CPHS–XR: A Unifying Framework for Understanding Cyber Physical Human Systems in the Realm of Extended Reality

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Abstract. As digital, physical, and human systems continue to converge, the vocabulary used to describe these integrations has become increasingly fragmented. Terms such as Human Computer Interaction, Human Machine Interaction, Cyber Physical Systems, Human Extended Reality Interaction, and Cyber Physical Human Systems (CPHS) describe varying system configurations in which humans, technologies, and environments interact to achieve shared goals. However, the proliferation and overlapping use of these terms have introduced conceptual ambiguity, complicating system comparison, evaluation, and design. This paper introduces the CPHSXR framework as an enhanced and structured extension of CPHS. While grounded in the foundational tripartite structure, which comprises cyber, physical, and human components, CPHSXR adds conceptual clarity by introducing technology enablers as cross-cutting elements that empower system components without altering their core integration. These enablers, such as extended reality, artificial intelligence (AI), Internet of Things, and perceptual technologies, give rise to diverse system behaviors, resulting in variations like immersive, adaptive, predictive, or actuated CPHS. Building on this foundation, the paper proposes a taxonomy based on three dimensions: immersion level, decision-making level, and granularity assignment. This taxonomy provides a systematic method for classifying CPHS variations as empowered configurations rather than as disconnected or standalone system types. By simplifying terminological complexity and contextualizing system evolution, the framework supports system classification, design, and analysis across domains. It also lays a foundation for future research in human-centered AI, immersive interfaces, and adaptive systems by ensuring that emerging technologies enhance rather than

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fragment the integration between human operators and cyber-physical systems.

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1 Introduction

The rapid advancement of interactive technologies, intelligent systems, and immersive interfaces has led to the emergence of numerous overlapping terms in academia and industry. Concepts such as Integrated Intelligent Systems (IIS) [59], Human Computer Interaction (HCI) [7], Human Computer Agent Interaction (HCAI) [38], Human-Machine Interaction (HMI), Cyber-Physical Systems (CPS) [60], Human Extended Reality Interaction (HXRI) [8,27], and Cyber-Physical Human Systems (CPHS) [2,42,58] have all been used to describe variations of systems in which humans, technologies, and physical environments interact. While each term originated in response to a specific disciplinary focus or application domain, these conceptual boundaries have become increasingly fluid, ranging from automation and industrial control to immersive simulation and human-centered artificial intelligence (AI).

This fluidity has led to overlapping terms that often obscure rather than clarify understanding. Yet confusion also stems from inconsistent definitions of individual terms across disciplines and authors. For instance, CPHS is defined in fundamentally different ways: some perspectives treat the human as an external operator [46], while others position the human at the center of the system with an active, decision-making role [2,55]. Some definitions even treat AI as an essential component that links CPS to the human operator [41]. Terminological conflation compounds this inconsistency. CPS and CPHS are frequently used interchangeably, despite the latter's explicit inclusion of the human component [50,57]. Likewise, the distinction between HCI and HMI is often overlooked, even though their system contexts and interaction modalities differ significantly. The rise of extended reality (XR) technologies such as virtual reality (VR) [18,44], augmented reality (AR) [25,34], and mixed reality (MR) [6,53] has introduced yet another layer of complexity, as interactions shift from traditional screens to spatial and embodied environments, giving rise to terms such as HXRI [27,28]. At the same time, AI-enhanced automation has transformed CPS into what many now call Integrated Intelligent Systems (IIS) [32,43], further blurring conceptual boundaries.

AI [21,31] refers to data-driven, learning-based system capabilities that allow adaptive responses based on input, context, or user behavior. This includes technologies such as machine learning models, intelligent agents, and large language models [9,33]. In contrast, traditional control systems such as rule-based algorithms or PID controllers [5,23,40] operate using predefined logic and do not adapt over time. Although both approaches can enhance system automation, AI introduces a capacity for learning and adjustment that expands how systems perceive, decide, and interact. Because the term *AI* is often used inconsistently across fields, sometimes even describing non-learning controllers, it is important to clarify this distinction. In the context of CPS, CPHS, HCI, and HMI, AI in this paper refers specifically to learning-driven intelligence that supports dynamic and context-aware system behavior.

1.1 Objectives and Contributions

This paper has three key objectives that together address the existing conceptual ambiguity in CPHS terminology, propose a unifying framework, and present a structured taxonomy. In doing so, the paper contributes both a clarified conceptual model and a practical classification scheme to guide future research and system design.

– First, to clarify the overlapping and inconsistently used terms describing human-machine-digital systems such as CPS, IIS, HCI, HMI, HXRI, and CPHS by mapping them to their foundational components and distinguishing their boundaries.
– Second, to propose a coherent framework for describing increasingly complex systems that integrate AI, XR, Internet of Things (IoT), and perceptual technologies, enabling clearer understanding of their roles in shaping human-machine interactions.
– Third, to apply this framework to create a structured taxonomy of CPHS variations based on how specific technological enablers influence and define system components.

2 The CPHSXR Framework

The accelerating convergence of intelligent, interactive, and immersive technologies has resulted in significant conceptual overlaps in how human, cyber, and physical systems are described. This section first unpacks this conceptual chaos, exploring how these terms have proliferated across disciplines, and then introduces the CPHSXR framework as a systematic approach to unify and clarify this evolving terminology.

2.1 Conceptual Chaos

CPHS represent an emerging paradigm where humans, physical components, and cyber technologies are interconnected through dynamic and reciprocal interactions to achieve shared goals. This stands apart from earlier models that treated the human as an external operator rather than an integrated system element [65]. Understanding CPHS requires examining different human roles in system interaction, including frameworks like human-in-the-loop (HITL), which emphasizes real-time human input in operations and decision-making. Despite the conceptual distinction, CPHS and HITL are often used interchangeably in the literature. Some sources even define CPHS as a HITL configuration [64]. This framing, however, fails to capture the broader potential of CPHS, which includes long-term adaptation, contextual awareness, and variable autonomy.

The rise of immersive technologies like augmented, virtual, and mixed reality [36,45] has added complexity, shifting interactions into spatial and embodied domains and inspiring terms such as HXRI [26]. In parallel, AI has played a key role in transforming CPS [4,51] into adaptive systems that blur the lines between existing definitions.

To clarify this transformation, we define AI in this paper as learning-based, data-driven components that include machine learning algorithms, intelligent agents, and large language models. This contrasts with traditional control systems that rely on fixed rules or model-based algorithms such as PID controllers. Classical control systems do not adapt beyond their programmed logic. AI components, on the other hand, adjust over time, respond to new contexts, and support personalized or autonomous behavior. This distinction is necessary, as some literature labels advanced but non-learning controllers as AI, leading to confusion.

Further complexity arises from adjacent terms. HCI focuses on digital interfaces like graphical user interfaces, touchscreens, and voice systems [54]. It is primarily concerned with usability, feedback, and interface design in computing environments. HMI, in contrast, involves engagement with physical systems such as industrial robots or vehicles. These interactions often use tactile controls, haptic feedback, or supervisory interfaces. As AI and multimodal technologies become embedded in these systems, the nature of interaction changes. Machines begin interpreting, adapting to, or anticipating human input, raising the question of whether traditional definitions of HCI and HMI still apply.

To describe these developments, terms such as Augmented HCI (A-HCI) [63] and Augmented HMI (A-HMI) [56] can be introduced. These refer to systems where AI-driven features reshape traditional modes of interaction. Similarly, HXRI refers to immersive human-system engagement enabled by XR and intelligent technologies. Although it shares similarities with HCI and HMI, HXRI emphasizes enhancing human perception and presence across digital and physical spaces.

These growing complexities prompt a broader question for CPHS research. When systems incorporate XR, AI, IoT, or advanced sensing, do they still align with traditional CPHS definitions? While these technologies do not alter the foundational architecture, they act as enablers that enhance how system components behave, interact, or adapt. Such enablers include immersive displays, machine learning models, sensor networks, and perception tools like computer vision and natural language processing. These are not standalone pillars of the system but augment existing components by adding new functionality or interaction capabilities.

This conceptual challenge highlights the need for a framework that retains the core structure of CPHS while systematically accounting for how emerging technologies reshape it. The CPHSXR framework was developed in response to this need and offers a clearer structure for understanding next-generation interactive systems.

2.2 CPHSXR: A Unified Conceptual Framework

Building upon the conceptual ambiguity outlined earlier, we now introduce the CPHSXR framework, which integrates the principles of CPHS with the immersive capacities of HXRI. At its core, CPHSXR retains the tripartite structure of cyber, physical, and human components that underpins related terms such as CPS, CPHS, HCI, and HMI.

Figure 1 presents a four-set Venn diagram that visualizes this framework. While the core triad remains the structural foundation, a fourth set, *Enabler*, is introduced to represent technologies such as XR, AI, IoT, or perceptual tools. These enablers do not constitute a new system component; rather, they function as augmentative layers that enhance the behavior, interaction style, or capabilities of existing CPHS elements without altering the system's core architecture.

This framework helps clarify how different system types emerge when one or more CPHS components are empowered by immersive, adaptive, or analytic technologies. For instance, integrating AI into the cyber domain enhances autonomy and intelligence; applying XR to the human interface creates HXRI; and embedding IoT or computer vision into physical systems enables real-time responsiveness and data-rich interaction.

Rather than proposing a new structural model, CPHSXR offers a systematic lens for examining how emerging technologies transform CPHS configurations. It facilitates design scalability and provides a shared vocabulary for analyzing and constructing interactive systems across domains. The following section builds on this conceptual foundation by introducing a taxonomy that classifies these variations according to which components are technologically empowered and how.

3 A Taxonomy of the CPHSXR Framework

This section introduces a structured taxonomy that organizes the CPHSXR framework. Each dimension reflects a distinct lens through which CPHSXR can be analyzed, enabling a systematic understanding of how these systems are composed, how they function, and the environments in which they operate. The dimensions describe the configuration and interaction logic that define how CPHS systems are built and how their components are empowered:

- *Immersion Level*: the degree of perceptual immersion experienced by the human user (e.g., screen-based vs. fully immersive XR).
- *Decision-Making Level*: the allocation of decision authority across human and machine agents (e.g., human-in-the-loop vs. autonomous).

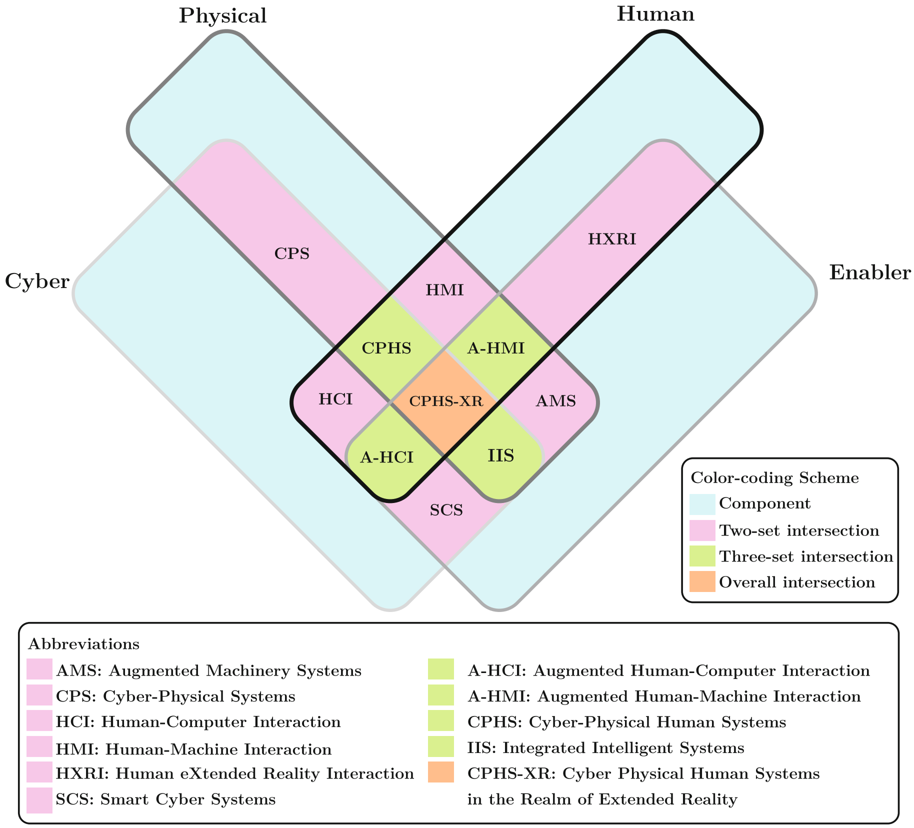

Fig. 1. The CPHSXR framework visualized as a four-set Venn diagram. The core tripartite system is preserved as the structural foundation, while the *Enabler* set overlays these components to illustrate how various system types emerge through their empowerment.

– *Granularity Assignment*: the unit of control or analysis applied to each component (e.g., individual, team, or subsystem level).

In what follows, we detail the three dimensions that constitute the foundation of the CPHSXR taxonomy.

The immersion level describes the extent to which the human user is perceptually engaged in the system. This dimension captures the interface quality and the depth of human engagement, ranging from passive observation to fully embodied interaction in virtual environments. We classify immersion into three primary levels: non-immersive, where interactions occur through traditional interfaces such as keyboards and 2D displays; semi-immersive, involving partially spatial or 3D visualized interfaces such as stereoscopic displays; and fully immersive, where XR technologies such as VR, AR, and MR provide the user with a sense of situational awareness [12,47,48,66]. This dimension allows us to situate HXRI as a class of interfaces rather than as a separate system type. For example, a CPHS used in industrial training might feature a fully immersive XR interface (e.g., a VR-based welding simulator), whereas a medical device interface might remain semi-immersive, involving a 3D rendering on a screen but limited bodily engagement. This framing enables distinctions between immersive and non-immersive CPHS configurations while maintaining consistency within the core structure [39,46].

The decision-making level addresses the distribution of authority and autonomy within the system, that is, the human's role in initiating, guiding, or responding to system actions. This dimension is central to understanding the complexity of HITL configurations and system responsiveness. We categorize decision-making along a continuum that includes: manual control [11], where humans perform all decisions; supervisory control [1,16,19], where the human oversees and intervenes selectively; shared or traded control [14,15,61], in which authority shifts dynamically between human and system components; and full autonomy [3], where the system operates independently with little or no human involvement. For example, in a shared-control surgical robot [49,62], the surgeon might guide motion while the system maintains stability and avoids collisions-illustrating traded decision authority. In contrast, autonomous delivery drones may operate under full autonomy but still allow human override in rare or emergency cases. This dimension captures such variations and situates them consistently within CPHS analysis.

Granularity assignment refers to how tasks are distributed between humans and system components, as well as the timing and handoff of responsibilities [29]. It captures who does what, and when that control shifts, especially across time scales ranging from moment-to-moment actions to long-term monitoring or strategic supervision [17]. This dimension is particularly useful for characterizing systems with temporal role shifts, such as those where the human initiates an action that the system later completes, or vice versa. We distinguish between atomic granularity [10] (e.g., continuous real-time input like joystick control), procedural granularity [52] (e.g., stepwise multi-stage tasks), and strategic granularity [22] (e.g., the human defines the goal but delegates execution to the system). Consider a CPHS used in aerospace: the human pilot may initiate takeoff procedures (procedural granularity), monitor altitude (strategic oversight), or intervene directly in turbulent conditions (atomic). The framework allows us to label and classify these interaction patterns with clarity [13,20].

These three dimensions provide a flexible and systematic lens through which CPHS variations can be analyzed and classified. By combining these dimensions, system designers and researchers can capture both structural configurations and technological enhancements, offering a richer understanding of system behavior and interaction dynamics. This approach results in a classification scheme supporting both system analysis and design exploration within the CPHSXR framework.

4 Discussion

This paper systematically unpacks the conceptual confusion surrounding CPHS and related terminologies, offering the CPHSXR framework as a structured solution. Through the proposed taxonomy, we provide a lens to classify CPHS variations along key dimensions that capture system structure, human roles, and task granularity. This unified approach allows researchers and designers to better navigate the fragmented landscape of human-cyber-physical integration.

The CPHSXR framework also provides a valuable lens through which to reinterpret dominant industrial paradigms such as Industry 4.0 and Industry 5.0. From the CPHSXR perspective, Industry 4.0 can be framed as a CPHS configuration heavily weighted toward Cyber and Physical elements, often enhanced through intelligence enablers (e.g., AI, IoT, analytics), but typically with limited or peripheral human engagement [24,35]. Human operators are frequently positioned in supervisory or on-the-loop roles, overseeing largely autonomous or automated processes. In contrast, Industry 5.0 introduces a renewed emphasis on human-centered collaboration, creativity, and personalization [30,37], aligning more closely with the CPHS core where Human components are meaningfully integrated alongside Cyber and Physical elements, often enhanced by interface enablers (e.g., XR, HXRI, HITL-based AI systems). The *Enabler* layer in CPHSXR serves to explain how systems evolve from Industry 4.0 configurations into more human-centered Industry 5.0 variations, without altering the foundational CPHS structure. In this way, CPHSXR does not position Industry 4.0 and 5.0 as conflicting paradigms but rather as differently configured CPHS variations, differentiated primarily by the presence or absence of human-centered enablers and the level of human engagement in system decision-making and interaction.

One of the central challenges addressed by CPHSXR is the terminological fluidity that permeates the field. As highlighted throughout this paper, terms such as CPS, IIS, HCI, HMI, HXRI, and CPHS often emerge as the result of disciplinary silos, evolving technologies, and shifting use cases. CPHSXR provides a structured explanation for their existence since these terms are manifestations of different intersections and empowerment strategies applied to the CPHS components. By situating these terms within the set-theoretic structure of CPHSXR, the framework allows for both clarification and contextualization of these terms without discarding them, offering a shared conceptual space where existing vocabulary can coexist while being consistently interpretable. In doing so, CPHSXR reframes the discourse away from terminological proliferation as a problem and toward terminological diversity as a reflection of system configurational richness, now anchored in a common structural foundation.

Beyond its immediate conceptual clarifications, the CPHSXR framework and taxonomy open multiple avenues for future research and practical applications. In education and training, CPHSXR can serve as a teaching scaffold for introducing students to complex cyber-physical-human integrations, helping them grasp both system structure and the evolving role of enabling technologies. In system design, the framework offers a tool for mapping design decisions across dimensions, allowing teams to deliberately choose levels of immersion, decision-making authority, task granularity, and enabling technologies based on user needs, domain context, and desired system behaviors. In the realm of human-centered AI and adaptive systems, CPHSXR provides a language for framing hybrid systems that blend automation with human engagement, supporting responsible AI design practices that foreground transparency, adaptability, and ergonomics. Furthermore, the framework offers potential to support standardization efforts, cross-disciplinary dialogue, and system comparison studies, serving as a neutral yet flexible reference model across domains such as healthcare, manufacturing, defense, and assistive technologies.

In summary, CPHSXR provides not only a conceptual lens to navigate the fragmented terminology and evolving system types in human-cyber-physical integrations but also offers a structured foundation for classifying, comparing, and designing these systems. By grounding diverse system variations in the consistent logic of CPHS components and technological enablers, the framework supports both analytical rigor and design flexibility. The following conclusion distills the key contributions of this work and reinforces the need for a shared conceptual language in this increasingly complex design space.

5 Conclusion

This paper addressed the persistent conceptual fragmentation in the fields of AMS, CPS, HCI, HXRI, HMI and SCS by introducing the CPHSXR framework. Through a systematic exploration of terminological overlaps and emerging system types, we clarified the foundational roles of cyber, physical, and human components, while recognizing the transformative influence of enabling technologies such as XR, AI, IoT, and perceptual technologies. We demonstrated that these technologies, rather than constituting new system components, function as enablers that empower CPHS components without altering the tripartite system architecture. This perspective allowed us to reinterpret a wide array of existing terms such as HXRI, IIS, and SCS within a coherent and consistent structural model. Building upon this foundation, the paper proposed a taxonomy of CPHS variations within CPHSXR, introducing three dimensions: immersion level, decision-making level, and granularity assignment. This allows for systematic classification of CPHS configurations. This taxonomy not only clarifies existing system terms but also supports scalable system design and analysis by enabling nuanced combinations of CPHS components and human roles. By systematically grounding the vocabulary of human-cyber-physical interaction within CPHSXR, this paper offers both conceptual clarity and a practical toolset for researchers, educators, and system designers navigating the increasingly complex space of intelligent, immersive, and interactive systems.

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