

# Research and Analysis of Human Cyber Physical Systems

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## ABSTRACT

The study of Cyber Physical Systems has gained relevance with recent technological developments. Gone are the days where embedded systems are an adequate description of modern devices. As these systems increase in complexity, the interactions between software and hardware, machine and the environment, and the system with the human component becomes more refined and detailed. Therefore, Human Cyber Physical Systems (HCPS) are an important research topic in recent academia, being a topic that focuses on such relations between machine, humans, and the environment. Through the survey and analysis of much prior research, this article attempts to provide an overview of HCPS through introducing the important aspects of these systems and its connection to the term Industry 4.0. The article will then explore the current framework and design paradigm of HCPS, will summarize new technologies and existing products on the market, and will end with the challenges and future direction of HCPS.

## 1 Introduction

Throughout the ages of technological advancement, the relation between humans and machines has grown ever so complex yet remains a foundational alliance for the purpose of industrial innovation and workplace efficiency. As hardware and software systems increase in complexity with the interactions between each other, the physical world, and the human component, it becomes progressively more important to take a HCPS lens in analyzing existing technological systems and designing new ones [1]. Focusing on the interactions between humans, hardware components, software components, and the environment will not only illuminate the best way to use current technologies, but how to best design future Human Cyber Physical Systems as well.

Existing literature on HCPS mainly focuses on the technical development side, and how improving the cohesion between humans and machines will allow for more advanced HCPS products and processes that will increase workplace productivity, to achieve goals in industry or further technological advancement. As much as these goals are important to society and important for economic gain in the industry, the future of HCPS should center around commercial use by everyday members of the community. The excitement is already beginning to center around technology such as wearable devices, devices for augmented, virtual, or mixed reality, and other devices for personal use. Such systems will only become commercially viable if successfully integrated with the human user in a way that is easy, intuitive, and attractive.

### 1.1 *Background on Cyber Physical Systems and Human Cyber Physical Systems*

Embedded technology has been a central component of many electronic systems, devices, and gadgets that have permeated throughout industrial and commercial use. What elevates Cyber Physical Systems (CPS) as a separate concept is the close interactions between the embedded electronic platform; the sensing, control, computation, and communication algorithms; and the physical and environmental components [1]. The cyber physical interface represents the constraints and boundary between the physical/environmental components with the other two components mentioned above. The explosion of CPS is directly connected to the increasing intelligence of embedded systems, and thus an increased ability to interpret information from the environment in order to more closely interact with the physical surroundings [1].

What separates HCPS with traditional CPS is the closer integration of the human components within the system – a notion called putting humans in the loop [2]. Such systems

must have humans be active participants in the execution of the goal, such as responding to perform maintenance or to a medical emergency, as opposed to passive participants that only are responsible for making observations [2]. HCPS must focus on the human perspective, and the people skills necessary to fully collaborate with the hardware and software components of the system. These systems have four main submodules: the entity that is controlled, the human operator, the autonomous controller, and the supervisory system acting as the boundary connection between the human and cyber components [3].

What makes a HCPS framework attractive in industry is the focus on maximizing productivity by focusing on what skills humans exceed machines in, and what skills machines exceed humans in, and how to best proceed with that relationship. This is especially a challenge given the trend of each successive industrial revolution. In the first industrial revolution, the steam engine replaced human manual labor [3]. In the second industrial revolution, electricity and assembly lines replaced human labor even further [3]. By the third industrial revolution, information technology replaced human mental exertions involving data processing and calculations [3]. Currently, after the fourth industrial revolution, with this era commonly referred to Industry 4.0, higher areas of human intellect such as analytics and predictions are being replaced with technology [3]. The trend is clear: humans are having less and less of a role in traditional methods of productivity, yet there are still many areas where humans can still excel at over machines. Navigating this relationship is the central question of many existing research papers on HCPS.

## 2 Human Cyber Physical Systems Design Framework and Paradigm

A common design paradigm for Cyber Physical Systems includes the five-layer pyramid: the connection level, the conversation level, the cyber level, the cognition level, and the configuration level from the bottom to the top [3]. HCPS brings another level to this framework by designating human roles and machine roles. At the connection and sensing level, humans can use their cognitive senses while machines have capabilities associated with integrated sensors, servers, and networks [3]. At this stage, the machine outperforms the human. At the conversing and analyzing level, humans possess memory and intellect in order to analyze data, while machines use programs and algorithms [3]. Both are necessary based on the scenario, but machines may have the edge. At the cyber and comparing level where data is compared and monitored, machines vastly outperform

human intellect and memory due to the strength of digital models, algorithms, and ability to store mass amount of data in digital memory [3]. At the cognition and prioritizing level where important decisions are being made, the cyber component has the role of providing results and options [3]. The human still has a unique role in this level, using a combination of experience, intelligence, and emotional intelligence to make decisions – something that cannot be replaced by a machine [3]. Finally, at the executing and adapting level, the machine is tasked with execution, instead of humans (given the trend through each industrial revolution of technology replacing human physical and intellectual labor) [3]. Through this paradigm, the preferred way to optimize HCPS is by understanding the human role in each layer, and to focus on the cognition and prioritizing level so that humans are effectively integrated into the loop of the system in order to maximize productivity.

Another important framework to consider when designing HCP Systems is the HABA-MABA table – in other words, what humans are better at versus what machines are better at [3]. A list of human skills that outpace the capabilities of cyber machines include performing flexible and improvised procedures, understanding the situation and exercising judgement, creating solutions, planning, looking at the bigger picture, applying common sense, and experiencing fulfillment [3]. On the other hand, machines are better at the following skills, which for some may have been under the HABA list in the past: performing faster, stronger, and more precisely; storing data; sensing and perceiving environmental conditions; analytical prediction; pattern recognition; and generating databases of knowledge [3].

Recognizing the areas that humans still have the advantage in is essential to integrating humans into Cyber Physical Systems successfully. Many of the skills under the HABA table are built on the consciousness and emotional intelligence that humans possess over machines – in other words producing meaning and understanding context [3]. These skills directly relate to the cognition and prioritizing level of the HCPS pyramid that should be the focus of human tasks. Given the current trend of increasing automation in many areas of industry, from testing and validation to the execution of embedded systems, shifting the training and educational framework for engineers to prioritize the skills under HABA is crucial in maximizing industry productivity. Therefore, using a HCPS framework in this context can allow humans to work better with machines, and not be replaced by them.

Another simple framework for classifying HCP Systems is the three-dimensional graph involving the following axes:

Cyber-Physical, Human Needs, and Human Roles [5]. The Cyber-Physical dimension includes the physical components involved in the system and the data they interact with [5]. The Human Needs dimension is inspired from Maslow's hierarchy of needs, and represent the human comfort, health, and wellbeing factors that should be optimized in a HCP System [5]. Finally, the Human Roles dimension include how humans can indirectly or directly interact with other components in order to improve the functionality of the HCP System [5]. This graph can even be extended into 4 dimensions by separating the cyber and physical dimensions, which could improve the granularity of analysis. This would be beneficial if both the cyber and physical components of a system are too complex to be represented by one axis. However, this model will lose the benefits of easy visual representation compared to a three-dimensional model.

Finally, a flowchart can best summarize the interaction between different components in a HCP System, which can then broadly be applied to any HCPS application. The three components can be thought of as the human presence, observation, opinion, behavior, and comfort; the cyber units; and the physical units [5]. The interactions between the three components form a triangle with each edge being a two-way street [5]. The human component can directly manipulate the physical units through observing and analyzing sensing data from the physical units [5]. The cyber units can automatically control aspects of the physical units through the sensing data it receives from the physical units as well, often using advanced algorithms and models [5]. Finally, the human component can provide inputs to the cyber units in response to feedback from the cyber units, so that the cyber units may better control the physical units [5].

### 3 Summary of Select New Technologies involving Human Cyber Physical Systems

Many new technologies can fall within the HCPS framework, whether these technologies are new electronic devices, software products, design methodologies, or even a combination of many interacting modules and processes. In this section, a few of these technologies or areas of research will be explored.

#### 3.1 *Pi-Minds*

Pi-Minds, referring to the technology patented by the company of the same name, combines human consulting with advanced algorithms and Artificial Intelligence in order to deliver a variety of positive outcomes for small to medium sized IT businesses [4]. Pi-Minds thus falls under software

products and design methodologies in category of technology. Instead of targeting a specific industry or sector of business, Pi-Minds utilizes modern software technology and human skills in order to add value to any type of business [4]. Common services where Pi-Minds produces deliverables are Internet of Things, Mobile Development, DevOps and Tech Support, Software Development, Cloud Services, and Outsourcing; these areas are covered by the following solutions: custom software development, web site development, and data-analysis [4].

Through the solutions and services that Pi-Minds offers, a HCPS analysis is essential to the successful operation of the business. The entire system involves the software, hardware, and environmental components of the IT businesses on the customer side and integrating those components with the technological analysis and human consulting of the Pi-Minds technology. Therefore, all components are present to classify this system as a HCPS. In fact, the HCPS framework is the core of what Pi-Minds need to be successful. The analysis of data through A.I. and other models allows the cyber system to take over most of the conversion/analyzing level and cyber/comparing level in the pyramid model mentioned earlier in this report. Yet the human consulting aspect of Pi-Minds, where Pi-Minds employees use the technology to provide services such as IT development tasks and initial project estimation, is a great example of taking advantage of the skills humans exceed machines in [3], [4]. This demonstrates how humans still dominate the cognition and prioritizing level in the HCPS pyramid mentioned earlier, so that the best decisions can be made for IT businesses. It will be interesting to see how Pi-Minds can expand in terms of the technology it takes advantage of, and how the company can continue training employees to become better partners to the technology being used. If a HCPS framework is successfully applied, there is a great chance that Pi-Minds can expand its solutions set, and work with larger and larger tech companies.

The benefits of this technology are a boast for smaller IT businesses in terms of obtaining the best technical support and resources in order to grow, given the strong combination of human and cyber components that Pi-Minds combine. A possible drawback would be the difficulty supporting Pi-Minds as a long-term business in the IT consulting industry – it will take much effort to continuously reevaluate its business model in order to keep ahead with the latest A.I. technologies and to keep humans in the loop of this technology. Otherwise, the same service for small IT businesses could eventually be provided by just the cyber side of more advanced A.I. and Deep Learning algorithms.

### 3.2 *Human Cyber Physical Systems applied to Smart Buildings*

The research and development of Smart Buildings is a common topic within the realm of embedded technology, as advanced sensors, control algorithms, and concepts from IOT can enhance the capabilities of modern designs for Smart Buildings [1]. It is predicted that the global market for Smart Buildings will increase by at least 42 billion USD in five years, from 2020 to 2025, to a total of 108.9 billion USD [5]. The major research areas supporting this enormous growth comes from the 5G, IOT, AI, cloud, and edge computing industries, all having serious applications in Smart Buildings [5]. Overall, Smart Buildings are defined as intelligent buildings with many added features and functionalities involved with sensing and controlling features of the building, such as temperature, humidity, occupancy, aesthetics, et cetera [5]. On the most basic level, Smart Buildings take measurements and execute actions, with the requirements of conserving energy and being human friendly [5]. Given these definitions of Smart Buildings, they already fall under the framework of Cyber Physical Systems due to the interface between hardware (such as sensors), and the cyber control system.

Although the research in Smart Buildings has already shifted from being concentrated in hardware (such as sensors) to the connectivity between components (IOT and wireless networks), the next research shift is incorporating a HCPS framework [5]. The goal of buildings is for humans to live comfortably or work productively in, and humans are directly involved in the performance of the building - for example indirectly or directly controlling the HVAC (heating, vitalization, and air conditioning) system and thus affecting the energy usage of the building [5]. Given this, a HCPS framework is important to consider when designing Smart Buildings. In fact, since 2014, there has been a sharp increase in HCPS research article pertaining to Smart Buildings, even though HCPS related articles still trail behind pure CPS related articles [5]. Common research areas for Smart Buildings in general cover occupancy detection, energy and comfort management, control algorithms, decision support, lighting, and thermal comfort; many of these areas overlap with the focus of HCPS research in Smart Buildings as well [5].

Specific examples of how HCPS is currently being applied in improving Smart Buildings begin with adding human comfort/satisfaction as a variable to optimize within the building energy management system (BEMS) - comfort most commonly meaning thermal and visual comfort [5]. This may involve learning human behaviors so that this data

can be inputted into control modules that run a variety of algorithms, such as artificial neural networks [5].

HCPS designs are also being applied to lighting within Smart Buildings as well, where human comfort and satisfaction can be included as inputs to lighting optimization models and algorithms [5]. In these scenarios, advanced sensors (passive infrared motion sensors, ultrasound array sensors, etc.) can be used to learn user lighting preferences through occupancy data, localization data, and information on general lighting preferences in order to calculate an automatic schedule for dimming lights, or for turning lights on or off [5]. This would be an example of the human component indirectly controlling the physical environment through the cyber component. In some systems, the human component may also directly control the inputs to the physical components as well [5].

Other design features of Smart Buildings under a HCPS framework include air quality control, and HVAC systems [5]. For air quality control (IAQ or indoor air quality), again human comfort is an input to the cyber and physical components of the system [5]. In modern buildings, sensors combined with deep learning algorithms can estimate skin temperature of occupants [5]. This data combined with other measurements of temperature, humidity, and the number of occupants can be used by the cyber components of the system to automatically control the airflow and temperature of the building [5]. HVAC is closely related to IAQ, where ultrasonic range finders can be used to detect the number of occupants in a room to provide input to the central control modules, so that the heating, ventilation, or air conditioning can be adjusted accordingly [5]. In the above system, the range finder and any heating, ventilation, or air conditioning adjustments are the physical components, the number of occupants is the human component, and the central control modules are the cyber components – thus demonstrating all requirements to be a Human Cyber Physical System.

Benefits of this technology are an increase in happiness, workplace or living place satisfactory, and an increase in productivity due to the prioritization of human physical and psychological comfort. A drawback would be the increased expense of owning and renting buildings that may not be justified by the benefits it brings.

### 3.3 *Human Cyber Physical Systems using Virtual Reality and Augmented Reality*

A very common technology where a HCPS perspective is currently being utilized more and more are applications involving Virtual Reality (VR) and Augmented Reality (AR). In fact, improvements in VR technology have

provided a platform for HCPS applications to succeed due to improving how humans can interact with the virtual world – and thus improving how humans can interact with the cyber components of existing cyber-physical designs and embedded systems [6]. VR technology consists of replicating the real world through a completely virtual interface for the human, often using technologies such as sensors to observe the real world [6]. Despite the improvements in the human-computer interface that VR technology brings, the challenges of applying such technology to real world systems are the possible discrepancies between the virtual world and the real world due to errors with the physical equipment observing the environment [6].

Combining VR technology with AR is a proven method to compensate for the challenges with pure VR technology [6]. AR involves interpolating the virtual world onto the real world to assist humans in interacting with the real world with additional overlaid information, and thus is inherently a more human-centered technology [6]. Current AR technology incorporates active human participation through real time gesture recognition, voice recognition, and other forms of real-world interactions [6]. Given this definition, AR technology itself can be classified as HCPS, with the human interacting with the physical environment through the hardware and the software of the AR technology. As such, AR and VR technology can be applied to many different industries and applications to closer align the industry or application with a HCPS framework.

There are already many applications where AR and VR technologies have brought success under the HCPS framework. With intelligent manufacturing, AR and VR technology assist with image modeling and workspace monitoring so that there is an interactive user interface when working with robots [6]. AR is also being used in routing algorithms for automatic guided vehicle systems to improve warehouse productivity [6]. AR is involved with many interfaces for monitoring electrical and mechanical equipment, providing maintenance for such equipment, and for remote control technologies – such monitoring and equipment maintenance can be done with smart predictive technology courtesy of AR [6]. Overall, AR technology such as the Microsoft HoloLens can greatly enhance the productivity of many smart manufacturing processes, and products such as smart automobiles, smart ships, and smart buildings, by providing a more stable and dependable human-computer interface [6]. In a very niche application, AR and VR can be applied to underground mining systems as well. The mining industry has challenges due to the harsh

and volatile environment for hardware that interferes with sensing and communication. Therefore, a completely cyber-robotic system is not feasible, and a HCPS framework would benefit this industry immensely [6]. By incorporating AR and VR technology with other hardware sensors and cyber technology, a solid foundation of virtual simulation information and real-time sensing information can be presented in a visually friendly manner so that humans can work together with machines to maximize productivity in the mining environment [6]. Applying HCPS to mining serves to provide the human operator with the most reliable information in order to make the best decisions, which demonstrates the effectiveness of human skills within the cognition and prioritizing level of the HCPS pyramid [6], [3].

In all these examples, the virtual elements created by the AR and VR technology serve to provide humans with more information to make decisions, and a greater capacity of influencing the cyber and physical components of the system [6]. The drawbacks to VR and AR technology are more sociological and psychological – it is unknown what the effect on human psychology and human society will be by increasing the amount of time spend in virtual or augmented realities, and if this will cause humans to be over reliant on technology for everyday activities.

### 3.4 *Wearable Technology*

A field much in its infancy, wearable technology is an area with enormous potential for HCPS products, given the proximity between humans and their clothing or accessories. Any wearable device should automatically be considered a HCP device, since at the most basic level, human comfort and visual aesthetics must be optimized for these products by virtue of them being items that are worn. Going further into the functionality of any wearable device, many require input or active participation from the human operator, thus the visual and cyber interface between the human and the device must be intuitive, attractive, and effective. Clearly, the human, cyber, and physical components are very closely related for wearable technology.

The most obvious example is the Apple Watch, which is arguably the first wearable device to see large commercial success. In fact, prior generations of apple products such as the iPod Shuffle or the iPod Touch can also be considered as HCPS but may not strictly in a sense be considered wearable technology. A big factor contributing to the success of these apple products may be the visual sleekness, and the intuitive human-computer graphical interface – both human components of the HCPS. Being stylish may yet be a huge

factor in achieving market success, which may explain the failure of the first iteration of the Google Glass. Newer iterations of smart eyewear may be picking up excitement - the TCL NXTWEAR AIR is a recent smart glass unveiled at the 2022 CES with the purpose of providing mobility to gaming, entertainment, and productivity [7]. The design methodology of this device includes a focus on comfort and style, which are important human factors that may end up determining how much success such a product will receive [7].

A huge class of wearable devices fall within wearable health products – smart watches and Fitbit products being at the forefront of mainstream use [8]. The explosion of wearable healthcare technology over the past decade can be summed from the statistic that around 80% of consumers saying that they would wear one [8]. These devices must be human centered in order to accurately track and measure health factors. Apple Watches and Fitbits only represent a single spectrum of wearable health devices that serve as recreational health trackers – other more medical products, such as biosensors and blood pressure monitors that are being integrated into wearable devices to send helpful data to doctors, are becoming popular as well [8]. These healthcare products must include cyber technology that measures the human health factors accurately, thus being a great example of HCPS.

The benefits of HCPS in wearable technology are enormous, given the many commercial and medical products that have the potential to vastly improve both recreational life and personal health. Wearable medical products can change the way healthcare is delivered, with the focus shifted from in-person appointments to remote care because doctors may receive accurate data without being physically with the patient – which is even more important in the context of a worldwide pandemic. The explosion of such technology can serve a huge boost to businesses in the wearable devices industry. The repercussions remain to be seen with such products, but possible negatives would be the sociological effect of having such devices be popular – only those who can afford such luxuries may benefit from wearable devices. Such devices may seem elitist if they remain expensive, which is especially problematic with wearable medical devices. Systemic and institutional barriers may prevent many people of certain identities from achieving the economic stability that justifies purchasing wearable medical technology. If wearable medical devices improve to the point where it can provide a large degree of benefits, many marginalized communities may be yet again left behind and not benefit from the improved health outcomes

that these devices may bring. Such technology may only further the divide between social classes and expose the glaring racial, structural, and classist issues of countries around the world.

## 4 Discussion and Conclusion

Even though there may be certain challenges and reservations for widespread adoption of HCPS methodologies and products, many of the reservations are more tied to the specific product or application of the HCPS, and not the ideology itself. This section will explore some of the remaining challenges for HCP Systems, and possible future solutions.

### 4.1 Challenges

By nature, HCPS is a field that will always bring benefits – the goal of any product or process can eventually be boiled down to “how will this help human(s),” thus it is necessary to consider the human perspective either actively in the control loop of the system, or passively by benefiting from the system. Yet on the same side of the coin, HCPS is a field that must constantly change and adapt to other changing technology. The rapid advance in other areas in industry will always produce new technology that will exceed the human ability in completing certain tasks. Given the trends in industry where machines, automation, and A.I. are displacing humans in the labor force, any HCPS framework will constantly need to be reevaluated to isolate and promote the skills and abilities that humans still exceed machines in. Once these skills are determined, the HCPS framework will need to adapt to optimize the human component working together with new technologies. In fact, the concept of discovering how humans may work in tandem with increasingly more advanced machines to optimize productivity is a concept of Industry 5.0, which many predict to be the next stage of the tech industry that businesses must adapt to for success [9]. Ultimately, only through constant adaptation will a HCPS framework continue to provide maximum effectiveness, which is certainly a challenge of this field.

Another challenge for HCPS related applications will be keeping the price down. Many products such as smart buildings and wearable technology are arguably considered luxury technology. Whether or not buildings have automatic temperature control systems and despite many of the fancy features of wearable technology, certain people may still find such things to be gimmicky and not worth the price hike. This is related to integrating many HCPS devices into commercial use, especially for wearable technology. By

virtue of focusing on the human component, HCPS products have an advantage over CPS products in becoming commercially viable. However, this is still a challenge, considering that despite an explosion of mobile technology over the past decade, the average number of embedded technologies that a person is likely to carry at all times is close to 1 – just a mobile phone.

#### 4.2 Future Direction and Potential Solutions

A shift in the engineering education within electrical and computer engineering, and computer science programs may be a potential solution in both increasing the commercial viability of HCPS products, and for adapting the HCPS framework to match advancing technology. McCormick already attempts this, with the Whole-Brain engineering philosophy that focuses both on the technical and creative side of engineering design. Part of this curriculum involves the DTC sequence, which teaches human-centered design. Yet further steps may need to be taken to fully take advantage of the HCPS paradigm. Perhaps having more social science requirements such as psychology, cognitive science, or sociology classes could prove to be immensely helpful in HCPS designs. Understanding the human component is key to successful HCPS applications and processes, which cannot be obtained by traditional engineering curriculums solely focused on STEM and technology. In this sense, a curriculum with psychology, cognitive science, or sociology built in will help engineers determine the skills humans possess that machines cannot offer, and how to best make HCPS devices commercially viable across society by optimizing the desirability of the product.

Another future shift within the HCPS framework considers the three dimensions mentioned previously: the Cyber Physical dimension, the Human Needs dimension, and the Human Roles dimension [5]. Currently, many areas where a HCPS methodology is being applied to focus on the Human Roles dimension – improving employee productivity in industry by incorporating human operators in cyber physical systems involved in the engineering process. The central question here is how humans can work together with hardware and software to deliver business and engineering goals. Yet, the future of the HCPS framework should shift to focus equally on the human needs dimension – creating commercial HCPS products where the human component is not an employee, but a customer. The central question here is how HCPS can improve the daily lives of people in communities around the world by considering human needs and desires. The future of HCPS are devices that people can

wear, bring anywhere, or use conveniently every day, which will become more of a reality as technology improves. Wearable devices, although a category that already exists, will be at the forefront of this movement. Cheaper smart watches with greater features, such as implementing holographic technology, is an example of this vision. Stylish smart glasses that hide the technology but delivers powerful AR features is part of this vision. Technology incorporated into more accessories or hidden into clothing that are efficient, attractive, and easy to use is part of this vision. Ultimately, the possibilities are endless if the Human Needs dimension of HCPS is enhanced, and wearable technology may be at the forefront of this technological shift.

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