Challenges for Artificial Intelligence-Machine Learning in Complex Systems and Systems of Systems

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***Abstract*—Complex systems and System-of-Systems (SoS) are now being increasingly inculcated with a significant footprint of intelligence in functionality and inter-connectivity. Artificial Intelligence-Machine Learning (AI-ML) and other advanced technologies are actively being leveraged to enable differentiated intelligence capability in most modern systems and SoS. These complex systems are envisioned to emulate comparable and beyond human intelligence to achieve the desired operational goals and surpass their "traditional" predecessors in functionality, efficiency, and performance. However, engineering these advanced technologies into complex systems and SoS demand different approaches, and pose unique challenges as compared to their predecessors. This paper summarizes the proceedings of the special track that focused on various systems engineering challenges pertaining to engineering Artificial Intelligence (specifically Machine Learning - including supervised learning, unsupervised learning and reinforcement learning) in complex systems and SoS.**

Keywords-complex systems, complex system-of-systems, artificial intelligence, machine learning, reinforcement learning.

I. INTRODUCTION

A system can be considered as an integrated and interacting combination of elements and/or subsystems to accomplish a defined objective [1]. These elements may include hardware, software, firmware and other support services. SoSs are large scale complex systems whose constituent elements are themselves systems with operational and managerial independence [2]. Complexity in a system is representative of the multiplex of relationships, forces, and interactions in the system, with difficulties in establishing cause-and-effect chain. Complex system and SoS are characterized by a holistic behavior, wherein it is very difficult to anticipate the system behavior from the knowledge of the subsystem behaviors [3]. Emergence, hierarchical organization, and numerosity are some of the characteristics of complex systems.

Complex systems and System-of-Systems (SoS) are now being increasingly inculcated with intelligence in functionality and inter-connectivity. Artificial Intelligence (AI) Machine Learning (ML) and other advanced technologies are actively being leveraged to enable differentiated intelligence capability in most modern systems and SoS. These advanced technologies are envisioned for systems to enable beyond human intelligence to achieve the desired operational goals. By incorporating intelligence, these systems are expected to surpass their "traditional" predecessors in functionality, efficiency, and performance.

However, engineering these advanced technologies into complex systems and SoS demand different approaches, and pose unique challenges as compared to their predecessors. The intent of the special track: "Challenges for Artificial Intelligence-Machine Learning in Complex Systems and Systems of Systems" is to bring attention these challenges and present approaches towards their solution. This paper summarizes the proceedings of the special track which focuses on various systems engineering challenges pertaining to engineering Artificial Intelligence (specifically Machine Learning - including supervised learning, and reinforcement learning) in complex systems and SoS.

II. OVERCOMING AI-ML CHALLENGES

There were four topics discussed during the proceedings of the track, spanning various challenges pertaining to AI-ML for complex systems and SoS. This section briefly discusses the key challenges and the approaches presented to address these challenges.

A. Metacognition for Artificial Intelligence Systems

Developing AI systems with metacognition is a step towards enabling systems to think, learn, and adapt in real-world environments. There are many potential safety failures that can arise, including skewed and biased outcomes. These failures may be caused due to challenges in the way AI systems are developed. An initial concept for a metacognition capability is proposed as a type of safe fail solution strategy in [4]. The AI system creates and maintains a metacognitive internal model for self-awareness, self-diagnosis, and self-evaluation. The mechanism enables the AI system to prevent failures by identifying indicators that a failure might occur and alerting a human operator or shifting itself into a failsafe or manual mode of operation. This addresses many challenges pertaining to human-machine risks including mistrust, overreliance, or operator-induced errors; epistemic uncertainty issues including data error, corruption, or incompleteness; and cyberattacks.

B. Extending Modeling Constructs for AI

Artificial Intelligence (AI) will require all stakeholders to re-examine their traditional methods for designing and engineering of all future intelligent and autonomous systems. A set of guidelines that are needed to extend system modelling languages to model AI entities is proposed in [5]. The paper elaborates many principles for an extension to System Modeling Language (SysML), including self-awareness, dynamic world modelling, machine-to-machine interactions, self-improvement through learning and enhanced autonomy (self-control or self-sufficient). The profile is organized into two top-level packages: the AI-Autonomy Library and SysML. The first package is a UML Model Library which defines datatypes and reusable concepts, while the second model incorporates the concepts of AI-autonomy data.

C. Reinforcment Learning for Emergent Behavior

In SoS context, the relationships between the Measures of Effectiveness (MOEs) of the constituent systems and SoS is critical to understand emergent behavior evolution in complex SoS. An approach towards using reinforcement learning models and techniques for evolving MOEs of the constituent systems and SoS towards addressing emergent behavior is discussed in [6]. In the proposed approach, a ML Classifier is used to advise the SoS-Constituent System MOE Relationship (SSMR) on positive and negative emergent behaviors. SSMR is built with the required intelligence to serve as the environment for the constituent system, and provide the required feedback based on the positive and negative emergent behaviors witnessed at the SoS level. The approach enables constituent systems to learn and adapt their behaviors in tandem with the evolution of emergent behavior at SoS level.

D. Deep Reinforcement Learning for SoS Architecture Path Selection

There is keen interest in the SoS community on the challenges pertaining to architecture, design, and development of complex SoS. A learning-based framework for managing interdependency-incorporated SoS architecture evolution and path selection is proposed in [7]. Deep-Q-Network (DQN) algorithms are leveraged to support SoS architectural path selection under uncertainty. The effectiveness of the proposed algorithm is demonstrated using case study of mosaic warfare comprising multi-mission units. The approach proposed involves building a simple parametric model to capture impact of interdependency on SoS capability.

III. CONCLUSION

The proceedings of the special track on challenges for AI-ML in complex systems and SoS highlighted some of the unique systems engineering challenges pertaining to inculcating advanced intelligence in these systems. As progress is made with further research, it is expected that the means to inculcate intelligence in systems will evolve significantly and reduce the extent of human-in-loop.

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