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Human-centered automation for resilient nuclear power plant outage control

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ABSTRACT

Nuclear power plant (NPP) outages are challenging construction projects. Delays in NPP outage processes can cause significant economic losses. In typical NPP outages, extremely busy outage schedules, large crew sizes, dynamic workspaces and zero tolerance of accidents pose challenges to ensuring the resilience of outage control, which should rapidly and proactively respond to delays, errors, or unexpected tasks added during outages. Two mutually interacting practical problems impede NPPs from achieving such resilient outage control: 1) how to control errors and wastes effectively during the “handoffs” between tasks, and 2) how to respond to numerous contingencies in NPP outage workflows in a responsive and proactive manner. A resilient NPP outage control system should address these two practical problems through “Human-Centered Automation (HCA),” which is improving the control process automation while fully considering human factors. Previous studies examined two categories of technologies that potentially enable HCA in outage control: 1) computational modeling and simulation methods for predicting states of field operations and workflows; 2) data collection and processing methods for capturing the reality and thus providing feedback to computational models. Unfortunately, limited studies systematically synthesize technological challenges related to these practical problems and underlying HCA principles.

This paper identifies the domain requirements, challenges, and potential solutions of achieving the HCA system that effectively supports resilient NPP outage control. This proposed system aims at significantly improving the performance of handoff monitoring/control and responding to contingencies during the outage. Firstly, the authors identified information acquisition and modeling challenges of achieving human-center automation for outage control. The rest of the paper then synthesizes potential techniques available in the domains of computer science, cognitive science, system science, and construction engineering that can potentially address these challenges. The authors concluded this literature and technological review with a research roadmap for achieving HCA in construction.

1. Introduction

In the United States, many nuclear power plants (NPPs) were built forty years ago [1] and require regular maintenance. NPPs typically shut down every eighteen to twenty-four months to refuel the reactors and execute repairs. Such processes are called “NPP outages.” NPP outages are challenging because they require coordinating thousands of activities in short time periods with an average time frame of thirty to forty days [2]. Moreover, most NPP outages require supplemental workforces that consist of hundreds of contract personnel who are not permanent employees of the NPP and are not familiar with the workspaces and procedures that vary from one NPP to another. The presence of such contract personnel in outages significantly increases the workload of permanent NPP employees, who train, guide, monitor, and coordinate the work done by contract personnel in conjunction with their regular work responsibilities. Interactions between permanent and contract personnel with diverse backgrounds also significantly increase the complexity of communication and information flow

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throughout outages procedures, thereby increase the error rates and delays in field operations [3–6].

Other challenges that cause delays, schedule overruns, and escalating costs in NPP outage projects include highly uncertain and frequently updated schedule due to contingencies (e.g., discoveries of hidden structural defects during field operations), multi-group coordination and communication, frequent changes of nuclear facility states, and highly uncertain human behaviors on job sites [7–11]. Unfortunately, any delays in the NPP outage processes will cause significant economic losses. For instance, a one-day delay can lead to one to two million dollars loss for the electric power company. All these factors pose challenges to ensuring "resilient" NPP outage control, which requires an approach that should rapidly and proactively respond to delays, errors, or unexpected tasks added during outages. In other words, a resilient outage control should reduce outage's cost, duration, labor, and accident rates by "*proactively and adequately adapt to perturbations and changes in the real world given finite resources and time*" [12].

In NPP outages, two practical problems are causing main difficulties related to the vision of "resilient outage control." The first practical problem is about how to control the efficiency and error rates of handoffs, which are the transitional stages between tasks. Handoffs involve highly uncertain activities, such as transports of resources and labors, inter-person and human-computer communications, field preparation, mobilization, and waiting. Transitional nature of handoffs causes time and resource wastes, incidents or accidents due to the involvement of multiple groups of workers and complex spatiotemporal interactions between space and resource needs of tasks, and decision difficulties under uncertainties. The second practical problem is how to respond to many contingencies in NPP outages so that workflows can quickly recover from interruptions and incidents due to field discoveries. In NPP outages, about 15% of tasks are "discovered" in the field because many problems could be unapparent due to the uncertainties about the field conditions and resource availability. Uncertainties about the field conditions and resource availability combined with the need to incorporate additional work adds extra stain to NPP outage control because workflows, workspaces and large crew sizes must be quickly adjusted and reconfigured.

Human factors play important roles in the two practical problems described above [1,13–15], while in current practice, outage management teams have been struggling with the manual management of the behaviors of field workers [3,16,17]. With experienced outage managers retiring, manual analysis of human factors in uncertain and dynamic environments of outages will challenge new generations of engineers in the coming decades. Specifically, 38% of the nuclear industry workforce will be eligible for retirement by 2018 [18] while young engineers still lack experience in real outages. In such a context, the Human-Centered Automation (HCA) techniques can be critical for assisting new generations of engineers in outage control [19–21]. These automation techniques help better managing human factors by enhancing situation awareness (SA) while reducing workloads, developing a communication protocol across outage participants, and building predictive models of human behaviors in various contexts. Researchers and field engineers have been working on examining various automation technologies to improve the information acquisition and modeling of human factors in NPP outages to enable HCA and resilient outage control [22–25]. These efforts revealed potentials of HCA techniques, but the lack of a comprehensive review of HCA for supporting resilient outage control impede researchers and engineers from approaching HCA in an outage with a systematically-designed research map.

This paper presents an extensive review of literature related to HCA for resilient NPP outage control. The aim is to establish a research roadmap that systematically incorporates human factors into the loop of automated outage control and synthesize technological gaps against domain requirements for such incorporation. The authors summarized nuclear plant operation documents and past studies to identify the information requirements and process automation needs and then reviewed related computational modeling and data collection/processing techniques that have the potential of addressing such needs. The focus is on data and modeling technologies that could address effective handoff monitoring/control and contingencies handling during outages, as those are practical bottlenecks. Such discussions will lead to the identification of technological gaps and fundamental scientific questions about HCA in construction, as well as technical tools necessary for answering those questions. Such tools include as artificial intelligence techniques that enable "self-learning human systems" that can automatically adjust systems design and automatically recommend continuous improvements of outage processes based on historical data.

The organization of the remaining parts of the paper is: Section 2 introduces the motivation of this review by presenting the two practical problems of achieving resilient NPP outage in detail, summarizing human factors in outages, and explaining why human factors are the key to achieving resilient outage control. Section 3 summarizes latest outage control practice and the data and modeling barriers to achieving HCA for resilient outage control. Section 4 synthesizes various technologies that have the potential of addressing the identified challenges of HCA in outage control. Section 5 presented the resulted research roadmap and then conclude.

2. Motivation: practical problems in resilient outage control

This section motivates HCA for resilient outage control. In this context, "resilient" outage control system refers to the ability to quickly recover from errors, delays, interruptions, and changes in schedules to achieve as-planned project productivity and safety [12,26]. The nuclear industry has developed a variety of technologies to improve the resilience, productivity, and safety of outages. For example, daily reports recording the progress and guiding resource allocations are prepared before daily meetings and distributed widely through outage information systems accessible to outage participants. In addition, performance metrics for different outage procedures exist to quantify and diagnose the performances of past and on-going outages [27]. However, these approaches of outage control are mostly manual, tedious and error-prone. Two mutually interacting practical problems are main barriers to resilient outage control: 1) handoff control, and 2) responding to contingencies. Sections 2.1–2.3 introduce these two problems in detail. Based on such introduction, Section 2.4 synthesizes how the human factors influence the outage performance, and why HCA is critical for achieving resilient outage control.

2.1. Practical problem one: handoff monitoring and control

Handoffs are transitional stages between tasks. Effective handoff control aims at reducing the durations of and the error rates in handoffs that involve traveling, communication, and waiting behaviors of workers. Handoffs between tasks represent a large portion of overall activities in construction workflows [28–30], and can significantly influence the project efficiency. Furthermore, NPP outages often operate under tight schedules that have a 10-minute granularity such that uncertainties of handoff durations could be longer than some task durations. In such cases, maintaining the as-planned task sequences is difficult [31]. Moreover, in packed schedules and workspaces, delays or mistakes in handoffs could propagate to many tasks and compromise the productivity and safety at large [32]. Being able to predict and control uncertainties within handoffs thus are critical for improving the efficiency of outages.

Besides tight schedules and large crew sizes, two other factors further exacerbate handoff problems in NPP outages. The first factor is relevant to the uncertainties of human behaviors in outages. NPP personnel are complex agents working in complex sociotechnical systems, and "their activities will not always follow some deterministic mechanism" [27]. Furthermore, NPP outages often need to involve