Research Proposal

Methods of Research

Agent Protocol Primitives for Digital Twins of Human Operators in Distributed Energy Resource Systems

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Submission Date: June 7, 2025
Word Count: 2,880 words (excluding abstract and references)

Abstract

Abstract: This research investigates how emerging agent protocol primitives—specifically the Model Context Protocol (MCP), Agent Communication Protocol (ACP), and Agent-to-Agent Protocol (A2A)—can be adapted and integrated with Digital Twin principles to create Human DER Worker Digital Twins (HDTs). The study addresses operational challenges in Distributed Energy Resource (DER) management, including communication gaps, coordination difficulties, and the need to simulate human operational behaviors in increasingly automated environments. Through a systematic literature review and compositional framework development, this research proposes an unexplored approach to modeling human operational behaviors within protocol-enabled digital twins, with potential applications for preserving and scaling operational patterns across distributed energy systems. The expected contributions include a validated framework for Human DER Worker Digital Twins, insights into protocol composition for energy system operator coordination, and processes for implementing human-centric digital twins in energy system operations.

1 Introduction and Background

The transformation of global energy systems toward decentralized architectures presents unprecedented operational challenges that fundamentally alter how maintenance activities must be coordinated and executed [1]. The proliferation of Distributed Energy Resources (DERs)—including rooftop solar installations, battery storage systems, and wind microgeneration—has created a complex multi-stakeholder ecosystem where traditional centralized maintenance approaches prove inadequate [2].

1.1 Problem Context and Significance

The DER ecosystem involves diverse stakeholders with varying technical capabilities, business objectives, and operational constraints. Individual homeowners with rooftop solar installations operate under different knowledge bases and decision-making frameworks than commercial facility managers, utility operators, or industrial microgrid controllers [3]. This **heterogeneity** creates significant challenges in preserving, transferring, and scaling human operational behaviors across the distributed energy landscape.

Current approaches to DER coordination rely heavily on centralized Distributed Energy Resource Management Systems (DERMS), which struggle to capture and utilize the **nuanced human operational behaviors** required for effective system operations [4]. Increasing automation of energy systems requires bridging the gap between human operational patterns and automated decision-making processes. Human experts possess tacit knowledge about equipment behavior, environmental factors, stakeholder coordination patterns, and operational trade-offs, but also exhibit operational uncertainties and inconsistencies that cannot be easily codified within traditional control systems [5].

The significance of this challenge extends beyond operations to encompass workforce and sustainability considerations. The aging workforce in the energy sector faces retirement without adequate **knowledge transfer mechanisms**, which risks losing decades of operational experience and behavioral patterns [6]. The effective preservation of human operational behaviors directly impacts the stability, integration, and democratization of energy systems [7]. Moreover, recent pandemics and the Iberian Peninsula blackout has highlighted the importance of resilient energy infrastructure that can maintain operations despite disruptions to traditional mentoring and knowledge transfer workflows.

The challenge is particularly acute in **DER operations** where human operational behaviors encompass complex coordination patterns—understanding how to balance owner preferences with grid stability requirements, how to prioritize competing operational demands under uncertainty, and how to adapt to local environmental and regulatory constraints [1]. Traditional one-on-one mentoring approaches fail to scale across distributed operations [8], and formal documentation systems cannot capture the tacit knowledge and operational uncertainties of operators in dynamic, multi-stakeholder environments [9].

1.2 Literature Review Synthesis

A preliminary literature review across four domains—human factors in energy systems, industry-academia collaboration, AI automation applications, and safety training methodologies—reveals consistent patterns pointing toward the need for more sophisticated human-technology integration in DER management.

Human Factors and Communication Gaps: Research in nuclear power plant operations demonstrates that human expertise remains critical for managing complex, safety-critical systems [10]. Studies of control room operators highlight the importance of tacit knowledge, situational awareness, and adaptive decision-making that cannot be fully automated [11]. In DER contexts, similar patterns emerge where human operators must navigate between technical system requirements and real-world operational constraints.

Digital Twin Technology in Energy Systems: The application of Digital Twin technology in energy systems has shown promising results for system optimization and operational coordination [12]. However, existing implementations focus primarily on physical asset modeling rather than capturing human operational patterns and expertise. Recent reviews identify the need for "Human Digital Twins" that can model operator behavior and decision-making processes [6].

Agent Protocol Primitives: Emerging agent protocol primitives, particularly MCP, ACP, and A2A, offer new possibilities for distributed coordination and knowledge sharing [13]. These protocols enable more sophisticated multi-agent interactions than traditional approaches, supporting complex negotiation, resource sharing, and collaborative problem-solving patterns essential for DER coordination.

1.3 Research Gap Identification

The literature synthesis reveals three critical gaps that this research addresses:

Theoretical Gap: Current Digital Twin frameworks, despite their strengths in modeling physical systems, exhibit a fundamental deficiency in representing human operational behaviors—a critical gap identified across a systematic review of extensive literature. They consistently fail to capture the tacit knowledge, adaptive reasoning, operational uncertainties, and contextual decision-making patterns vital to human expertise in DER operations.

Methodological Gap: There is a significant methodological gap, as existing agent protocol primitives have not been systematically evaluated in published research for their efficacy in modeling complex human operational behaviors within industrial energy settings. This represents a potentially critical, unexplored intersection of agent computing and human factors engineering, demanding methodological approaches grounded in established research paradigms yet adapted for this unique context.

Practical Gap: The DER industry lacks validated frameworks for creating Human DER Worker Digital Twins that can model human behaviors across distributed operations while simulating the adaptability, contextual awareness, and inherent uncertainties that characterize human expert performance, with potential for future scaling applications.

These represent a significant barrier to realizing the full potential of DER systems for sustainable energy transition. Without effective mechanisms for modeling and potentially preserving human operational behaviors including their uncertainties, the increasing automation of energy systems is less able to capture critical operational patterns while at risk in losing the coordination necessary for large-scale renewable energy integration.

2 Research Objectives and Questions

2.1 Research Objectives

Overarching Research Objective: This research aims to develop and validate a framework for creating Human DER Worker Digital Twins (HDTs) using agent protocol primitives to effectively model human operational behaviors in Distributed Energy Resource operations.

Objective 1: Identify and structure the essential components of Human DER Worker operational behaviors—including tools, knowledge resources, communication patterns, and uncertainty management—that can be effectively modeled and represented within an HDT framework using agent protocol primitives.

Objective 2: Design protocol-enabled HDT architectures that can model various Human DER Worker behaviors within specific DER Application Contexts such as operational knowledge management and stakeholder interaction.

Objective 3: Develop an evaluation framework which may be grounded in the Design Science Research principles adapted in Phase 2, for assessing HDT effectiveness across technical efficacy, representation fidelity, and human factors to analyze, interpret, or define the inherent uncertainties and limitations of the proposed HDT architectures.

2.2 Primary Research Questions

Overarching Research Question: How can agent protocol primitives (specifically MCP, ACP, and A2A) be adapted and integrated with Digital Twin principles to create Human DER Worker Digital Twins that effectively model human operational behaviors?

Question 1: What are the essential components of a Human DER Worker's operational behaviors that can be effectively identified, structured, and modeled within an HDT framework using agent protocol primitives?

Question 2: How can different agent protocol architectures be effectively mapped and implemented to model various Human DER Worker behaviors within specific DER Application Contexts such as operational knowledge management and stakeholder interaction?

Question 3: What multi-faceted evaluation framework is required to assess the impact of HDT integration on DER operations, and how does performance feedback contribute to refining HDT representations or defining limitations of HDT representations?

3 Scope and Limitations

This research is bounded by the following scope and limitations:

Protocol Focus: The analysis and conceptual design will be strictly limited to the application and adaptation of MCP, ACP, and A2A protocols. Other agent protocols or general communication standards will not be explored in detail.

Use Case Specificity: The research focuses solely on modeling human operational behaviors for DERs through digital twins. Applications in other DER functions such as energy trading or grid stability services are outside the scope.

Framework Development: This research will develop a structured framework for HDT creation and evaluation rather than building fully operational software systems, and will not include full-scale system implementation or field deployment testing. Validation will be conducted through literature-based analysis and conceptual framework evaluation rather than empirical field studies.

Stakeholder Coverage: The research focuses primarily on technical operators and maintenance personnel, with limited attention to policy makers or regulators. Whether to include other stakeholders will be determined by the research findings.

4 Theoretical Framework

4.1 Core Conceptual Model

The theoretical framework is structured around concepts operating within two primary domains: Reality (Human-Centric) and Digital Twin (Protocol-Enabled).

Human DER Worker: The fundamental human element encompassing operational behaviors, tools (SCADA interfaces, diagnostic equipment), knowledge resources (technical manuals, historical data, regulatory frameworks), and communication patterns (SOPs, reporting formats, escalation pathways). Current literature reveals significant gaps in representing cognitive processes within industrial environments [8] [9], highlighting inadequate formalization for the operational uncertainties that characterize human expert performance in complex operational contexts.

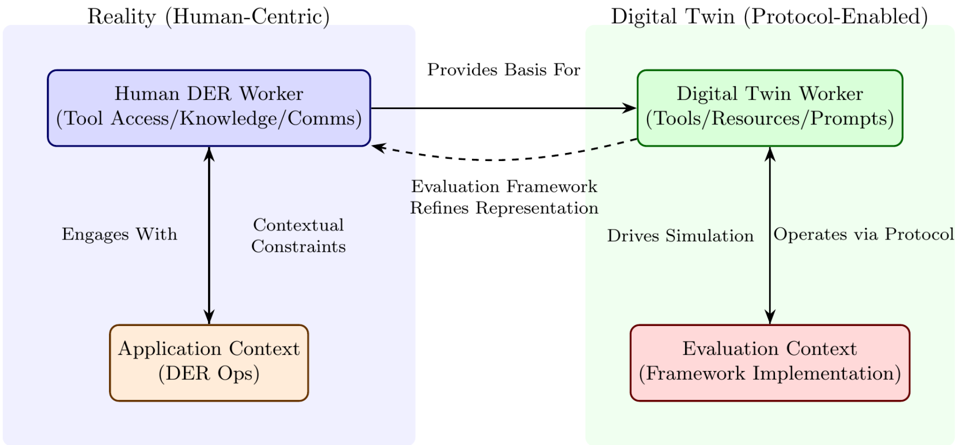

Figure 1: Conceptual Model of Human DER Worker Digital Twins

Application Context: The operational environment where DER systems require behavioral pattern preservation and transfer across distributed locations and stakeholders, characterized by distributed system complexity and real-world operational constraints.

Digital Twin Worker: An agent-based software system that models and replicates human DER worker operational behaviors through structured protocols, featuring tool access layers, AI-driven natural language uncertainty, and agent protocol primitives **interfacing the layers**. The selection of these specific agent protocol primitives is grounded in their complementary capabilities for modeling different aspects of human operational behaviors [14] [15]. The Model Context Protocol (MCP) provides a popular Artificial Intelligence framework for **agent-to-resource** communication, where "tools, resources, and prompt" function analogously to the physical and informational resources that human DER workers utilize in their daily operations (from SCADA interfaces and diagnostic equipment to technical manuals and regulatory databases), while **context requests** parallel human decision-making about which resources to consult, and **context responses** mirror the information gathering and tool utilization patterns that characterize operational behavior [14]. The Agent Communication Protocol (ACP) provides foundational communication standardization for **multi-agent** interactions, while the Agent-to-Agent Protocol (A2A) enables complex interagent collaboration through standardized **task management and message exchange**, potentially modeling coordination patterns between human operators across different organizational domains and technical specializations [15]. These protocols collectively provide the interface layers between the human operational context and digital twin representation, providing new opportunities over current Digital Twin frameworks.

Evaluation Context: As no comprehensive theoretical framework currently exists for evaluating the effectiveness of human digital twins in operational contexts [16] [17], the systematic assessment framework strives to validate HDT effectiveness through fidelity metrics, operational efficiency measures, human factors, or safety outcomes assessment.

4.2 Framework Integration and Theoretical Contributions

The four core concepts operate within a structured interaction model where Human-Centric Reality provides foundational operational behaviors, Protocol-Enabled Digital Twins model and augment human behavioral patterns, bidirectional relationships facilitate learning and refinement, and evaluation frameworks validate effectiveness and drive iterative improvement. This framework addresses the identified gaps in agent protocol composition for human behavioral modeling and dynamic human-AI collaboration models, providing theoretical foundations for protocol architecture design that consider human operational behavior modeling requirements and bidirectional learning mechanisms between human experts and their digital twin representations.

5 Research Methodology

5.1 Methodological Approach

Several alternative methodologies were evaluated for their suitability in addressing the research objectives, notably:

Design Science Research: While offering comprehensive framework development capabilities, this approach was deemed inadequate to address the time constraints and resource limitations identified in methodological limitations analysis. Design science research typically requires extended iteration cycles as demonstrated in digital twin applications [12], ranking lower in feasibility assessment for the current research timeline.

Action Research: Considered for its emphasis on stakeholder inclusion and iterative problem-solving as applied in tacit knowledge elicitation processes [8], but excluded due to lacking systematic framework development capabilities needed for theoretical contribution, and lack of disciplinary requirements for protocol composition analysis.

Grounded Theory: Evaluated for theory development potential following established approaches in knowledge elicitation research [8], but deemed inappropriate given the existing theoretical foundation and the need for multi-disciplinary integration requirements identified in the limitations analysis.

Case Study Methodology: Extensively used in DER and digital twin research as demonstrated across multiple domains [9] [6], but rejected due to limited generalizability beyond specific operational contexts and insufficient capacity for systematic protocol composition analysis required for this research.

Digital Twin Methodology: While highly relevant given the research focus and extensively applied in energy systems [17] [18], this approach was considered too implementation-focused for the current research stage, which requires foundational framework development before moving to full digital twin implementation.

5.2 Selected Methodology

This research employs a combined methodology following established patterns in digital twin research [12] and human factors integration studies [6]. This methodology addresses the nascent validation frameworks for human-centric digital twins [16], limited integration of multi-disciplinary methodologies [17], and insufficient real-world operational context integration [19].

Phase 1: Systematic Literature Review (6-8 weeks): Systematic analysis of protocol composition patterns and integration approaches, focusing on agent protocol primitives in DER contexts and human behavioral modeling techniques. This phase addresses the identified limitation of a lack of multi-disciplinary integration across human factors engineering, digital twin technology, and energy systems management domains.

Phase 2: Compositional Framework Development (8-10 weeks): Building upon Design Science Research principles, adapted for this intersectional context, this phase involves the systematic analysis of how MCP, ACP, and A2A protocols are composed for HDT implementation. It focuses on developing an architectural framework that maps protocol capabilities to different HDT functional layers for modeling human operational behaviors and will define processes for evaluating multi-protocol agent architectures in human-centric applications.

Phase 3: Proof of Concept Development (4-6 weeks): Rapid prototyping based on the framework to demonstrate the feasibility of behavioral modeling from current agent protocol primitives and to validate the framework against operational scenarios.

5.3 Addressing Methodological Limitations

The proposed methodology addresses the limitations identified in Digital Twins research approaches [18] [17]. The combined approach explores various aspects of the new protocol primitives by combining multiple research methodologies. The compositional framework development phase establishes validation frameworks for HDT effectiveness using protocol primitives, addressing consideration of human operational behavior modeling over prior methodologies focused on physical system fidelity.

6 Ethics and Sustainability

6.1 Ethical Considerations

Data Privacy and Human Expertise: The modeling of human expertise necessitates rigorous adherence to established ethical research principles, particularly concerning intellectual property rights and the potential commodification of tacit knowledge. This research will develop and apply consent frameworks for expertise capture, ensuring respectful and transparent representation of human capabilities.

Human-AI Collaboration Ethics: Upholding established ethical standards for human-AI collaboration is paramount. The development of HDTs will be guided by principles that prioritize augmenting human capabilities rather than replacement, to preserve human agency and decision-making authority in critical operational contexts.

Algorithmic Transparency: Agent-based systems must maintain transparency in their decision-making processes to ensure human operators can understand and validate automated recommendations.

6.2 Sustainability Integration

Environmental Dimensions: This research aims to contribute to UN Sustainable Development Goal 7 (Affordable and Clean Energy) by developing frameworks intended to enhance the operational efficiency of renewable energy systems through robust simulation, thereby facilitating more effective integration of distributed energy resources.

Social Sustainability: This research is designed to support workforce development and crucial knowledge transfer, laying stronger foundations for achieving SDG 4 (Quality Education) and SDG 8 (Decent Work and Economic Growth) by advancing simulation frameworks for training and operational support.

Economic Sustainability: Enhanced DER coordination, as potentially enabled by the outcomes of this research, can contribute to reduced operational costs and improved system reliability, thereby supporting the economic viability of energy transitions while preserving valuable human expertise assets.

7 Risk Assessment and Implementation Plan

7.1 Risk Management

- **Complexity of Human Expertise Modeling:** Mitigation through incremental framework development and focus on well-documented expertise domains.
- **Limited Access to Proprietary Protocols:** Mitigation through emphasis on publicly available protocol specifications and academic literature.
- **Literature Quality Variability:** Addressed through systematic quality assessment criteria and multiple validation sources.
- **Rapid Technology Evolution:** Managed through focus on fundamental protocol principles rather than implementation-specific details.

- **Scope Creep:** Mitigation through clearly defined protocol focus and scope reviews.

7.2 Implementation Timeline

Weeks 1-8: Systematic literature review and gap analysis completion (Resource: researcher's access to digital libraries and tooling). **Weeks 9-16:** Compositional framework development and protocol analysis (Resource: technical workstations, institutional access to protocol documentation). **Weeks 17-20:** Proof of concept development and validation (Resource: development environment, expert consultation through institutional channels). **Key Milestones:** Literature review methodology validation (Week 4). Comprehensive gap analysis completion (Week 8). Initial framework architecture design (Week 12). Compositional protocol analysis completion (Week 16). Final framework validation and documentation (Week 20).

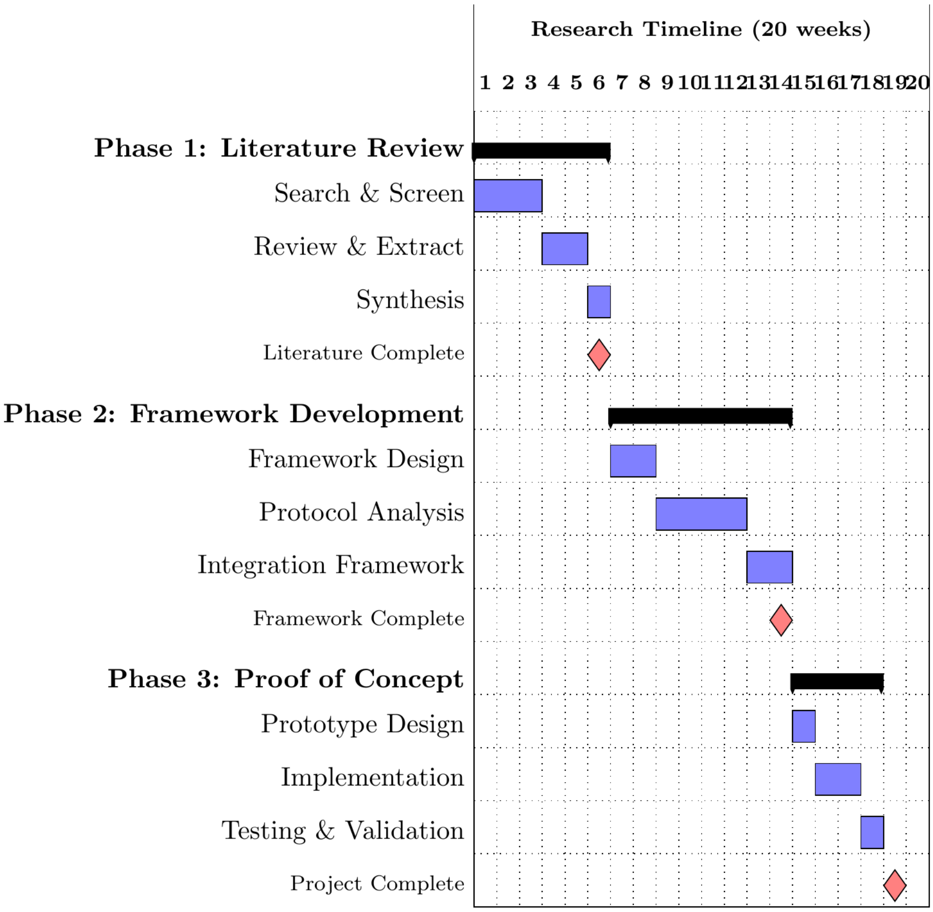

Figure 2: Research Implementation Timeline

8 Expected Results and Contributions

8.1 Anticipated Outcomes

Theoretical Contributions: A validated framework for Human DER Worker Digital Twins that bridges human operational behavior modeling and agent protocol primitives, providing insights into protocol composition for multi-agent coordination in energy systems.

Methodological Contributions: Systematic methodology for evaluating agent protocols in human behavioral modeling contexts, including validation criteria and implementation guidelines for HDT development.

Practical Contributions: Detailed reference for DER industry practitioners seeking to implement human-centric digital twins, including protocol selection, implementation processes, and evaluation frameworks.

8.2 Impact and Significance

The research is expected to advance both the theoretical understanding and practical implementation of human-centered digital twins in energy systems. The framework will provide a foundation for practical value in simulations for DER operators seeking to scale operational behaviors across distributed operations, while offering a look at future research potentials in language-based AI implementations in the energy sector.

The integration of agent protocol primitives with Digital Twin technology represents a novel or unexplored approach to addressing the challenge of preserving and scaling human operational behaviors in energy systems. This research contributes to the broader goal of sustainable energy transition by developing frameworks that could improve the operational efficiency and reliability of distributed renewable energy systems through better preservation of human operational patterns.

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