Cognitive digital twin of an emergency situation based on a hypergraph model of regulatory and methodological data

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***Abstract*—Digital twins are considered a promising tool for intelligent decision support in the management of complex dynamic systems. In the context of emergency situations, their application requires not only modeling the current state of the environment but also interpreting heterogeneous data, analyzing possible scenarios, and generating solutions that comply with applicable regulatory requirements. This work proposes the concept of a cognitive digital twin for emergency situations, which integrates situational awareness data, dynamic simulation tools, a domain-adapted large language model, and a regulatory and methodological knowledge base. A hypergraph model linking regulatory documents to their application contexts serves as the key component of the cognitive loop. A prototype of the system was tested on regional emergency scenarios and achieved an incident classification accuracy of 92% when using agentic search, compared with 67% for classical RAG (retrieval-augmented generation) and 55% for the base language model. The obtained results demonstrate the viability of incorporating a regulatory–cognitive loop as a component of a digital twin for emergency situations.**

***Index Terms*—digital twin, emergency situation, artificial intelligence, large language model, decision support system**

I. Introduction

The management of emergency situations represents a class of problems wherein the system state is subject to continuous change under the influence of numerous interacting factors, and decisions must be rendered under significant limitations of time, information, and available resources [1], compounded by high levels of ambiguity in the incoming data [2]. In this context, the consequences of incorrect decisions can be severe, and the response strategies employed are required to comply with regulatory provisions across multiple governance tiers-ranging from the federal level down to regional and local authorities [3].

One of the promising approaches to managing such systems is the use of digital twin technology [4], [5]. In general, a digital twin creates a digital representation of a real-world object or process, acquires data on its current state, and enables the analysis of possible future developments [6]. In the context of emergency situations, the object of the digital twin is not a static physical system but rather a dynamically evolving set of events, resources, participants, and managerial decisions [7].

For such a problem, a classical digital twin based solely on numerical modeling and structured data is insufficient. A substantial portion of information about an emergency situation is presented in unstructured form: operational reports, textual descriptions of incidents, regulatory documents, and methodological guidelines. Therefore, a digital twin for emergency situations must incorporate a cognitive loop capable of interpreting natural language information and linking the state of the simulated situation to available response algorithms [8].

A particular challenge is posed by the regulatory support of decisions. The regulatory and methodological framework of the disaster medicine service includes documents at various levels of regulation, which may have overlapping content but differ in their scope of applicability [9]. Simple semantic matching of a query against document texts does not reliably determine which regulatory source should be applied in a given situation [10].

In this work, we propose to consider the regulatory and methodological framework as a regulatory–cognitive loop of the digital twin for emergency situations. Its task consists in the dynamic formation of an information environment that corresponds to the current context of the emergency and in providing the operator with normatively justified recommendations.

II. Materials and methods

A. Concept of a digital twin for emergency situations

The proposed digital twin for emergency situations has a hybrid architecture that combines two interconnected loops [11].

The first loop is concerned with the dynamic representation of the emergency state. It incorporates incoming structured and

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unstructured data, information on forces and resources, geographical objects, and incident characteristics. On this basis, a digital representation of the current state of the emergency situation is formed and, prospectively, simulation of possible development scenarios is performed.

The second loop is cognitive in nature. It provides semantic interpretation of incoming information, determination of the situational context, retrieval of applicable regulatory and methodological materials, and generation of recommendations for the operator. At its core, it employs a domain-adapted large language model [12], [13].

The interaction between the two loops allows the digital twin to be viewed not merely as a means of visualization or simulation of an emergency situation, but as an intelligent system that links the state of the emergency, regulatory constraints, and possible managerial actions.

At the same time, the operator retains the function of making the final decision, while the digital twin serves as a tool for analysis and the preparation of well-founded action alternatives.

B. Regulatory-cognitive loop

To implement the regulatory loop, a database of 1 239 regulatory and methodological documents at the federal and regional levels was compiled, containing 246 507 semantic fragments. Each fragment was associated with contextual attributes, including region, emergency type, executor role, and response stage.

The regulatory space was represented as a hypergraph $\mathcal{H} = (\mathcal{C}, \mathcal{E})$, where $\mathcal{C}$ is the set of semantic fragments of regulatory and methodological documents, and $\mathcal{E}$ is the set of hyperedges that group fragments according to common contextual features [10].

Such a representation enables a transition from independent storage of regulatory documents to a contextual model of the regulatory space. As the characteristics of the emergency situation change, so does the set of regulatory materials considered by the digital twin as potentially applicable.

The cognitive loop employs a two-stage processing pipeline. At the first stage, the language model determines the characteristics of the current situation, including the type of emergency, territory, executor role, and response stage [14]. At the second stage, retrieval of regulatory information is performed within the corresponding fragment of the hypergraph [15].

This implements the principle of separating semantic relevance from normative applicability. A document must not merely be similar to the query in terms of content but must also correspond to the context of the specific emergency situation.

III. Results

Based on the proposed architecture, a prototype of an intelligent decision support system for the disaster medicine service has been developed. The system allows the operator to formulate a query in natural language, after which it performs situation analysis, retrieval of regulatory grounds, generation of recommendations, and identification of medical organizations and forces that can be involved in emergency response. The final decision remains with the human operator.

The system operates locally, without transmitting processed information to external services. The language model employed is Qwen3-32B, and a two-level FAISS index is used for vector search.

The prototype's performance was evaluated on real regional scenarios that required classifying the incident and generating a substantiated recommendation with references to regulatory documents and a list of medical organizations.

The emergency classification accuracy reached 92% when using agentic search [16], 67% when using classical RAG with filtering [17], and 55% when using the base language model without additional context.

The obtained result demonstrates that the inclusion of a specialized regulatory-cognitive loop significantly affects the system's ability to interpret the situation and select applicable response algorithms.

The practical value of the approach lies in reducing the time required to search for the necessary regulatory algorithms, mitigating the risk of using incorrect documents, and enhancing the transparency of recommendations by providing references to regulatory grounds.

IV. Conclusion

An architecture of a cognitive digital twin for emergency situations is proposed, combining a digital representation of the dynamically changing environment with an intelligent regulatory-cognitive loop.

Unlike approaches in which the digital twin is used primarily for monitoring and modeling the state of an object, the proposed architecture enables the connection of the current emergency state with regulatory constraints and possible management actions. The key mechanism enabling this interaction is a hypergraph model of regulatory and methodological knowledge, which allows the formation of a context-relevant regulatory space.

The developed prototype of the decision support system demonstrated an emergency classification accuracy of 92% on regional scenarios when using agentic search, which surpasses the results of classical RAG and the base large language model. The obtained results confirm the promise of the regulatory-cognitive loop as a key component of a digital twin for emergency situations.

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