimizing Agricultural Robotics*, which this book addresses.

Throughout the course of human history, agriculture has maintained profound significance and served as the cornerstone of civilization. Its importance extends beyond the feeding needs of a growing population. It also encompasses the production of medicines, fiber, and fuel. Through the continual progression of scientific knowledge, technological innovation, and equipment refinement, the introduction of agrochemicals and genetically modified food into agriculture aims to attain maximal yields of reliable, high quality products, while reducing labor and energy costs. These innovations align with the goal of maximizing productivity and efficiency in agricultural practices.

During recent years, agriculture is undergoing the so-called fourth revolution. It is driven by significant advances in four technological domains: Information and Communications Technologies (ICT); Precision Agriculture (PA); computation (including Cyber, AI, and big data); and agricultural robotics. The overarching objective is to enhance both the quality and quantity of crops while minimizing the utilization of natural resources, attaining resilience, and optimizing the usage of human labor. Task Administration Protocols (TAPs) and Cyber-Collaborative Protocols (CCPs) of a Cyber-Physical System (CPS) are, in a way, the "missing link": They are designed to harness, integrate, and make the new four technological domains work effectively in agriculture.

This inspiring book offers an extensive background, overview, fundamental principles, and practical implementations of Cyber-Collaborative Protocols (CCPs) within Cyber-Physical Systems (CPS). These tools are important in many fields of work and service. The implementation in agricultural automation and robotics adds meaningful clarity. May this knowledge serve as a guiding beacon in this exciting journey.

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Preface

We are inspired to write this book by a simple observation: in today's world, systems are becoming increasingly interconnected and, at the same time, more complex. These evolving characteristics of systems create key challenges to effective management and control. Moreover, technological advancement has led to agents in modern systems becoming more distributed and decentralized, further complicating the task of maintaining rational control, guidance, and oversight.

These challenges in modern systems call for the exploration of new management strategies. The need becomes especially evident in sectors like agriculture, where precision, efficiency, responsiveness, and adaptability are not just desirable but also required for long-term sustainability and, eventually, solving a bigger problem, food security problems, which have become more severe nowadays.

The most challenging context as an agricultural system is where the concept of Cyber-Collaborative Protocol (CCP), which offers a new approach to managing complex tasks and systems with collaboration, efficiency, and intelligence, truly shines. This book aims to translate the intricacies and potential of CCP into practice, with a particular focus on modern complex systems such as Agricultural Robotics Systems (ARS). We focus on providing a balanced mix of theoretical foundations, practical implementations, and forward-looking perspectives on the future of collaborative systems in the cyber age. Our exploration of CCP goes beyond technical intricacies; we also delve into real-world implications. Through our primary case study, ARS, we highlight the power, potential, and capability of CCP in various levels of collaborative systems.

Importantly, we would like to express our gratitude to our colleagues, contributors, and collaborators whose invaluable insights have made this book a reality. We acknowledge the support received from the PRISM Center at Purdue University; BARD Grant IS-4886-16R for "Development of a robotic inspection system for early identification and locating of biotic and abiotic stresses in greenhouse crops," PI A. Bechar, and by NSF Grant #1839971: "Pre-Skilling Workers, Understanding Labor Force Implications and Designing Future Factory Human-Robot Workflows Using Physical Simulation Platform," PI K. Ramani. We also thank our friendly Springer staff members who have helped us prepare and bring this book to you. We trust

that our readers will discover this book to be both instructive and inspiring in their respective fields.

Lastly, welcome all readers to the world of Cyber-Collaborative Protocols, where humans and systems collaboration meets science and technology.

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Chapter 1
Introduction: Cyber-Collaborative Protocols

Abstract Just as a good concert cannot be performed without a conductor, and a computer cannot work without an operating system, every collaborative system must be guided and administered to accomplish its goals. Task Administration Protocols (TAPs) have been developed to administer and manage complex, automated workflows in collaborative work of agents: humans, robots, and software. When cyber-physical systems emerge, new requirements and capabilities also emerge. Cyber-Collaborative Protocol (CCP) is a special type of TAPs that also administer and manage collaborative work, but are designed to do so for cyber-physical systems. For effective, automated and optimized cyber-physical operations, TAP and CCP are required to handle real-time complexities that are beyond communication, workflow, and coordination. TAP and CCP are introduced and defined in this chapter, along with examples of their design and application. Furthermore, current research in various production tasks utilizing TAP and CCP is summarized. In addition, the comparison of TAP and CCP with communication protocols and algorithms is explained and clarified. And just as better conductors will lead to better quality concerts, and superior operating systems will result in better computing, so do better designed TAPs and CCPs. This chapter aims to present the fundamental knowledge of TAP and CCP, which are the critical tools whose better design and effective utilization are the subject of this book.

1.1 Overview of Task Administration Protocols (TAPs) and Cyber-Collaborative Protocols (CCPs)

This section provides background knowledge about Task Administration Protocol (TAP) and Cyber-Collaborative Protocol (CCP). Also, this section explains TAP's/CCP's roles in smart, optimized interactions, and in Cyber-Physical Systems (CPS).

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1.1.1 What is TAP, and Why is TAP needed?

To administer means to manage or control the operation of an organization, a business, or a system. In the modern world, the complexity of production and service systems increases significantly due to the integrations, communications, and interactions among participating system agents, such as resources, machines, human and robot workers and managers. A system such as service system, manufacturing system, warehouse system, and agricultural system comprises advanced technologies, massive flows of information, and multiple agents, intending to achieve higher levels of performance. The system, however, has a new challenge to overcome: more complex and timely interactions among internal and external agents (e.g., customer agents), sometimes under changes and disruptions. New technologies that enable decentralized and distributed agents drive the need for a methodology to collaborate, synchronize, and coordinate agents and their roles. Particularly, replanning, rescheduling, resequencing, reallocating, and reprioritizing become necessary. Therefore, a protocol called Task Administration Protocol (TAP) was developed for management and control of effective operations and interactions in systems [29, 42, 60, 65]. TAPs aim to optimize system performance by assigning and reassigning, synchronizing and resynchronizing, as needed, system agents and other system components. Each TAP utilizes rules, decision tools, heuristics, and interaction procedures managing agents, algorithms, and databases to achieve optimal workflow performance in dynamic and uncertain environments.

Figure 1.1 illustrates the general TAP model. Let us assume a system that can be decomposed to multiple operational stages, where a following stage is the consequence from the previous stage. To progress to the next stage, a decision needs to be made, and actions need to be executed. Furthermore, the system's progress keeps continuing until the system has reached the final stage in accomplishing its goal. Then, it repeats to achieve the next goal, again, with an optimized set of control, administration, or management decisions.

There will be a group of autonomous initiator agents ($\pi_i \subset \pi$) and autonomous responder agents ($\pi_r \subset \pi$) to decide and execute the operation at each stage. A group of agents will perform task ($\tau_a \subset \tau$) to obtain the transition stage ($\gamma_s \subset \gamma$). (Note that π is a set of participants or agents, τ is a set of problems or tasks, and γ is a set of transition stages).

Moreover, there will be a set of activities of each agent (φ). Note that $\varphi_k \subset \varphi$ will indicate the availability of the agent at a particular time. Therefore, the combination of π_i, τ_a, and φ_k will indicate the task dependency (δ_{ijk}) where δ is a set of dependency and $\delta_{ijk} \subset \delta$.

TAP, which applies a set of coordination/workflow protocols (σ), is designed, defined, and evaluated as a cyber tool for basic task-solving problems in a given system, under dynamic and uncertain changes and disruptions. TAP, as an advanced version of coordination protocol, will coordinate the agents to perform activities, with a coordination mechanism ($\sigma_p \subset \sigma$). A coordination protocol (σ_p) will harmonize, namely, coordinate, manage, synchronize, and prioritize δ_{ijk} so that the system

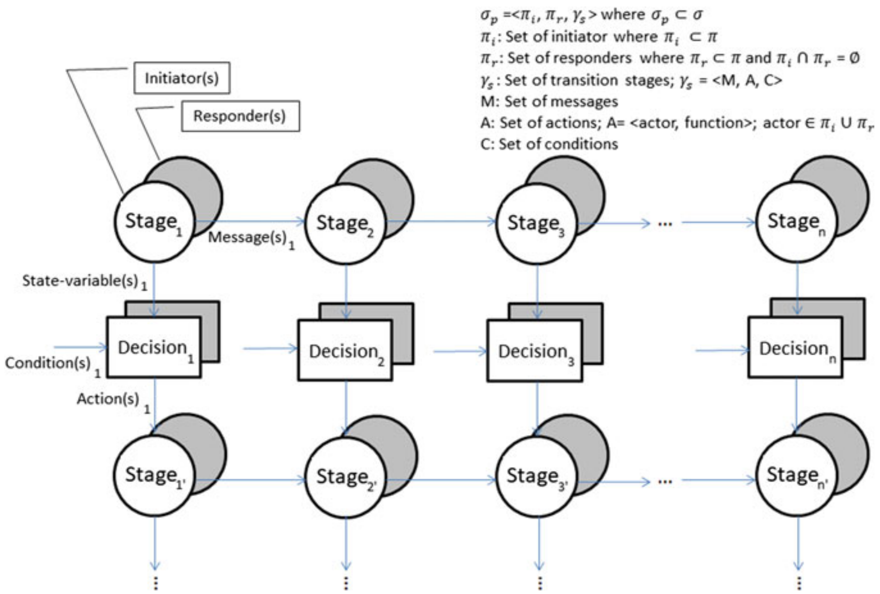

Fig. 1.1 General TAP model; able to handle, repeatedly, changing and disrupted conditions and state variables

achieves its goal, or series of goals, under the current, changing and disrupted conditions.

1.1.2 What is Cyber-Collaborative Protocol (CCP)?

CCP is a specific type of TAP, also designed for a decentralized and distributed system, but where the system is cyber augmented, or Cyber-Physical System. In a decentralized and distributed system, agents are given the authority to decide without command from the center (a centralized controller). Over time, there will be multiple requests and flows of information between agents. While a TAP itself can be cyber augmented (but meant for non-Cyber-Physical Systems), CCP has been derived from TAP with the augmentation of cyber element/method in the Cyber-Physical System (CPS) to enable smart interactions and collaborate interactions among agents. In this context, the cyber element/method in CPS comprises four aspects: computing, communication, real-time control, and brain models [63].

1. **Computing**: The cyber element of the system must be able to compute the given decisions about each task. Therefore, the computational power can be relatively larger or smaller due to the potential task assigned to the agents.
2. **Communication**: The communication element of cyber enables agents to connect and exchange information with each other. Communication allows agents