Title of the PhD Proposal

Towards a Persistent Interoperability Framework for Long-Term Collaboration Based on Reusable and Heterogeneous Simulation Models

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Host Laboratory:

Laboratoire des Sciences des Risques (LSR), IMT Mines Ales

Short Abstract:

This PhD proposal aims to develop a socio-technical interoperability framework to support persistent, long-term collaboration among heterogeneous and distributed systems. Emphasizing the reuse and coordination of diverse simulation models and services, the framework will leverage the High-Level Architecture (HLA) standard and dynamic ontologies (including Short-Lived Ontologies) to ensure semantic and technical interoperability across dynamic long term collaborative environments. Domains such as healthcare, crisis management, and distributed industrial operations will benefit from the ability to integrate and maintain simulation-based models over time. While Virtual Reality (VR) can be used as an optional visualization and interaction tool, the project's core focus is on enabling sustainable interoperability, model persistence, and semantic coherence. The outcome will be an open-source, interoperability framerwork facilitating the integration of new tools and actors into dynamic, interoperable ecosystems.

Short Description of Hosting Research Group / Lab:

The Laboratoire des Sciences des Risques (LSR) at IMT Mines Ales specializes in the engineering of complex systems, focusing on risk management, interoperability, and simulation. With expertise in distributed simulation, semantic modeling, and decision-support technologies, the lab is particularly recognized for integrating advanced technologies to address real-world challenges in fields such as healthcare and crisis response. The LSR promotes interdisciplinary approaches to enhance collaboration across technical and organizational boundaries.

Description of the PhD Proposal

Context and Scenarios:

The increasing complexity of collaborative environments and the diversity of digital tools have exposed critical gaps in interoperability. Many sectors, such as healthcare, crisis management, and manufacturing, struggle to maintain seamless integration among heterogeneous models and services. These challenges hinder adaptability, increase integration costs, and reduce the reuse potential of developed solutions.

Previous research has highlighted the potential of distributed simulation (DS) and system federation for collaborative modeling. For example, healthcare training simulations and emergency planning have demonstrated the value of integrated models in improving preparedness and coordination.

Scenarios for this research include:

1. **Healthcare**: Reusable simulations for resource management in hospitals (e.g., dialysis unit modeling during a pandemic). (Possik et al., 2021).
2. **Crisis Management**: Simulating large-scale emergency responses, such as natural disasters or terrorist attacks, to enhance coordination among first responders (Jabbour et al., 2023).
3. **Industrial Collaboration**: Long-term collaborative planning in distributed manufacturing environments, where multiple stakeholders need to coordinate production schedules and resource allocation (Grangel-González et al., 2016).

Problem and Objective:

The primary problem addressed by this research is the lack of a robust, scalable, and accessible interoperability framework that can support long-term collaboration among heterogeneous systems and users. Current solutions often rely on ad-hoc integrations that are difficult to maintain and scale, leading to inefficiencies and increased costs (Chen et al., 2008).

The main objective of this PhD project is to develop an interoperability framework that integrates heterogeneous components, leveraging the HLA standard, dynamic ontologies (including Short-Lived Ontologies), and immersive interfaces to enable seamless collaboration and decision-making. Specifically, the framework will:

1. Facilitate the integration of heterogeneous collaborative services through a federated architecture (Zacharewicz et al., 2009).
2. Ensure semantic interoperability through the use of evolving ontologies, including Short-Lived Ontologies (SLOs), that adapt to new technologies and user needs (Zacharewicz et al., 2009).
3. Offers immersive VR interfaces as optional tools for enhancing decision-making and model understanding.
4. Provide a scalable and open-source platform that can be easily adopted and extended by the community.

Brief Overview of the State of the Art:

Interoperability in distributed systems has been extensively studied, with the federated approach and HLA standard being widely recognized as effective solutions for integrating heterogeneous models. The HLA standard, developed by the US Department of Defense, provides a framework for synchronizing distributed simulations and ensuring communication between disparate systems. It has been successfully applied in various domains, including defense, healthcare, and industrial systems (Zacharewicz et al., 2009).

Ontologies have proven valuable for semantic interoperability, enabling data exchange and interpretation across systems. For example, in healthcare, ontologies such as SNOMED CT and HL7 have been used to standardize medical terminology and facilitate data sharing between electronic health records (EHRs). However, these ontologies are often static and do not adapt well to new technologies or evolving user needs (Namaki et al., 2024).

The concept of **Short-Lived Ontologies (SLOs)**, introduced by Zacharewicz et al. (2009), represents a significant advancement in the field of semantic interoperability. SLOs are designed to be context-sensitive and adaptable, making them particularly suitable for environments where collaboration requirements and data semantics evolve rapidly. For example, in a crisis management scenario, the meaning of certain terms (e.g., "emergency level" or "resource availability") may change depending on the phase of the crisis (e.g., preparedness, response, recovery). SLOs can dynamically adjust to these changes, ensuring that all collaborators share a common understanding of the situation (Zacharewicz et al., 2009).

Research Questions:

1. How can heterogeneous simulation models be integrated and reused across time and domains?
2. What mechanisms ensure sustainable semantic interoperability using dynamic ontologies?
3. How can persistent federated architectures support evolving collaborations?
4. What role can immersive tools play in enhancing understanding without becoming central dependencies?

Theoretical Foundations:

The research is grounded in theories of interoperability (Chen et al., 2008), distributed simulation, and human-computer interaction. It draws on the HLA standard for technical interoperability and ontology engineering (including Short-Lived Ontologies) for semantic interoperability.

1. **Interoperability**: The research builds on the federated approach to interoperability, which emphasizes the integration of heterogeneous systems while maintaining their independence. This approach is particularly relevant for long-term collaboration, where systems need to evolve and adapt to new technologies and user needs (Chen et al., 2008).
2. **Distributed Simulation**: The HLA standard provides the theoretical foundation for synchronizing distributed simulations and ensuring communication between disparate systems. (Zacharewicz et al., 2009).
3. **Human-in-the-Loop (HITL):** Decision-making in complex systems. (Jabbour et al., 2023).

Approach and Methods:

The research will follow a multi-level approach, addressing technical, semantic, and organizational interoperability:

1. **Technical Interoperability**: The research will integrate HLA models and standardized protocols to ensure communication between heterogeneous systems. This will involve developing a federated architecture that supports real-time synchronization and scalability (Zacharewicz et al., 2009).
2. **Semantic Interoperability**: The research will develop dynamic ontologies, including Short-Lived Ontologies (SLOs), that evolve with new technologies and user needs. These ontologies will provide a shared understanding of collaborative objects and facilitate data exchange across systems (Zacharewicz et al., 2009).

3. **Organizational Interoperability**: The research will implement governance mechanisms, such as access rights management and version control, to support the long-term adoption of the framework.

The methodology includes the following steps:

1. **Prototyping**: Development of a prototype that integrates heterogeneous components (including SLOs).
2. **Experimentation**: Testing the prototype in real-world use cases, such as healthcare training and crisis management simulations (Possik et al., 2021; Jabbour et al., 2023).
3. **Evaluation**: Assessing the performance of the framework based on latency, adaptability, and usability.

Evaluation of the Contributions:

The contributions of the research will be evaluated through:

1. **Performance Metrics**: The framework will be tested for latency, synchronization, and scalability in distributed environments.
2. **User Feedback**: End users, such as healthcare professionals and crisis responders, will provide feedback on the ease of use and accessibility of the framework.
3. **Impact Assessment**: The adoption of the framework in real-world scenarios will be monitored, and its contribution to standardization efforts will be assessed.

Nature of Digital Collaboration

The PhD targets technology-mediated human activities that involve collaboration among heterogeneous groups. The focus is on:

- **Function**: The research addresses various functions of collaboration, including communication, information sharing, coordination, and decision-making. In healthcare, for example, the framework will facilitate communication between medical teams and the sharing of patient data (Possik et al., 2021). In crisis management, it will enable coordination among first responders and decision-making in high-pressure situations (Jabbour et al., 2023).
- **Type**: The research will support both synchronous (real-time interactions) and asynchronous (long-term planning and data exchange) collaboration. For example, in a healthcare training scenario, medical teams may engage in real-time simulations, while in a crisis management scenario, long-term planning may involve asynchronous data exchange and analysis.
- **Time Scale**: The framework will support collaboration across various time scales, from seconds (real-time decision-making) to years (long-term collaborative planning). For example, in a crisis response, real-time coordination is critical, while in industrial collaboration, long-term planning may span months or years (Grangel-González et al., 2016).
- **Group Size**: The research will target collaboration among groups of varying sizes, from small teams (e.g., healthcare teams) to large collectives (e.g., crisis response networks). The framework will be designed to scale according to the size and complexity of the collaborative environment.

The research will explore how distributed simulation can enhance collaborative activities by ensuring seamless interoperability across systems.

Contribution to Digital Collaboration: Expected Results and Impact

The PhD is expected to make the following contributions:

1. **Empirical**: The research will provide insights into the effectiveness of distributed simulation in enhancing collaboration in real-world scenarios. For example, in healthcare, the framework will improve training outcomes by providing immersive simulations that replicate real-world conditions (Possik et al., 2021). In crisis management, it will enhance coordination and decision-making by enabling real-time collaboration among first responders (Jabbour et al., 2023).
2. **Theoretical**: The research will contribute to the theoretical understanding of interoperability in long-term collaborative environments. The development of a socio-technical framework that integrates heterogeneous components/simulations (including SLOs) will provide a foundation for future research in this area (Zacharewicz et al., 2009).
3. **Methodological**: The research will provide guidelines for integrating HLA collaborative systems. These guidelines will be based on the lessons learned from prototyping and experimentation in real-world use cases.
4. **Technical**: The research will result in an open-source platform for interoperable collaboration. The platform will be designed to be scalable and adaptable, enabling its adoption in various domains, including healthcare, crisis management, and industrial collaboration (Grangel-González et al., 2016).
5. **Impact**: The research will have a significant impact on the fields of healthcare and crisis management by improving decision-making and collaboration. The framework will facilitate the integration of new tools and partners without requiring a complete system overhaul, reducing costs and increasing efficiency. Additionally, the research will contribute to the standardization of interoperable models, enabling their adoption in other domains.

Positioning in the eNSEMBLE Program

This project aligns with the eNSEMBLE program's focus on enhancing digital collaboration through innovative technologies and interoperability frameworks detailed in Theme 1 & 2. It directly contributes to the themes of distributed simulation and long-term collaboration, particularly in the context of healthcare and crisis management. The development of an open-source, scalable framework supports the program's goal of fostering sustainable, interoperable digital ecosystems.

The research will also contribute to the eNSEMBLE program's objective of promoting interdisciplinary collaboration by bringing together experts in computer science, systems engineering, and human factors. The framework will serve as a platform for future research and innovation, enabling the integration of new technologies and the exploration of new collaborative scenarios.

References

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