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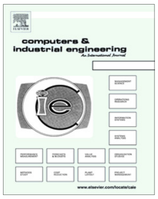

The dynamic lines of collaboration model: Collaborative disruption response in cyber–physical systems

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ABSTRACT

Cyber–physical systems (CPSs) are emerging engineered systems with combined efforts in cybernetics and computerized physical components. The pervasive links between CPS elements improve their connectivity, but inevitably enable failures to propagate to large-scale disasters. External responders (repair-agents) often need to collaborate concurrently with peers to perform emergency services and repair operations. Systematic understanding of the collaborative response to ongoing cascading failures is required for responders to effectively prepare response teams and arrange disruption response. Previous modeling approaches are lacking the ability to capture the dynamic interactions between a CPS and its response teams. In this work, the Dynamic Lines of Collaboration model for Collaborative Disruption Response (DLOC/CDR) is established. It can capture general requirements of collaborative responders to respond to and to resolve ongoing disruptions with cascading effects. Two depot allocation policies are tested and compared to examine the new model over different CPS structures. Four performance measures (response time, maximum cascade, travel distance by responders, and preventability) are designed to compare different parametric settings. It is observed from the experiments that the small-world phenomenon increases the difficulty of resolving cascading failures in CPSs by response resources. Experiments on both conceptual networks and the Hetch Hetchy water system case study validate that the collaboration ability and the centrality-based depot allocation policy improve the disruption response performance with statistical significance. While these experimental observations support intuitive rational, the model for DLOC/CDR also provides specific guidelines for emergency responders, and serves as a base model for future research in the effective disruption management and response area.

1. Introduction

Any cyber–physical system (CPS) includes complex interactions and interdependencies among a large group of production and control facilities and organizations. With rapid development in information technology and cybernetics, intensive computing resources are used to connect computerized physical devices to provide control, communication, coordination, and collaboration. Networked manufacturing systems, intelligent transpiration systems, smart infrastructures, and power grids are all appropriate examples of emerging CPSs. CPSs are often mission critical networks. If not handled correctly and in time, small disruptions in some part of them can lead to severe disasters. In spite of the rapid development of CPSs, it is still challenging to maintain continuity and availability of critical CPS functions. For instance, disruptions in power grids have affected at least 14 million people in the U.S. between January and September in 2014 (EIA, 2014). An effective disruption response in CPS should quickly stabilize the incident, restore functionality, repair disrupted components and linkages, and prevent further damages (adapted from DHS, 2011). A comprehensive model of CPSs' characteristics in response to disruptions is necessary to uncover the defensive ability of networked systems and the role of emergency and responders.

CPSs requires Collaborative Disruption Response (CDR). General electric is developing *Industrial Internet* which enriches the collaboration and connectivity for large-scale system maintenance: A wireless device, carried by a wind farm engineer, can indicate which turbine has a problem, transmit technical problem information, and enable visual sharing with peers at other locations (Annunziata & Evans, 2013). The heterogeneity of CPS disruptions causes different response requirements, and, therefore, dynamic and flexible collaboration is an expected service from the response team. From the team structure point of view, the *Dynamic Lines of Collaboration* (DLOC) behavior summarizes the changing command and control line segments inside response teams as their

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responsibilities vary according to different tasks. The control of the DLOC is an emerging sub-filed of Collaborative Control Theory (CCT; Nof, 2007). DLOC has many applications when the collaboration in a team shows dynamicity and flexibility in team structure to process different tasks. Table 1 illustrates several examples of DLOC applications.

CPSs and response teams show sophisticated multi-scale behaviors, but understanding the behaviors is lacking in organizational, functional, and evolutionary aspects (Surana, Kumara, Greaves, & Raghavan, 2005). Structure, which is a fundamental property to reveal the physics of networks, shall be useful for such understanding. Previous research has suggested that complex network theory can help to characterize the robustness, resiliency, and survivability of CPSs (Nair & Vidal, 2011; Pathak, Dilts, & Biswas, 2007; Thadakamalla, Raghavan, Kumara, & Albert, 2004). As complex networks provide rigorous and measureable abstraction for CPSs, more properties of CPSs and response teams are expected to be discovered by modeling CPSs as complex networks.

In this work, related models for studying CPS networks and disruption response dynamics are reviewed. The key concluding observation is that existing models lack specific details to capture the requirements of studying the interactional dynamics in disruption response. This work, therefore, focuses on the following facets of disruption response in CPS: (1) A modeling approach is established based on complex networks which are abstracted from CPSs with external response resources to handle cascading disruptions. (2) The concurrent collaboration is modeled by dynamically establishing and removing command and control line segments connecting the responders. (3) Two policies of deploying responders are tested to study the usefulness of the new modeling approach.

Based on the analysis of conceptual experiments and of a realistic case study, recommendations are then derived from the simulations for improving CPS emergency response management.

2. Background

Emerging CPSs are often connected through several different channels. For instance, a smart grid is a typical advanced CPS for energy supply. Power plants, transformer substations, energy consumers are nodes in the network. The nodes are connected by both power lines to transmit energy and by computer networks to transmit control and sensing signals. The integrated cyber and physical system has many dependencies implemented by their links. If one station fails, dependent facilities will stop functioning due to lack of power, and if a given control center is disconnected from the control network, the related power stations will refuse to work. The propagation of disruptions is often modeled as cascading failures in complex network theory (Albert, Jeong, & Barabási, 2000; Motter & Lai, 2002a).

Realizing that cyberspace and the physical world are two interdependent networks, researchers start to use two (sometimes more) interdependent networks to model CPSs. In Buldyrev et al. (2010), network robustness of interdependent networks is modeled as the existence of the remaining giant component after random attacks. It successfully captures the cascading effect occurring in CPS. Based on this property and model, design considerations through simulations are provided (Yagan et al., 2012); the authors recommend the strategy of adding bi-directional links regularly to every node in each network (deterministically allocate each node exactly the same number of inter-edges) to increase robustness against random failures. In addition, Wang, Wu, and Li (2015) have provided analysis on the influence of load across interdependent networks to improve the robustness of the networks against cascading failures. Despite the significant contributions in modeling CPSs as interdependent networks, the models above are not sufficiently able to express the disruption response activities in CPSs, especially when external resources are necessary to handle disruptions for CPSs. The following subsections address three major needs required to model disruption response behaviors.

2.1. Response to cascading failures in complex networks

CPS plays a fundamental role in our society. Once disruptions propagate, the damage may cause a major disaster to humanity. In the current work, responders' responsibility is defined as the response operations to handle the immediate and short-term effects of CPS disruptions. These response operations include diagnose the disruption, stabilize the disruption, repair the disruption, and prevent the disruption from propagation. The goal is to reduce damage to property, and to minimize system down time.

The recent decade has seen a major increase in literature exploring the emergency management and disaster relief models and systems from different angles (Ortuño, Cristóbal, Ferrer, Martín-Campo, Muñoz, et al., 2013). Most of significant related work, e.g., Yi and Ozdamar (2007), focus on post-disaster relief problems, including evaluation operations, resource dispatching, etc. The response operations, however, during ongoing disruptions are not well studied (Day, 2014). Several strategies on how to respond to cascading failures have been presented in Buzna et al. (2007), considering network structure, response time delay, and the overall disposition of resources. The network representation, however, has a severe incompatibility if used to model disruption response in CPSs: The response time (from the start of disruption to the end of repair) is assumed to be independent of the availability of external resources. In addition, the resources deployed cannot be reassigned to other disruptions. These assumptions are not practical in the case of CPS disruption response. Consider the case when several power stations are failing cascadingly. A team of responders, as external resources, needs to be deployed to the stations. If the resources are limited, the responders have to resolve the problems one by one and thus the response time is dependent on the availability of resources. Besides the response time, the responders can be repeatedly assigned to new tasks.

In previous research, e.g., Chen & Nof (2012), the constraints for errors and conflicts in large systems are modeled as complex networks. This work provides centralized and distributed algorithms to monitor and re-form the constraint network to detect, prioritize, and prevent propagating errors. The fitting of evolutionary constraint networks to conventional network models, however,

Table 1
DLOC application examples.

DLOC application example	Collaborative design	Collaborative disruption response	Reconfigurable manufacturing cell	Supply network selection
Agents	Designers	Responders	Peripherals	Suppliers
Collaborative tasks	Design products	Provide response services	Assemble products	Yield products
Realization of dynamic collaboration	Dynamic team of designers	Dynamic team of responders	Dynamic configuration of peripherals	Dynamic selection of suppliers