Cyber-Physical & Human Systems (CPHS) – A Review and Outlook

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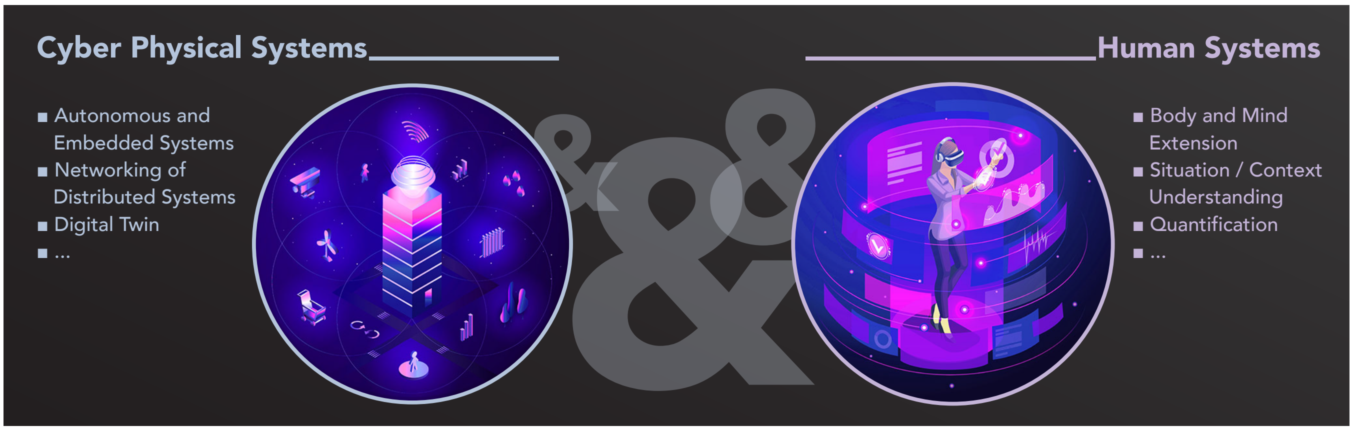

Figure 1: Cyber-Physical & Human Systems (CPHS) are cyber-physical systems (CPS) and human systems that interact on physical and digital levels. CPS are network embedded systems for various applications, such as medical, security, and environmental systems. CPHS enable "hybrid intelligence" [13] where humans and technology leverage upon each other's capabilities, e.g. in assistance systems.

ABSTRACT

This paper explores the concept of Cyber-Physical & Human Systems (CPHS), which consist of cyber-physical computer systems and humans that interact on different levels, physically and digitally. CPHS focuses on two aspects: the cyber-physical system and the human system, and how they are linked by artificial intelligence (AI). This concept applies in various applications, such as medical systems, assistance systems, and environmental systems. Aside from providing a comprehensive overview of CPHS and its related concepts, the paper ultimately contributes a definition and closes with an outlook.

CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile computing**; **Ubiquitous and mobile computing theory, concepts and paradigms**;

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KEYWORDS

Cyber-Physical & Human Systems, artificial intelligence, human-machine symbiosis, digital twin, assistance systems.

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1 INTRODUCTION

Cyber-Physical & Human Systems (CPHS) consist of cyber-physical computer systems and humans. Cyber-Physical Systems (CPS) are distributed or network systems formed by networking embedded systems through wired or wireless communication networks. The multidisciplinary research of CPS covers the following fields of application: medical systems, assistance systems, control-, automation-, and logistics-systems, security systems, systems for influencing and monitoring the environment, communication, and culture, e.g. in the context of a digital twin. CPHS brings in a new perspective, namely the interactions between CPS and humans. The interactions between technology and humans occurs on different levels, physically and digitally in cyberspace and represent the basis of "hybrid intelligence" in which humans use the capabilities of technology and vice versa, such as in modern assistance systems.

Historically grown, the concept of CPHS was established and named in the "First International Workshop on Cyber-Physical-Human System Design and Implementation" [28], which is held annually since May 2016. This demonstrates the timeliness and continuous interest in CPHS.

In this paper, we provide a common definition of CPHS, as it is often used with fuzzy meaning and definitions (Wu [38] vs. Yildiz [39]). In other publications, the concept of CPHS is entirely unknown or they mistake it for HCI[4, 20]. In providing a survey and a theory contribution, we also highlight the differences to related topics and trends. In this discussion, we point out the importance and the legitimacy of CPHS.

2 RELATED TOPICS AND CONCEPTS

There are many concepts in research that intersect with CPHS. It is not absolutely clear how these concepts and research fields relate to each other, demonstrating a potential lack of taxonomy. Therefore, we introduce and define related concepts that we consider as intersecting research topics. These were compiled from a systematic literature review, in which we searched for human aspects in theoretical computing concepts. However, with arising trends and niches, we cannot guarantee a complete review. For each concept, we cite impactful papers that we believe have a meaningful definition.

2.1 Cyber-Physical Systems (CPS)

Although commonalities within the various definitions of CPS exist, each have certain nuances. For instance, Wan et al. define CPS as: *"Cyber-Physical Systems (CPS) integrate computation with physical processes. By merging computing and communication with physical processes CPS allows computer systems to monitor and interact with the physical world."* [35]

In contrast, Baheti and Gill also include the human: *"The term cyber-physical systems (CPS) refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. The ability to interact with, and expand the capabilities of, the physical world through computation, communication, and control is a key enabler for future technology developments. Opportunities and research challenges include the design and development of next-generation airplanes and space vehicles, hybrid gas-electric vehicles, fully autonomous urban driving, and prostheses that allow brain signals to control physical objects."* [2]

In contrast to CPHS, the definition fails to consider the human as the primary focus. The need for the human is not a necessity, although the system can communicate with humans or other systems [22]. In CPS, the human is replaceable and optional: *"[CPHS] contrasts with conventional wisdom, where humans are considered independent entities that are passive and consume, use, or operate these systems."* [39] In the following, we introduce and discuss concepts that showcase how the human can be somewhat interwoven with technology.

2.2 Human-in-the-loop (HITL)

HITL seamlessly integrates the human as a crucial entity in cyber systems [12]. Embedding the human in machine control is close to CPHS, although the human is not stated as a central element Loop defines *"[HITL as] the process of combining machine and human intelligence to obtain the best results in the long-term"* [25].

Similarly to HITL, Jiang et al. defines the term *Human-in-Cognition Manufacturing-Loop*. The difference between HITL and HCML (the term will be explained later) is the utilization of some type of cognitive software and human resources [23]. Here, Artificial Intelligence (AI) technology, more specifically machine learning, is considered as an aspect, while AI is supposedly capable of operating independently. In contrast to these trends, CPHS goes one step further and defines the human as the center of a cyber-physical system.

2.3 Human Computer Interaction (HCI)

The term HCI is comparably old and was first mentioned in 1975 [7]. Meanwhile, we define HCI as *"a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them."* [30]. HCI combines methods of interaction and communication between computer-based system and humans [21]. The quality of HCI is important for the human to understand, access, navigate and enter information [21]. The functionality and usability seems to be a major focus of HCI following the number of empirical contributions published at the premier conference CHI.

The idea of a seamless connection between technology and user was already postulated, such as by Weiser [36]. However, it has only become more realistic with the rise of AI. In CPHS, we see AI as a central and connecting part between both entities.

2.4 Human-Computer-Agent Interaction (HCAI)

HCAI is considered a part of HCI, with a difference of adding an agent. *"We define an agent to be a program that automates some stage(s) of this human-information–processing cycle. This definition does not apply to software-only agents found in multiagent systems and excludes HCIs involving simple direct-manipulation actions or explicit command-line requests."* [24] HCAI could be seen as a pre-step of Human-Robot Collaboration.

2.5 Human-Robot Collaboration / Interaction (HRC / HRI)

Bauer et al. describes HRC as follows: *"As robots are gradually leaving highly structured factory environments and moving into human populated environments, they need to possess more complex cognitive abilities. They do not only have to operate efficiently and safely in natural, populated environments, but also be able to achieve higher levels of cooperation and communication with humans"* [3].

The term interaction in HRI introduces a slight difference: *"Interaction is a more general term, including collaboration. Interaction determines action on someone else. It is any kind of action that involves another human being or robot, who does not necessarily profit from it."* [3]

Both HRC and HRI focus on the communication and cooperation between humans and robots. This can occur on physical and cognitive levels, during the completion of a common task. The relation to CPHS is clearly the collaborative aspect between both entities. However, in CPHS, we see a more seamless connection by using AI, making the robot rather invisible to the user.

2.6 Human-Centered Machine Learning / Artificial Intelligence (HCML / HAI)

Chancellor et al. states: *"HCML combines human insights and domain expertise with data-driven predictions to answer societal questions."* [8]. Here, the human is somewhat integrated in an AI system. The integration of the human in such an AI system is considered a key challenge, since it also involves ethical aspects.

Gillies et al. explains the advantages of HCML as follows: *"Machine learning allows people to 'program' a computer to perform a task by providing examples of how to perform the task [...] A human-centered approach to machine learning that rethinks algorithms and interfaces to algorithms in terms of human goals, contexts, and ways of working can make machine learning more useful and usable."*

The concept of HCML / HAI emphasizes that algorithms must be designed with awareness to improve the usability, trustworthiness, and ethics of AI and ML systems for human users. These aspects are also important for CPHS, but with a focus on the interactions between cyber-physical systems and humans, while using AI as a link.

2.7 Human-Computer Integration (HInt)

"HInt is an emerging paradigm in which computational and human systems are closely interwoven. Integrating computers with the human body" Mueller et al. [27]. *"HInt in the broad sense [is] a partnership or symbiotic relationship in which humans and software act with autonomy, giving rise to patterns of behavior that must be considered holistically."* Farooq and Grudin [17]

Particularly striking is that computers are now envisioned to become invasive in different ways, including the form factor (e.g., wearables, implants,...) and omnipresent tracking and looping back of information into our everyday life's. Some researchers consider HInt as the next step post HCI instead of being a part of it. Certainly, HInt is paving the way to a more seamless CPHS, as the human is integrated within the cyber-physical system. While HInt enables a more implicit interaction and a seamless integration of both entities, we also see in CPHS an explicit collaboration that can also be external to the human.

2.8 Physiological Computing

Another intersecting abstract concept involving the human is called Physiological Computing, which aims to *"employ real-time measures of psychophysiology to communicate the psychological state of the user to an adaptive system"* following Fairclough [15].

This idea links closely to HITL and Adaptive User Interfaces [5], while specifically considers physiological signals, such as brain waves, heart rate, skin conductance, eye movements, etc., as implicit input for computational systems. In CPHS, Physiological Computing can play a significant role in integrating the human into a CPS as a whole.

2.9 Biocybernetic Adaptation / Systems

The concept of Biocybernetic Adaptation or Biocybernetic Systems is closely linked to Physiological Computing. Here, *"real-time psychophysiology is used to capture and to represent an intentional action or state change"*, following Fairclough et al. [16]. In other words, *"Biocybernetic Adaptation involves a 'loop upon a loop,' which may be visualized as a superimposed loop which senses a physiological signal and influences the operator's task"*, following Stephens et al. [33].

Biocybernetic Systems are typically used to adapt visualizations and presentation interfaces to the user [10]. In this form of biofeedback training, the operator can learn to self-regulate their mental state, such as by receiving implicit feedback from the system. In contrast, CPHS have a broader scope as they are not limited to physiological data. CPHS encompasses various types of systems, applications, and domains that involve complex interactions between cyber, physical, and human components.

3 CPHS

Is CPHS seen equally, or is it used as new buzzword in different ways? This section will shed some light different interpretations of CPHS and how the term was historically coined. We start with related definitions and present our own definition, as well as challenges and an outlook on future steps for CPHS.

3.1 Related Definitions

Several researchers and workshops have already dealt with this particular topic, which has also engendered slightly different definitions. To our knowledge, the term CPHS was first mentioned in 2009 by Wing [37]. Since then, an increasing number of researchers became involved with the concept of CPHS. Also, NASA implicitly deals with CPHS, although a definition is not offered. However, NASA describes the importance of the integration of the human with the cyber-physical system, with the primary focus on reducing the cognitive overload [21]. Later on, a workshop at IFAC in 2016 [28] was established. IFAC is one of the leading symposiums in this research field, in which they souhgt to define CPS also. This section showcases the definitions and point out how these definitions evolved throughout the past few years.

- 2009 *"The other type of cyber-physical systems are closed-loop human machine systems, or cyber-physical-human systems. In these systems, a human operator is able to interact with the other elements of the system only if and when needed. The system is a cognitive system, able to learn from the environment, from the human and from itself to make decisions in real-time, but the human remains an integral part of the system's decision-making process."*[37]
- 2012 *"Cyber-Physical-Human [are used] to optimise the overall Quality of Service to benefit primarily human beings in terms of survival, health and safety, and the the protection of nature, property and valuable infrastructures."*[18]
- 2013 *"[CPHS] consists of a loop involving a human, an embedded system (the cyber component), and the physical environment. Basically, the embedded system augments a human's interaction with the physical world. A [CPHS] infers the user's intent by measuring human cognitive activity through body and brain sensors. The embedded system in turn translates the intent into robot control signals to interact with the physical environment on the human's behalf via robotic actuators. Finally, the human closes the loop by observing the physical world interactions as input for making new decisions."* [29]
- 2014 *"Cyber-Physical-Social Systems (CPSSs) is a relatively new research field. Such systems tightly integrate physical, cyber,*

and social worlds based on interactions between these worlds in real time. CPSSs rely on communication, computation and control infrastructures commonly consisting of several levels for the three worlds with various resources as sensors, actuators, computational resources, services, humans, etc. "[31]

2016 Sowe et al. writes: *"Cyber-physical-human systems (CPHSs) consist of interconnected systems (computers, cyber-physical devices, and people) "talking" to each other across space and time, and allowing other systems, devices, and data streams to connect and disconnect."*[32] and collect this information from Smirnov et al. from 2014[31]

2021 Annaswamy and Yildiz at NASA puts the human as a central part in cyber-physical systems. He defines CPHS as *"Cyber-physical-human systems (CPHS) is an emerging field where the human, the physical system, and enabling cyber technologies are interconnected through complex interactions to accomplish a certain goal. This sharply contrasts with a conventional perspective where the human is treated as an isolated element who operates or uses the system."* Annaswamy and Yildiz [1] This fact is important, because the difference between every thing with an human and CPHS is on first sight not obvious.

2016-2022 The workshop series, starting in 2016, was held with the goal to crystallize the upcoming opportunity of growing technology. Although there was no clear definition provided yet, which was still to be shaped throughout the workshop, there were four main topics listed that embody CPHS [28]: [1] Human-Machine Symbiosis (e.g. smart prosthetics), [2] Humans as operators of complex engineering systems (e.g. aircraft pilots, car drivers, process plant operators and robotic surgery), [3] Humans as agents in multi-agent systems (e.g. road automation, traffic management), [4] Humans as elements in controlled systems (e.g., comfort control in homes). Throughout the workshop series, the main topics are expanded. KI and ML become a big part of achieve the main topics. In 2020, the human was granted a more central focus [6]. In 2021, CPHS was stated to be the *"foundation of many emerging applications"*, such as home assistance, healthcare and wellbeing, smart infrastructure, smart manufacturing, and human-robot interactions [9]. In 2022, CPHS was defined as the integration of cyber-physical systems and humans using advanced AI and technology, while the need for new scientific and technical solutions to enable dynamic, seamless, and high-performance interactions and impacts was postulated [11].

3.2 Our Definition

CPHS are systems that consist of interconnected cyber-physical and human elements that interact on physical and digital levels to achieve a common goal. Cyber-physical systems are network embedded systems that use computing, communication, control, and learning technologies for various applications. Human elements are users, operators, or elements that provide input, feedback, or control to the system. CPHS aim to seamlessly link CPS to the human using a layer of AI. While the user is the central focus of CPHS, it can promote implicit symbiotic interactions, though not exclusively. A result of CPHS may be a hybrid intelligence that ultimately enhances the human's capabilities and values in various domains, such as healthcare, manufacturing, transportation, and education.

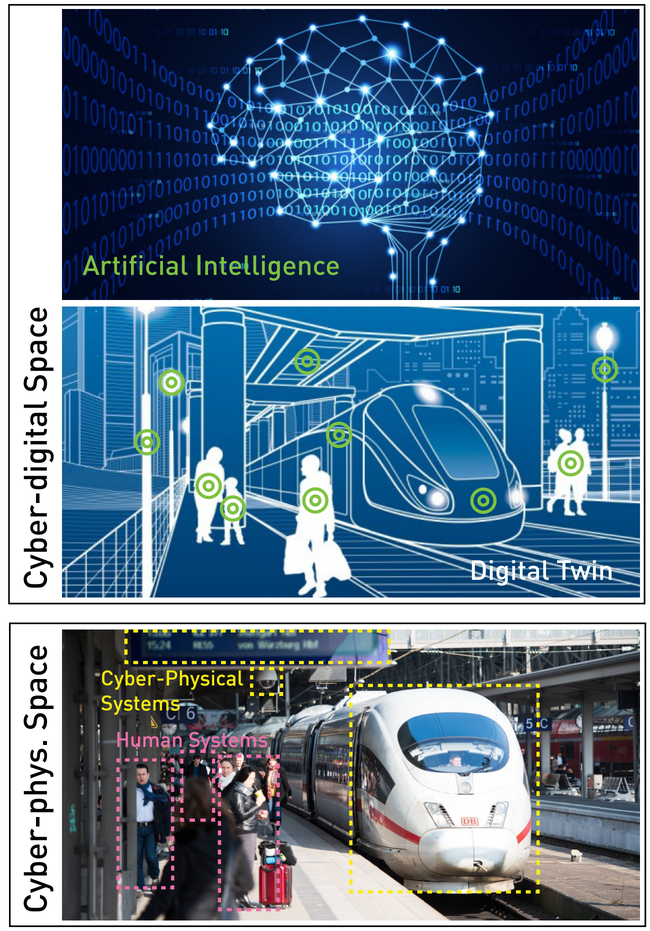

Figure 2: Showcasing CPHS with an example based on a train station, where sensors, actuators, software, infrastructure, and users interact with each other on different levels, in the Cyber-Physical Space and in the Cyber-Digital Space. The implementation of Digital Twins enables an Artificial Intelligence to optimize and adapt both spaces, with the primary goal to maximize the benefit for passengers.

3.3 Example

Envision a train station (*see Figure 2*), where physical and human systems are integrated to provide efficient, safe, and comfortable transportation services.

The *Cyber-Physical System* may consist of a computational component with various sensors, actuators, communication devices, and software systems that collect, process, and exchange data and commands. For example, cameras and RFID readers that monitor the number and location of passengers and luggage. Smart ticketing systems can validate and charge fares. Digital signage and speakers can provide information and guidance. Furthermore, we have a conventional physical infrastructure that enables the transportation of passengers, for example, tracks, platforms, trains, gates, escalators, elevators, etc.

The *Human System* is embodied by the passengers, staff, and operators who interact with the Cyber-Physical System and each other. For example, passengers may enter the platform and board a train, where they implicitly interact with the physical system, while they can also explicitly interact with the Cyber-Physical Space by using their smartphones or smart cards etc.

The interaction between the Cyber-Physical System and the Human System is apparently occurring in the *Cyber-Physical Space*, but not only. Overlaying that, we see a *Cyber-Digital Space* that incorporates a digital / virtual representation of each system [34] based on a great variety of sensor data. These Digital Twins show properties of their corresponding physical entity, such as by certain KPIs [14]. Cyber Physical Systems are not only quantifiable by KPIs but with other additional information also. The same applies to Human Systems. Here, physiological signals from passengers, such as heart rate, skin conductance, facial expression can be used to infer ones emotional state, such as stress, anxiety, satisfaction, etc.

An *Artificial Intelligence* can then make complex decisions by considering the state of all entities and the dynamics of their interrelationships similar to the overarching Cognitive Twin framework [26]. The system can utilize biocybernetic adaptation to modify the Cyber-Physical System or the task based on the inferred state. For example, the system can adjust the lighting, temperature, music, or scent of the station environment to create a more pleasant atmosphere for passengers. The system can also provide personalized information or guidance to passengers based on their preferences or needs.

Learning from experience by machine learning techniques, based on the generated Digital Twins, a CPHS can predict the demand and supply of trains and passengers, and adjust the train schedule and capacity accordingly. The system can autonomously control and regulate the speed of an incoming train and change the platform if too crowded. A real-time response to anomalies or emergencies, such as delays, accidents, faults, etc. can be communicated with the Cyber-Physical Space in various ways, including means of voice-based interaction for passengers and staff. This way, the AI can communicate processed information that may have been undisclosed to the human previously. Conversely, the human also has specific, non-quantifiable senses, such as intuition that the AI can leverage for decision-making. This bidirectional interaction between the computational system and the human is something we understand as hybrid intelligence [13], which CPHS enables. It is imperative that human is always within the primary focus of CPHS and in case of the train station, the primary goal is to ensure a safe and pleasant journey for the passenger.

3.4 Challenges

CPHS face challenges such as understanding human intent and behavior, providing seamless integration and smart assistance, and ensuring ethics, privacy, and security. Specifically, these are challenges to overcome in the future:

Complex heterogeneity: CPHS involve different types of elements, such as physical, cyber, and human, that have different properties, behaviors, and interactions. This makes it difficult to model, analyze, and design CPHS as a whole.

Lack of appropriate abstractions: CPHS require new abstractions and computational theories that capture the essential features and dynamics of the system, while hiding unnecessary details. Existing abstractions and theories may not be suitable or sufficient for CPHS.

Dynamic black-box integration: CPHS often involve dynamic integration of heterogeneous systems that may not be fully known or understood by each other. This poses challenges for ensuring compatibility, interoperability, and coordination among the systems.

Complex requirements: CPHS have to meet various requirements for functionalities, performance, and quality of services, such as reliability, safety, security, efficiency, usability, and adaptability. The requirements may be conflicting or changing over time and context.

Design, implementation, and maintenance: CPHS require new methods and tools for designing, implementing, and maintaining the system to meet the requirements. These methods and tools have to deal with the complexity, uncertainty, and evolution of CPHS.

3.5 Outlook

As technology advances and society evolves, CPHS will become more prevalent and pervasive in our daily lives. CPHS will enable new possibilities and opportunities for enhancing human well-being, productivity, and creativity. However, CPHS will also pose new challenges and risks for ensuring human safety, security, and integrity. Therefore, it is essential to develop a scientific foundation and a practical framework for designing, implementing, and evaluating CPHS that can meet the needs and values of human users in various contexts. Future research on CPHS should address the following aspects:

Developing new abstractions and computational theories that can capture the essential features and dynamics of CPHS as a whole, while hiding the unnecessary details.

Developing new methods and tools for modelling, analyzing, verifying, and testing CPHS properties and behaviors, such as reliability, safety, security, efficiency, usability, and adaptability.

Developing new techniques and algorithms for enabling seamless integration and coordination among heterogeneous systems in CPHS, such as networking, communication, control, learning, and optimization.

Developing new paradigms and mechanisms for enabling smart assistance and interaction between cyber-physical and human elements in CPHS, such as sensing, perception, cognition, emotion, and action.

Developing new guidelines and principles for ensuring ethics, privacy, and social responsibility in CPHS design and use, such as fairness, accountability, transparency, and explainability.

4 CONCLUSION

In this paper, we have (re)defined the concept of cyber-physical human systems (CPHS). We have reviewed the current state of the art, which included related concepts and previous definitions. Ultimately, we conclude with identifying some of the key challenges the future implementation of CPHS face, as well as providing an outlook for future directions.

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