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DEVELOPING A BI-LEVEL AND INTEROPERABLE FRAMEWORK FOR DIGITAL TWINS: AN APPLICATION FOR THE UNDERGROUND MINING INDUSTRY

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ABSTRACT

The study presents an innovative modular, technical, and bi-level Digital Twin architecture, specifically designed for underground mining systems. Aligned with Industry 4.0 principles, it aspires to integrate and enhance mining activities across the mining value chain. Spanning its entire value chain, the architecture considers lifecycle phases, physical assets and operations in six functional layers, addressing interoperability between the IoT, data, and various models. This holistic design facilitates remote control of underground operations and provides flexibility to craft decision tools tailored to individual configurations. The focus is on merging real-time data with decision tools to achieve a granular system portrayal and facilitate informed operational decisions. The architecture adopts a service-oriented approach, necessitating the partitioning of data and decision models, ensuring a flexible, extensible lower-level Fleet Management System using UML methodologies. Ultimately, this architecture is poised to revolutionize mining processes and resiliency, driving operational efficiency, safety and adaptability to new heights.

1 INTRODUCTION

Industry 4.0 is characterized by deep interconnectivity, enhanced automation, and pervasive digitalization. As part of Cyber-Physical Systems, Digital Twins (DT), go beyond mere simulation and offer an encompassing virtual reflection of physical operations, presenting a promising solution for agile reactions in complex systems. While the manufacturing sector is progressively adopting these innovations, Underground Mining (UM) remains primarily in the conceptual phase. The domain confronts challenges such as geological unpredictability, spatial constraints, operational uncertainties, ensuring safety, and logistical intricacies (Khazaei and Pour-rahimian 2021; Chimunhu et al. 2022). Also, the few digital solutions proposed for mining are often adaptations of models originally designed for manufacturing. Such transpositions, although beneficial, overlook the intrinsic, distinct needs of the complex mining environment. addressing this void, there's a rising demand for DT engineering, manifesting as a structured architectural roadmap or testbed. This research, therefore, proposes a modular DT architecture specific to the UM environments, and narrows to implement it for the Fleet Management System (FMS).

2 METHODOLOGY

In the endeavor to design a DT framework tailored for underground mining, we adopted a methodical tripartite strategy. Initial stages involved exhaustive review of existing DT frameworks across the manufacturing and the UM sectors, highlighting aspects such as scalability, adaptability, and extensibility, leading to the discernment of a Reference Architecture (RA). Notably, deviations from proper modeling methodologies can impose developmental and implementational constraints on DT applications (Tao 2022). RAs helps to define the essential components of a DT and their interrelationships (Uslander 2022), serving as an infrastructure for achieving full functionality (Tao 2022; Minerva 2020). Building on this foundation, the second stage involved defining the pivotal modules of the DT. These are anchored in three distinct dimensions: lifecycle phases, physical operations and equipment, and six functional layers containing various types of modules. These dimensions are crucial for the effective integration of the DT into UM operations. We underscore the importance of decomposing the FMS data and decision systems, enhancing its modularity and addressing interoperability. In our methodology's final phase, we will assess the challenges and potential of integrating DTs in underground mining, providing an insightful view of DTs in the intricate setting of underground mining.

3 CURRENT RESULTS

Our current findings present an intricately engineered framework, specifically devised as the upper-level DT for underground mines. For underground mining, special considerations for designing DTs are taken into account in three layers: twins, models, and services. Within these foundational layers, specialized modules for decision, geology, network models, as well as equipment, sensors, and operational actors have been adeptly integrated. As a result, these modules, which have been architected hierarchically, are in tune with the particularities inherent to the mining value chain. The incorporation of Service-Oriented Architecture (SOA) principles confers benefits of modularity, reusability, and interoperability. As a precursor to future endeavors, the Unified Modeling Language (UML) has been employed to sculpt the lower-level class diagram, providing a clear representation of the architecture and facilitating precise intermodular interactions for the FMS. Through this integration, the framework enhances its ability to detect changes in real time and respond accordingly, providing a holistic approach to navigating the complexities inherent in UM operations.

4 CONTRIBUTION

This dissertation provides a seminal contribution to the field of DT engineering and the UM domain by introducing a holistic, functional, bi-level DT architecture. Our research is novel in three important respects. Firstly, through an advanced approach in DT engineering, we have identified and endorsed an optimal RA, rectifying deficiencies in existing models, ensuring a robust, customized solution for UM scenarios. Secondly, our comprehensive description of the essential components and features, merged with the integration of a SOA, emphasizes the commitment to modularity, agility, and real-time decision-making. Lastly, the insights into the inherent challenges and prospective opportunities related to DT implementation illuminate a clear pathway for future advancements. These accomplishments highlight the study's significance as a leading reference for both academic and industrial sectors in the complex world of underground mining.

5 CONCLUSION

The convergence of the digital and physical realms through DTs holds transformative potential for underground mining. While challenges in fidelity, interoperability, and standardization exist, the ongoing research endeavors to address these, aiming for a holistic and integrated solution. The future of UM lies in the seamless fusion of real-time data with intelligent decision-making systems.

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