Cyberphysical Intelligence as AI-Driven CRIS Infrastructure: Adaptive Metadata Generation and Governed Interoperability in Forensic Psychiatry

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Abstract

This paper proposes Cyberphysical Intelligence (CPS-I) as a new way of thinking about Research Information Systems (CRIS) in forensic psychiatry. Rather than serving solely as repositories of finalized research outputs, CRIS are here approached as active infrastructures capable of supporting both clinical activity and the continuous production of research-relevant data. In this perspective, CPS-I functions as a transformation and representation layer, converting ongoing multimodal cyberphysical streams into structured, derived research information objects.

By combining digital twins, extended reality (XR), and AI-driven semantic enrichment, the framework enables the dynamic generation of metadata while maintaining controlled and traceable forms of interoperability. Particular attention is given to the constraints inherent to forensic psychiatric settings, where ethical, legal, and security considerations shape how data can be structured, accessed, and shared. Within these boundaries, CPS-I aligns with FAIR principles at the level of metadata and derived representations.

More broadly, the framework suggests a shift in how CRIS infrastructures are conceptualized: from static registries toward dynamic, epistemic environments capable of capturing embodied, real-time processes. This evolution remains compatible with CERIF standards, while extending their scope to domains where research unfolds as a continuous, situated, and tightly governed activity.

1. Context and Motivation

The present work is grounded in an ongoing initiative titled CIINEF (Centre d'immersion et d'intégration numérique forensique / Center for Immersion and Integrated Forensic Digital Systems), currently being developed at the Institut national de psychiatrie légale Philippe-Pinel (INPLPP) in Montreal, Canada. CIINEF aims to operationalize a Cyberphysical Intelligence (CPS-I) framework to support both high-resolution forensic research and clinical intervention in extended reality (XR) environments (Brideau-Duquette et al., 2025).

Current Research Information Systems (CRIS) are vital infrastructures for research documentation, evaluation, and collaboration. However, they often struggle to represent dynamic, real-time, embodied research processes, particularly in high-stakes domains like forensic psychiatry. We propose a novel vision of CRIS rooted in Cyberphysical Intelligence (CPS-I): a dual-purpose system deployed to both support adaptive psychiatric care and generate structured, research-grade information from XR-based clinical environments. This architecture is currently under development and early deployment at the Institut national de psychiatrie légale Philippe-Pinel (INPLPP, Montreal, Canada), a leading forensic psychiatry hospital in the use of XR technologies.

INPLPP is a high-security, university-affiliated institution specialized in the treatment, supervision, and rehabilitation of individuals with severe mental disorders and a history of violence. It combines clinical, legal, and public safety mandates while supporting interdisciplinary research. This setting presents unique challenges in balancing ethical data governance, safety-critical monitoring, and openness to the research community.

2. Core Concepts and Definitions

Cyberphysical Systems (CPS) refer to the integration of computation, networking, and physical processes (Chen et al., 2021; CPSWG, 2017; Lee, 2008). Sensors and actuators interface with software to interact with the physical world in real-time. Classic examples include self-driving cars, industrial robotics, smart grids, and assistive exoskeletons. In all cases, feedback loops between sensing, computation, and action are central.

Cyberphysical Intelligence (CPS-I) expands upon CPS by incorporating AI-driven reasoning, adaptive feedback, and data-aware governance into these systems. It emphasizes embodied and situated interaction, as well as the ability to generate insights, predictions, and real-time regulatory support. In psychiatry, this includes using XR environments, biometric data, and behavioral modeling to support both care and research.

Digital twins (DT): A digital twin is commonly defined as a dynamic, computational representation of a real-world system, continuously updated through data streams to reflect its current state, model its evolution, and explore future scenarios. In industrial contexts, digital twins are used to simulate system behavior, anticipate maintenance needs, or test control strategies without intervening directly on physical assets. When applied to human-centered systems, the digital twin shifts from a mechanical replica to a trajectory-based model of situated behavior, integrating physiological signals, actions, and contextual variables over time. Within the CIINEF initiative at the Institut national de psychiatrie légale Philippe-Pinel, this concept is applied to forensic psychiatry: the digital twin is conceived as a living representation of a patient's regulatory, perceptual, and interactional patterns, informed by immersive XR environments and multimodal sensing. Rather than serving as a static profile or predictive score, it functions as a supportive "shadow" within a cyberphysical system, enabling fine-grained research analysis and the adaptive, ethically governed support of clinical care and public safety (Barricelli & Fogli, 2022; Nguyen, 2022; Spitzer et al., 2023).

Presence is the subjective experience of “being there” in a mediated or virtual environment. In our context, presence is treated not only as a psychological state, but as an indexable, physiological and behavioral phenomenon (ISPR, 2000). Eye tracking, head orientation, posture, and heart rate variability are examples of data that reflect levels of immersion and engagement in XR.

Situation Awareness (SA) refers to the ability to perceive, understand, and anticipate the elements of a dynamic environment (Endsley, 1995). Originally developed in aviation and defense contexts, SA is now recognized as crucial in healthcare, training, and XR research. From the patient's perspective within the CIINEF environment, the system helps bring relevant elements of the immediate surroundings into focus through XR augmentation, supporting a clearer perception of what matters in the situation. This facilitates a situated understanding of the environment in relation to the patient's current task, emotional state, and social context, and supports the ability to anticipate upcoming events and possible actions, fostering more stable and regulated engagement (Alsamhi et al., 2024).

Self-Regulation (SR) is the ability to modulate affective, cognitive, and behavioral responses in alignment with environmental demands (Baumeister and Vohs, 2007). For psychiatric patients with impulsivity, psychosis, or violent histories, self-regulation may be unstable or fragile (Billen et al., 2023; Weissman et al, 2019). As part of the CIINEF roadmap at INPLPP, CPS-I is being designed to eventually leverage adaptive sensory environments and digital twin modeling to enable dynamic assessment and scaffolding of self-regulatory capacities.

3. CPS-I: Architecture and Objectives

Cyberphysical Intelligence (CPS-I) refers to an integrated system where patients, clinicians, XR environments, AI agents, and sensor-rich infrastructure form a dynamically coupled feedback loop. The system serves two intertwined missions:

- **Clinical mission**: CPS-I enables fine-grained regulation and behavioral support via embodied feedback in immersive and mixed-reality environments.
- **Scientific mission**: CPS-I generates structured behavioral and contextual metadata through digital twin modeling, allowing real-time analytics, trajectory mapping, and research synthesis.

The architecture includes:

- XR platforms (VR/AR/MR) with programmable scenarios and biometric interfaces;
- Multimodal sensing (for instance: EEG, HRV, gaze, posture, speech);
- AI modules for classification, anomaly detection, and prediction;
- A digital twin layer continuously updated with semantic annotations;
- Secure data pipelines with role-based access, traceability, and audit logs.

Together, these components form a tightly coupled cyberphysical loop in which sensing, research information generation and clinical action are co-produced rather than sequentially separated.

The AI modules embedded in CPS-I serve a dual function: (1) real-time behavioral classification and anomaly detection for clinical support, and (2) automated generation of research-grade metadata through semantic enrichment of multimodal streams. This positions CPS-I as an AI-driven CRIS infrastructure where machine learning actively contributes to metadata quality, ontological alignment, and interoperability - core challenges identified in the AI4RIS working group.

4. Presence, SA, and Digital Twin-Based Instrumentation

CPS-I treats embodied presence and SA as key indicators of patient stability, used both for real-time therapeutic feedback and as research variables. These are operationalized through:

- Real-time tracking of embodied interaction within real and XR worlds;
- Physiological coupling and temporal synchronization across modalities;
- Embedding of extracted features in a live digital twin model, forming a behavioral knowledge graph over time.

Self-regulation emerges as a dynamic property inferred through fluctuations in presence and SA levels. For instance, dropouts in attentional engagement, freezing behaviors, or mismatch between gaze and task can be used to trigger regulatory feedback in XR.

Within CPS-I, presence and situation awareness are not treated as static constructs but as temporally evolving indicators that mediate the coupling between embodied experience, regulatory capacity, and system-level adaptation.

5. Interoperability and FAIR/CERIF Alignment

The CIINEF cyberphysical intelligence framework can be understood as a boundary case for contemporary CRIS and CERIF-based (Common European Research Information Format) research information infrastructures. Rather than treating continuous biometric and XR data streams as datasets to be integrated into a CRIS, the proposed architecture deliberately positions them as governed cyberphysical traces, whose informational status is mediated through CERIF-compliant research information objects.

From this perspective, CERIF is not extended to host primary data. Instead, it is used to formally represent the existence, provenance, semantic type, derivation logic, temporal scope, and access conditions of dynamic, high-sensitivity behavioral streams. Digital twin–derived states, trajectories, and aggregated indicators are therefore modeled as secondary research information entities. This enables interoperability while preserving the distinction between operational cyberphysical data and research information.

FAIR (findable, accessible, interoperable, reusable) principles are implemented at the level of metadata, semantic relations, and derived representations, rather than through the exposure of raw biometric traces. Findability, interoperability, and reusability are preserved through standardized identifiers, event-level semantics, and explicit governance constraints, while accessibility remains strictly conditional and role-based. In this sense, the approach aligns with the Barcelona Declaration on Open Research Information by operationalizing openness through design transparency and semantic interoperability, rather than unrestricted data access.

From a CRIS perspective, this architecture raises concrete implementation challenges, which are addressed through a phased experimental roadmap. These include the definition of CERIF-compatible descriptors for dynamic embodied interaction, the modeling of digital twins as modular epistemic objects within CRIS environments, and the development of middleware services supporting secure, auditable, and role-sensitive access to behavioral metadata. Integration with institutional and open CRIS infrastructures is therefore conceived as selective and layered, preserving the logic of open research information while respecting the legal, ethical, and security constraints intrinsic to forensic psychiatry.

This architecture demonstrates how specialized, security-sensitive CRIS implementations can actively contribute to open research infrastructure ecosystems. By operationalizing the Barcelona Declaration through design transparency, standardized semantic layers, and selective but governed data exposure, CIINEF offers a model for sectors where full openness conflicts with ethical or legal constraints - yet where research interoperability remains essential.

The digital twin's structured behavioral states are mapped to CRIS entities using extended event ontologies, enabling incorporation into institutional and open research information systems. Compatibility with CERIF, FAIR, and the Barcelona Declaration on Open Research Information is preserved at the metadata and design level, even where full data exposure is not feasible (Jörg, 2010).

6. Roadmap and Governance

The CPS-I roadmap involves three deployment stages:

1. **VR Laboratory Trials**: Controlled assessment of perceptual and regulatory thresholds;
2. **Mixed-Reality Clinical Integration**: Real-time feedback and twin refinement in psychiatric wards;
3. **Community-Based Ambulatory Monitoring**: XR overlays, wearable sensing, and behavioral prediction in real-world settings.

Throughout, cybersecurity governance ensures secure identity management, encryption, threat modeling, and breach mitigation - guided by an interdisciplinary board (clinicians, technologists, ethicists, legal advisors). Role-based access and audit trails ensure full compliance with both institutional policies and research oversight.

This roadmap reflects a deliberate progression from controlled experimental settings toward ecologically valid deployment, while maintaining continuous governance and security oversight.

7. CRIS as Epistemic Infrastructure

By integrating CPS-I systems with CRIS logic, we envision a future where CRIS are no longer passive registries but semi-autonomous epistemic environments able to:

- Generate real-time metadata linked to experimental timelines;
- Dynamically update data models from embodied interaction;
- Support situated, ethically governed research.

This vision is consistent with both the FAIR data principles and the Barcelona Declaration, while explicitly accounting for the limits of openness in security-sensitive, psychiatric-legal domains (Kramer, Neylon and Waltman, 2024).

Beyond metadata generation, CPS-I enables the development of novel, ethically grounded assessment metrics for forensic psychiatry research - tracking not only outputs but therapeutic trajectories, behavioral stabilization indicators, and safety outcomes in ways that respect patient dignity while informing evidence-based practice.

8. Conclusion

Cyberphysical Intelligence constitutes a next-generation approach to adaptive research infrastructure in forensic psychiatry. Through digital twins, XR, and secure AI feedback, CPS-I platforms enable the co-production of clinical insight and research data within one unified, ethically accountable system. Their integration into the CRIS ecosystem requires new modes of semantic modeling, metadata interoperability, and governance but holds vast potential to reshape the role of CRIS in clinical research, especially in psychiatry, rehabilitation, and public safety contexts.

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