Operations Engineering in the 5th Industrial Revolution

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Introduction

The Fifth Industrial Revolution (5IR) is an emerging concept that builds upon the Fourth Industrial Revolution (4IR). While the 4IR focused on automation, artificial intelligence, and efficiency, 5IR reintroduces the human element into technology-driven transformation. It emphasizes collaboration between humans and machines, ethical technology use, and sustainability (Kumar and Shankar, 2022). This shift is significant because it addresses the growing need for ethical, inclusive, and empathetic use of technology in a world increasingly shaped by intelligent systems.

System operation

System operation refers to the real-time processing, management, control, and adjustment of production and services. In 5IR, systems are designed to foster synergy between operators and intelligent machines, emphasizing trust, adaptability, and human empowerment (Parasuraman, Sheridan & Wickens, 2000).

Human factors

The most significant factor affecting system operation is human performance. Human factors refer to the study and application of knowledge about human capabilities, limitations, and behaviors to optimize the design of machines, systems, tasks, and environments for safety, efficiency, and usability. Applying human factors ensures that machines and interfaces align with operator needs and cognitive strengths (European Commission, 2021).

Challenges in Human–Machine Collaboration

Errors

As systems become more complex, they are harder to monitor, predict, and control, which increases the likelihood of both human and system errors. Human and system errors can disrupt performance, especially when interactions are complex. Understanding and preventing these errors is key to designing resilient, human-centric systems (Leveson, 2012).

Errors are often unexpected and sometimes unpredictable. Models of error generation are complex, and the costs of error prevention can be extremely high.

Operational complexity

Most human errors do not result from carelessness but from design oversights in these systems. These errors usually stem from interactions, hidden dependencies, and emergent behaviors in complex situations, rather than individual negligence.

Modern systems are increasingly complex, with interactions, hidden dependencies, and emergent behaviors that obscure predictability and control.

Seamless operation

System operation is often too complex because operations may not be consistent. This complexity is mainly due to the way we constrain normal and exceptional operations. The translation of controls to functions is rarely consistent; it depends on the system situation. The challenge is to facilitate seamless operation, ensuring a consistent transition from controls to functions. Moreover, in exceptional situations, operators are expected to troubleshoot unpredictable scenarios across both routine and exceptional circumstances. Design must minimize cognitive load by ensuring predictable control–function translation and providing clear guidance for troubleshooting unexpected events.

The Costs and Consequences of Errors

Errors have multifaceted consequences—financial loss, reduced safety, lower trust in automation, hindered innovation, and threats to sustainability (Leveson, 2012). The costs of errors are multidimensional, affecting not only financial performance but also human safety, trust, innovation, and sustainability (Dekker, 2014). For example, human error contributes to nearly 90% of industrial accidents involving advanced automation systems (World Economic Forum, 2020).

Inherent safety

Traditionally, error investigations blame operators rather than addressing root causes such as flawed system design. A core goal of 5IR is to reframe error prevention as a design responsibility. For example, design inconsistencies often make operations unnecessarily complex. Operators must handle both routine and exceptional scenarios, sometimes without clear guidance. This inconsistency increases cognitive load and the likelihood of errors.

Engineering challenges

Blame culture

Traditionally, error investigations blame operators rather than addressing root causes such as flawed system design. A core goal of 5IR is to reframe error prevention as a design responsibility. For example, design inconsistencies often make operations unnecessarily complex. Operators must handle both routine and exceptional scenarios, sometimes without clear guidance. This inconsistency increases cognitive load and error likelihood.

Preventing errors in system operation is critical not only for productivity and safety but also for maintaining trust in human–machine partnerships (Dekker, 2014).

Design Responsibility for Safety

The challenges are:

- To shift investigations from operators blame to identifying and eliminating root-cause design flaws
- To Develop operational rules and interfaces that inherently prevent common interaction failures.

Affordability

Budget resources for simulation-based testing, interdisciplinary teams, and continuous user-feedback loops to ensure that human factors are integrated from the outset.

Error prevention requires upfront investment in design, training, monitoring, and technology. Investing in error prevention involves various direct and indirect costs. These investments are proactive and aim to reduce or eliminate the far greater costs of errors down the line, such as accidents, downtime, reputation damage, or legal liability (Reason, 1997).

Rule-based operation.

Coping with complexity manually is costly and error prone. Rule-based operation may facilitate operation, yet a design based on numerous rules can become too expensive and error-prone. The industry challenge is to develop generic operational rules that, when employed, will eliminate all kinds of errors.

Rule-based operation relies on predefined rules, which can become brittle and expensive when covering numerous edge cases. Employing AI is essential for coping with this complexity.

Cost balancing

Investing in human-centered design, training, and monitoring has upfront costs but mitigates much greater long-term losses such as downtime, reputational damage, and legal liabilities.

Rule-based operation, while helpful, becomes costly and fragile if overloaded with specific rules. The challenge is to create generalized operational rules that are adaptable, cost-effective, and reliable. Here, artificial intelligence plays a crucial role in managing complexity.

Model-based operation design

Model-based operation design is a structured, proactive approach that uses formal models to predict, reduce, and prevent human and system errors during operation.

Model-based design uses dynamic representations of system behavior to anticipate and adapt to varying conditions in real time. This makes model-based systems more flexible and robust in complex, unpredictable environments. It uses formal models to predict, detect, and prevent errors. These models include representations of normal and abnormal interactions. In complex, automated, and human-integrated systems, this approach is especially crucial for ensuring reliability, safety, and usability. Deviations from modeled norms can then be flagged and corrected in real time (Parasuraman & Riley, 1997).

Such models are composed of modular sub-models that represent common interaction failures. These sub-models are typically developed through empirical analysis of operational data, expert input, and simulation of known failure scenarios. Validation involves iterative testing and refinement to ensure that each sub-model accurately captures specific types of breakdowns in interaction under various conditions. For example, a failure model might define a typical scenario where a user misunderstands a control function due to ambiguous system feedback. Designing with these models helps ensure that normal operation is intuitive and resilient.

Modeling

The method for error prevention is based on a model of interaction failure. This model comprises mini models, each describing a typical way in which the interaction might fail. Failures are expressed as deviations from a model of normal interaction. Normal operation is expressed in the form of rules.

Conclusion and Future Outlook

AI-Assisted Design

As AI technologies continue to evolve, their integration into software and systems engineering will become increasingly essential for organizations seeking to minimize errors and maximize value. Artificial intelligence can analyze operational data to generate generalized rules, predict failures, and suggest design improvements, reducing the burden on operators and designers alike.

AI for human factors engineering

As 5IR evolves, the integration of human factors into the design of intelligent systems becomes not just desirable but essential. Human-centric design, combined with model-based methods and AI, can create safer, more sustainable, and more trustworthy systems.

Organizations that prioritize these principles will be better equipped to navigate the challenges of complex human-machine collaboration, achieving both innovation and resilience. As a practical next step, organizations should invest in interdisciplinary design teams and simulation-based testing environments that integrate human factors early in the development process.

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