Human errors and influencing factors in digital control rooms: a review and some suggestions

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Abstract: The digitalization of main control rooms (MCRs) in nuclear power plants (NPPs) has been increasingly adopted due to its potential to improve operation and maintenance safety and efficiency. However, implementing digital MCRs may also lead to new risks, including those related to human errors. Various efforts have aimed at understanding the impact of digital MCRs on human errors and Human Reliability Analysis (HRA) by considering the new working environment and interface modality, etc. Yet, issues concerning automated systems that may introduce more secondary tasks and new human errors are still under investigation. Recent work by the authors has explored human errors and performance influencing factors (PIFs) in the operation of autonomous ships, considering human failure mechanisms in the interaction between operators and automated systems. The work can be further extended to the digitalized human-computer interactive systems, such as digital MCRs. As a first step the present paper summarizes the human errors and relevant PIFs in digital MCRs and further discusses automation-related influencing factors and human errors. The Levels of Automation (LoAs), automation transparency, and their effects on human trust in automation and situation awareness (SA) have been a subject of discussion in fields of automated vehicles and autonomous ships operation. This paper aims to supplement the existing HRA methods by considering human errors and PIFs from the perspective of automation characteristics.

Keywords: Digital control rooms, Automated systems, Human reliability analysis, Human factors

1. INTRODUCTION

With the development trend towards increasing use of automation, information technology and artificial intelligence, digital main control rooms (MCRs) for nuclear power plants (NPPs) are emerging rapidly, both as upgrade to the current fleet's control rooms, as well as the control rooms of future design such as small modular reactors (SMRs). Compared to traditional analog MCRs, digital MCRs are equipped with digital human-system interfaces (HSI) and increased automated functions in the control rooms, such as integrated information display systems, computerized procedure systems, and soft controls[1].

In the past decade, notable digital MCR concepts have been developed or are currently in operation in several countries[2]. Multi-functional soft controls were developed for discrete and modulation control in digital interfaces instead of traditional hard controls in analog interfaces[3]. Furthermore, computerized procedure systems (CPS) provide the crew in different workstations with computerized rather than the paper-based context sensitive operation guides and navigation links to the soft controls for normal and emergency circumstances [4]. In addition, digital information systems and multiple large overview displays are used for overall process monitoring of the plant to be shared among operating crew[5]. Advanced alarm systems are also being developed, aiming to provide integrated information and signals[6]. While the digitalization of MCRs assists operators with a better understanding of emerging conditions and performing calculations and may automate even actions that would otherwise be executed manually; it brings challenges to human reliability analysis (HRA), since the circumstances of human activities may significantly change.

HRA methods are commonly used to model and analyze human errors and their contributors. To assess HRA methods' suitability for digital MCRs, it is necessary to understand if and how digitalization impacts operators' tasks and the context that may impact human performance, e.g., through data collection of operators' performance in digital MCRs. For instance, the HuREX framework was developed for HRA data collection from digital MCR simulators in Korea, and the EMBRACE HRA method was proposed to calculate human error probabilities (HEPs) via the HuREX [7]. The SHEEP program at the Idaho National Laboratory in the US, is aimed at similar studies based on a simplified simulator. It explores HSI and procedure in digital MCRs, complementing current HRA studies with consideration of the unique issues of digital MCRs [8]. Data collection activities from HAMMLAB, EPRI, and Czech Republic, and SACADA database are also used to support HRA development in digital MCRs [9]. Meanwhile, new human error modes and contextual factors are discussed in some studies [10], considering for example HSI quality[11], procedure quality[12], team communication[12], etc.

Nevertheless, it is clear that the impact of PIFs on human performance in digital MCRs is less explored (with the except of a limited number of studies on the effects of task complexity [13], procedure clarity [14], communication quality [15]. For instance, CPS quality as a potential PIF is mentioned in several research projects; however, discussion of specific issues such as automation/software performance and human trust are rare. .

This paper aims to summarize the identified human errors and PIFs in current studies, and also discuss the relevant knowledge and insights in other domains involving human-automation collaboration automation, characteristics of LoAs and automation transparency and their effects on human errors. The paper is organized as follows: Section 2 presents a summary of human errors and PIFs identified in current studies for digital MCRs. Section 3 proposes the effects of automation on human performance and errors in other human-automation collaborative systems, followed by Section 4, which offers concluding remarks.

2. DESIGN ELEMENTS IN DIGITAL MCRS AND RELEVANT HUMAN ERRORS AND PIFS

This section discusses several new elements in digital MCRs within the categories of soft control, CPS, information display systems, large display panels, and advanced alarm systems.

2.1 Soft Control

NUREG-CR/6635 defines soft controls as input interfaces connected to control and display systems that are mediated by software rather than physical connections [16]. They can be accessed from multiple locations within a display system and their functions can be variable and context-dependent. Behind soft control, the automated systems are the essence, which involve automatically processing information, monitoring the status of tasks implementation, managing display spaces, and detecting and correcting operators' input errors. Operators interact with technical systems through soft controls, consisting of its back-end software and front-end HCI. Human errors that occur during interaction with soft controls were identified [6-7, 17]. Operations performed on soft control have been considered in the action phase of an operator's cognitive process [17]. Human error modes and PIFs were identified and shown in Table 1 [6-8, 17].

Table 1 Human errors and PIFs in soft controls operation identified in current studies

Human error	1. Operation omission: omit a necessary operation after selecting procedure and right control device in soft controls. 2. Wrong object: select a wrong control device in soft controls and continue with the execution. 3. Wrong operation: take wrong actions even when appropriate screen navigated and soft controls are correctly selected. 4. Module confusion: performing an operation on the wrong module in the correct screen. 5. Inadequate operation: execute the operation too early/late or too long/short, 6. Delayed operation: due to the wrong selection of screens or devices and failure to recover, an operation is not be performed at the right time. 7. Mode conversion: select "auto" or "manual" mode mistakenly. 8. Confirmation omission: failure to click confirmation button after performing all operations.
PIFs	1. Procedure quality. 2. Practice level: operator training only in simplified nuclear simulator. 3. Operation type: whether the operation is continuous or discrete. 4. HSI design.

2.2 Computerized Procedure Systems (CPS)

NUREG/CR-6634 defines CPS systems to encompass computer systems that support procedure presentation and use, aiming to reduce cognitive workload, make fewer errors in transitioning through procedure, etc.[18]

CPSs can provide different levels of functionality and automation [19]. The advanced functions of CPS include 1) automatic retrieval and display of specific information and/or controls to perform a step, 2) automatic processing of step logic and displaying the results, 3) automatic checking of prerequisites or preconditions, and 4) providing cautions or warnings based on current plant conditions. An experiment was conducted by

INL to compare three types of computerized procedures: (1) basic CPS is similar to paper-based procedures but displayed on a screen; (2) the intermediate level of CPS includes live process data and step logic with visual cues and links to additional displays and controls, which are linked to separate systems; (3) the advanced level of CPS encompasses the above functionalities and also embeds soft controls and is able to automatically carry out procedure sequences [20].

Operators can benefit from the automation functions provided by the CPS. For instance, the CPS will not require operators to perform logic calculations directly [19]. CPSs enhance human performance by enabling faster task completion, reducing overall and cognitive workloads, and minimizing errors during procedural transitions. However, since CPSs have restricted display space, operators' cognitive and physiological workloads may increase due to the need to manipulate windows. Moreover, due to the high levels of automation, operators' situation awareness may decrease and potential out-of-the-loop (OOTL) performance problems occur. On the other hand, when a CPS is not available to operators owing to its failure, a CPS operation should be switched to a paper procedural operation rapidly, which is kept in MCR for backup. As such, operators are required to act more carefully owing to the loss of automation provided by a CPS, such as logic processing and highlighting. With respect to team cooperation with CPSs, several operators can view the same procedure at the same time. Thus, a cross-checking among operators is performed for a procedural operation.

Table 2 Human errors and PIFs in CPS operation identified in current studies

Human error modes	1. Procedure Following Errors: - Skipping Steps: Operators may skip critical steps due to poor interface design. - Incorrect Sequencing: Steps may be followed out of order if the procedure flow is not clearly indicated. 2. Monitoring and Detection Errors: - Missed Indicators: Important plant indicators may be missed due to over-reliance on automated systems or limited display capabilities. 3. Transition Errors: - Failure of logic process and highlighting, when the operator switches to a paper-procedural operation when the automated CPS fails.
PIFs	1. Procedure Types: paper-based, electronic, computerized with automated functions. 2. Automation levels of information processing and display. 3. Information Overload. 4. Cognitive Workload: caused by managing complex interfaces and navigating procedures. 5. Situation Awareness: Over-reliance on automated systems may reduce situational awareness, making it harder to detect and respond to system faults. 6. Training Quality. 7. Environmental Factors: The physical layout of control rooms and ergonomic factors. 8. Cross-checking: May make achieving a common understanding more difficult.

2.3 Advanced information systems and large display panels (LDPs)

NUREG/CR-6633 defines the advanced information system as those aspects of the HSI that provide information to the operator about the plant state using novel forms [21]. Three key design characteristics of advanced information systems requirements include, representational systems, interface management functions which are considered in the soft control and CPSs, and display devices including video display units (VDUs), LDPs, etc. The design of advanced information systems focuses on: 1) the information that operators need to monitor and control the plant, and 2) the representation in which the information is presented to operators. Specifically, representation involves display elements, display format, display pages, and display networks referring to an entire set of display pages within an information system. As the number of pages is large, knowing where information is located is difficult.

In terms of required information, one of the most noticeable characteristics is that shift supervisors are able to check the plant status by themselves using process variables from the advanced information systems, while they would ask board operators to check the plant status in conventional MCRs. Moreover, the LDP is designed to be able to prioritize the display of critical safety systems over fewer essential details to reduce visual clutter and enhance usability during high-stress situations [22]. It helps operators quickly grasp the overall plant condition, improving situational awareness and enabling faster, more informed decision-making during emergencies. Regarding information representation, the new design of digital indicators enables operators to measure the process variables clearly and confirm their trend effectively using graphs on the operator console. However, since the process variable indicators may be installed in various locations, operators' cognitive workload may increase. Considering the above, the relevant human errors, influencing factors, and design issues were discussed in current studies[4-5, 12-14], and are listed in Table 3.

Table 3 Human errors and PIFs in advanced information systems /LDP operation identified in current studies

Human error modes	1. Failure to identify critical information due to dense displays obscuring important data, complicating situation assessment and decision-making 2. Wrong information source attended 3. Failure to correctly interpret numerical data due to improper redundant measurements 4. Failure to timely assess plant status due to the distribution of information across separate display pages, leading to incorrect situational awareness
PIFs	1. Quality of Information Representation (display elements, format, pages, networks) 2. Task Switching: Frequent switching between different interfaces and tasks can disrupt situation awareness 3. Poor communication and coordination level 4. Level Training and Experience. 5. Feedback Mechanisms: Insufficient or delayed feedback can hinder error detection and correction

2.4 Advanced Alarm Systems

NUREG/CR-6684 defines an alarm as the specification of the types of process parameters selected to be monitored and displayed by the alarm system, and the setpoints to be used to represent those parameters [23]. Functions of advanced alarm systems include: 1) alarm definition: specifies the process parameters monitored and displayed by the alarm system, and the setpoints defining alarm conditions; 2) alarm processing: involves signal validation, analysis, and filtering to ensure that only significant alarms are presented to the operator; 3) alarm prioritization: establishes the priority of alarms based on their significance to plant operations; 4) alarm display: presents alarm information in a way that is easy for operators to interpret and act upon, including visual and audible alerts; 5) alarm response procedures: provide detailed instructions for operators on how to respond to specific alarms, including potential causes and required actions; 6) alarm control and management: allows operators to manage alarms, including acknowledging, silencing, and resetting alarms.

Wu et al. (2016) investigated the effects of information display systems and advanced alarm systems on operators' situation awareness and concluded that the bar-based integrated display supports better situation awareness than other display ways [24]. Liu et al. (2016) proposed a new layout planning of alarm display and found it could shorten operators' diagnosis time and increase accuracy [25]. New potential human errors and influencing factors were also discussed in the studies and are shown in Table 4.

Table 4 Human errors and PIFs in advanced alarm systems operation identified in current studies

Human error modes	1. Information incorrectly processed or missed: Alarms that demand attention inappropriately can fragment the operator's situation assessment, causing them to incorrectly process or miss critical information. 2. Mode Errors: Mode errors occur when operators fail to recognize the current operating mode of the system. This can lead to improper interpretation and use of the information provided by the alarm system. 3. Cognitive Overload: Cognitive overload happens when the alarm density and the complexity of information exceed the operator's capacity to process effectively. 4. Misinterpretation of Automated Adjustments: Operators may misunderstand the significance of automated adjustments to alarm setpoints or configurations.
PIFs	1. System Feedback and Alerts 2. Redundancy and Signal Validation 3. Training and Familiarization 4. HSI Design

2.5 Discussion

Based on the above elaboration of elements' functions in digital MCRs, automated systems (ASs) have been applied to several elements for assisting operators in different cognitive phases, e.g., perception augment, automated diagnosis and execution, etc. For instance, in the CPS, the AS may diagnose the current situations, decide the execution strategies and execute procedural steps automatically, depending on its task allocations with operators. Current studies discussed the relevant human errors in information, decision, and action phases, and the HSI and automation related PIFs. However, there is limited consideration of underlying automation properties, for example, how operators and automation allocate their tasks, how much trust the operators have on the automation, and whether operators are able to know the automation status. Current studies emphasize the "mode transition error" , and the "feedback mechanism" behind the HSI, which could imply automation transparency. In addition, the "interpretation of operators regarding the automated adjustment" implies the effects of AS on humans' situation awareness.

3. AUTOMATION-RELATED INFLUENCING FACTORS

In the general automation-human collaboration, proposed by Sheridan et al. (1978) [26], AS is expected to assist human in the four stages shown in Figure 1, performing different Levels of Automation (LoAs) as shown in Table 5. The more stages AS can help indicates it presents the higher LoAs. Furthermore, AS's transparency, which reflects how the functionalities are performed by AS, is significant to operators in shaping their confidence and mental model on the AS. Hence, the following two influential aspects of AS are discussed.

Table 5 Levels of Automation (LoAs) of decision and action selection [26]

LoA	Description
High ↑	10. The computer decides everything, acts autonomously, ignoring the human.
	9. informs the human only if it, the computer, decides to
	8. informs the human only if asked, or
	7. executes automatically, then necessarily informs the human, and
	6. allows the human a restricted time to veto before automatic execution, or
	5. executes that suggestion if the human approves, or
	4. suggests one alternative
	3. narrows the selection down to a few, or
	2. The computer offers a complete set of decision/action alternatives, or
Low	1. The computer offers no assistance: human must take all decisions and actions.

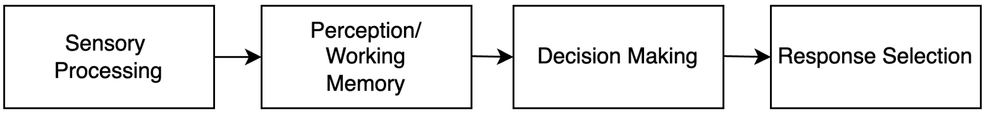

Figure 1. General four-stage model of human information processing

3.1 Level of Automation (LoAs) and Transition

In human-automation collaboration, task allocation can either be static (i.e. a fixed task allocation between the operator and the machine [27], or adjusted over time and tailored to operators' competences and current workload, for achieving an optimal collaboration.

In the domains of automated vehicles and autonomous ships, LoAs have been widely discussed and applied. In relatively simple scenarios, e.g., light traffic situation, calm river area etc., the higher LoAs are expected to allow the AS to take complete authority under operators' supervision but no intervention, as shown as the left part in Figure 1. In these scenarios, the automation performs as "automated mode", and operators can be regarded as being in a supervisory loop and only need to take control until the AS cannot handle the situation [27-28]. However, in relatively complex scenarios, the AS may "degrade" from "automated mode" to "manual mode". That means the AS cannot perform the tasks independently, but only assist operators partially depending on the design of AS, and finally execute commands, as shown in the right part of Figure 2.

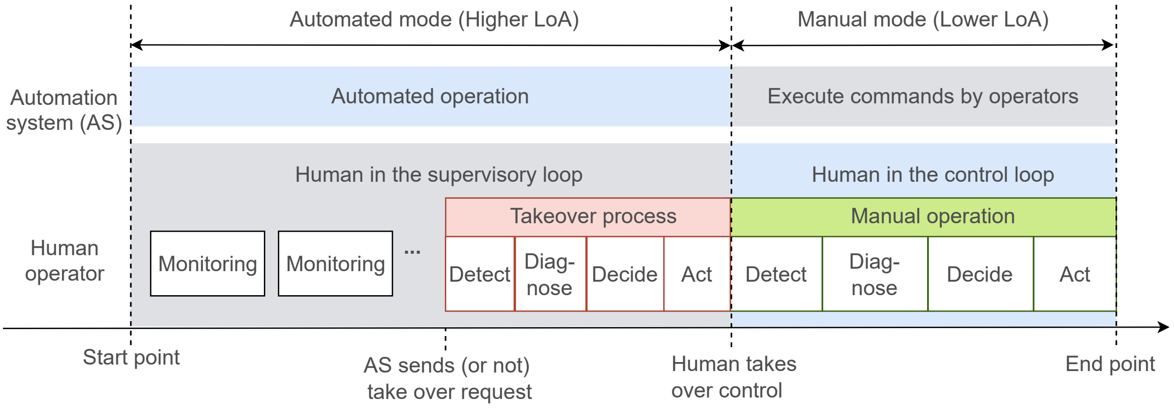

Figure 2. Human-automation interactive process [27]

In case the AS has failed, operators have to take over control. AS may or may not send a takeover request, depending on whether it recognizes that it cannot handle the current situation. In case where the AS knows itself cannot handle the scenario, it would alert and request humans to takeover control - humans perform “passive takeover”; however, in case the AS does not recognize it has failed, humans have to perform additional tasks to observe and find the danger, in order to take over control timely – humans perform “proactive takeover” [28]. At this point, the human error in both cases is failure of takeover control, but behind them, humans’ cognitive tasks are different, which are dependent on the information the AS provides.

Studies in automated vehicles and ships demonstrated that in both types of takeovers, the higher LoAs in which AS handles more scenarios and operators monitor AS for longer periods, lead to higher human error rates of takeover control [27,29]. Survey investigations indicate that the reason for takeover failure could be that the operators reduced their Situation awareness (SA) and further led themselves to Out-of-the-loop (OOTL). Moreover, operators’ over-trust in automation may be another potential reason[30].

To take the CPS in digital MCRs as an example, CPS would be embedded with automated functionalities of diagnosing scenarios, executing procedural steps, etc. The LoAs of CPS determine how many scenarios the CPS can handle independently, and how long the operators can refrain from intervening. It implies that improper LoAs of CPS may weaken operators SA, and further lead to operators’ takeover control failure. Furthermore, despite operators taking over control successfully and the AS transitioning to manual mode, it is still necessary to investigate whether operators’ SA recovers timely and how long this recovery needs.

3.2 Automation Transparency

Transparency is another important property in automation. It refers to communication of information about the AS to allow operators to form an appropriate mental model and develop appropriate levels of trust [31]. More recently, Bhaskara et al. (2020) propose that transparency may allow operators to use ASs more accurately and efficiently by facilitating their understanding of the reasoning underlying ASs’ recommendations, and what they should expect to happen if they are followed [32]. Different degrees of automation transparency are distinguished and have different effects on human performance.

Minimal transparency which provides only basic functional details may result in lower SA and trust in automation for operators. For example, unmanned aerial vehicles (UAVs) that did not inform operators about changes to their flight paths, have led to reduced operator understanding and misuse of the system [33]. Moderate transparency offers more detailed information about the automation's processes, which may improve situational awareness and trust. High transparency provides comprehensive information, and significantly enhances SA and trust, as operators can clearly understand the automation’s behavior and future actions. Wright et al. (2020) demonstrated high transparency by displaying detailed icons and colors representing the agent’s status, goals, reasoning, projected outcomes, and uncertainties [34]. However, the drawbacks brought by high transparency are also discussed.

Skraaning and Jamieson (2021) examined the impact of automation transparency on human performance in NPP operations in the Halden HAMMLAB[35]. While transparency was found to enhance human performance for component-level automation (automating specific parts independently), it did not show benefits for agent-level automation (using intelligent agents for system-wide control). Distraction and over-reliance on automated feedback can happen, which may hinder operators' detection of process deviations in NPPs.

Sargent et al. (2023) investigated the effects of automation transparency on human performance, focusing on trust, SA, response times, and accuracy [36]. The meta-analysis of current literature reveals that the increased automation transparency leads to improved humans' trust in automation, SA, and faster response times. However, increased transparency can also increase mental workload, potentially reducing effectiveness during automation failures.

Merwe et al.(2024) synthesized findings from 17 experimental studies across domains such as military, automotive, civil defense, civil aviation, nuclear, and robotics [37]. Results indicate that higher transparency generally enhances trust and SA, leading to improved operator performance without significantly increasing mental workload. However, it was pointed out that inappropriate transparency may lead to over-trust in automation, resulting in using the AS when it should not be.

Transparency issues may be relevant in all elements in digital MCRs. Improper transparency of the ASs in soft controls, CPS, advanced information systems, LDPs, and advanced alarm systems may lead to operators' distrust or over-trust, as well as incorrect SA and potential mental workload. These weakened performances may not cause human errors directly but could contribute to human error probabilities.

4 AUTOMATION-RELATED HUMAN PERFORMANCE AND ERRORS

The discussion in Section 3 presents automation's characteristics and their effects on human performance. This section further discusses how deteriorating human performance evolves into human errors.

4.1 Trust in Automation

Improper LoAs and AS transparency may cause human distrust or over-trust, also known as over-reliance and complacency on automation [30]. "Trust" was originally defined as "the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability" [31], and has also been applied to various industries involving human-machine interaction. Human trust in automation acting as an intervening variable can mediate a human's behavior of information processing, decision making, and action taking [38]. Human trust in automation is said to be mis-calibrated when the level of trust is not corresponding to the actual level of AS ability and reliability.

From the perspective of human factors, distrust acts as a significant barrier to adoption and can lead to premature and incorrect interventions (e.g., braking maneuvers) [38]. Drivers who distrust automation are often more vigilant and experience more exacerbated fatigue and more intervention failure [39]. On the other hand, over-trust occurs when drivers overestimate the capabilities of the AS and become overly reliant on it. This leads to decreased vigilance, reduced SA, and delayed reactions to hazards. Regarding digital MCRs in NPP operation, the issues caused by AS were emphasized, e.g., opacity of a digital system, and trust on automation [2].

However, from the perspective of HRA, current HRA methodologies lack attention to "trust" from the angle of automation, but only consider trust in relation to organizational culture, teamwork, and resource. In Phoenix HRA methodology [40], human trust is indirectly considered as a factor – "Confidence in information, which refers to the team's belief in their information in terms of accuracy, validity, credibility, etc." Yet, confidence in information may heavily rely on automation reliability, transparency, etc.

Therefore, for the sake of investigating the effects of trust in automation on human performance and further on human error probabilities, the automation characteristics should be included in the current PIF sets.

4.2 Situation Awareness (SA)

As discussed in Section 3, human SA could be affected by both LoAs and automation transparency. SA was formally defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” [41]. It is usually measured in terms of operator performance in human factors engineering for NPPs. The Situation awareness rating technique (SART), Situation Awareness Global Assessment Technique (SAGAT), and Situation Present Assessment Method (SPAM) have been used to measure the operators’ SA in various industries [42].

In digital NPPs, (Lin et al., 2016) compared the effects of CPS and paper-based procedures on operators’ SA [5]. The CPS context, encompassing ASs, was found to provide higher SA to participants, compared to paper-based procedures, which indicates to the operators had better attention and understanding, and significantly reduced inquiry communication while using CPSs. They believe that with employing entire features of CPSs in the future, other automation-related problems may occur and affect operators’ SA.

SA was decomposed into a series of human cognitive errors in the digital MCRs context [43], e.g., information comparing error. These errors are consistent with the human error modes in current HRA methodologies. E.g., “information comparing error” which refers to operators not timely or correctly “compare” the factual and procedure-required parameter to identify whether it is abnormal, is consistent with “Plant/system state misdiagnosed by following procedure” in the Phoenix HRA methodology.

On the one hand, it is difficult to directly observe or assess each of the SA errors; moreover, in case where SA is not failed but presents degraded performance, the deteriorating SA would affect the next human activities and can even lead to human errors. For instance, SA reduction due to improper LoAs or automation transparency would lead to takeover control failure.

Overall, the transition errors of incorrectly terminating automated execution and taking over control, and incorrectly releasing control authority to the AS may happen due to incorrect SA or inappropriate trust. In addition to transition errors, manual operation failure after takeover may also happen, due to incorrect diagnosis of the situation caused by reduced SA.

5. CONCLUDING REMARKS

This paper discusses some of the design elements and their functionalities in digital MCRs, and the relevant human errors and PIFs identified in current studies. We note that in current CPS, advanced information systems and alarm systems in digital MCRs, automation-related human errors and PIFs are mentioned frequently. The mode transition error, which refers to the failure of transition between manual operation and automated operation, was emphasized. However, there are other underlying automation characteristics that need to be explored. Thus, we refer to the knowledge in other domains involving human-automation collaboration, and discuss automation characteristics of LoAs and automation transparency and their effects on human errors. Through analyzing the transition process between LoAs, degraded SA issues occurring in the transition process are underlined. Moreover, automation transparency and its effects on human trust in automation and SA are discussed from the perspective of human factors.

It is clear that from the perspective of HRA, current PIF sets do not adequately consider the automation-related features in digital MCRs. To extend current HRA methodologies for digital MCRs, we propose the following points for further investigation: 1) how the LoAs and automation transparency impact humans’ trust in automation and SA, also considering other aspects of automation e.g., reliability, predictability, etc. 2) how humans’ trust in automation and SA impact the takeover control failure and corresponding probability. 3) how to measure human trust in automation and SA in digital MCRs operation, and incorporate them into the current PIF sets of HRA methodologies.

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