Leveraging Transdisciplinary Engineering in a Changing and Connected World
P. Koomsap et al. (Eds.)

doi:10.3233/ATDE230594

A Design Framework for Cyber-Physical-Human-Systems

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Abstract. Cyber-physical-human systems (CPHS) represent significant extensions of cyber-physical systems (CPS) to include aspects of human interactions and usage. A class of CPHS of interest here is smart products that offer services to their customers, supported by back-end systems (e.g., information, finance) and other infrastructure. We argue that although the domain of CPS relies on engineering and computer science as its foundations, the emerging field of CPHS does not have an underlying scientific foundation. Transdisciplinary teams of researchers are needed to integrate the engineering, computing, and human behavioral fields that are central to CPHS to develop new foundational theory and methodology. Furthermore, a new design methodology is needed for CPHS, given the transdisciplinary nature of the field, that anticipates human acceptability and usability considerations as well as emerging behaviors that result from human-system interactions. In this paper, we propose a framework for such a design methodology. The domain of assistive and rehabilitation technology is used in this paper to provide an example field of practice that could benefit from a systematic design methodology. A CPHS design example is provided to illustrate the application of the methodology framework.

Keywords. Cyber-physical-human system, design methodology, emergent behavior, usability, acceptability

Introduction

Cyber-physical-social systems (CPSS) are typically considered as an evolution of cyber-physical systems to include human interactions; further, that interactions among humans through CPSS can lead to emergence of social or community structures and behaviors [1]. We can identify a subset of CPSS as cyber-physical-human systems (CPHS) that are smarts product or systems that offers services to its customer, supported by back-end systems (e.g., information, finance) and possibly other infrastructure. That is, CPHS are scoped to the individual and their interactions with the physical and cyber systems. This emphasis on the individual is not meant to lessen the importance of the social and community aspects of CPSS, but rather to reduce the research scope to individual human interactions without the complications arising from social (human-human) interactions.

At the same time, CPHS can be considered as expansions of cyber-physical systems (CPS) that are typically considered as tightly coupled mechatronics system [2], with one group defining them as "physical and engineered systems whose operations are

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monitored, coordinated, controlled and integrated by a computing and communication core," [3] typically with a real-time control aspect.

Considerable research in CPHS has been pursued in recent years. A model-based approach to CPHS design was proposed using systems engineering principles as a foundation [4]. Similar work emphasized the importance of usage contexts in CPHS design [5]. A body of work is emerging on applications of CPHS to the design of smart and intelligent manufacturing systems [6, 7], with some focusing on specific areas such as additive manufacturing [8]. Some work expands on the CPS paradigm to include human users in real-time systems and investigates their modeling as interplay between reinforcement learning and game theory [9]. Ethics is also being examined in the context of CPHS, with one study proposing that ethical controllers be embedded into these systems [10].

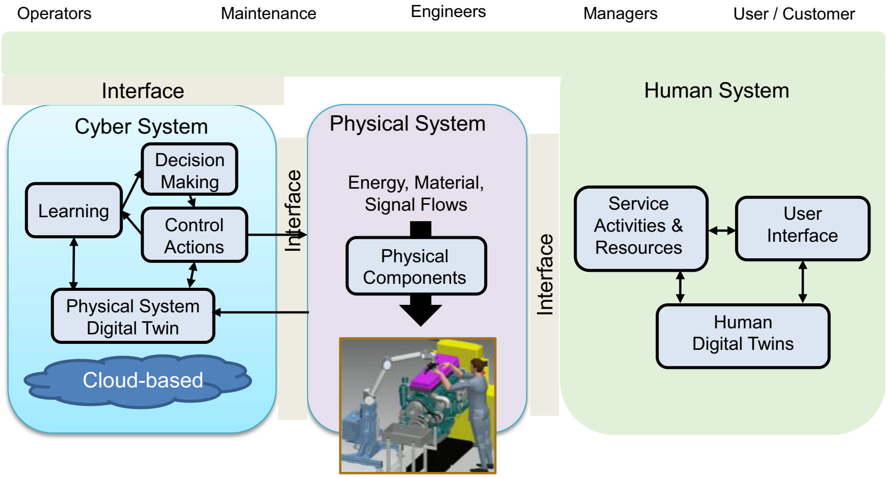


Figure 1. Schematic of a cyber-physical-human system [11].

A schematic of a CPHS is shown in Figure 1 [11]. The physical system consists of components with flows of energy, material, and signals that cause the system to perform functions. The cyber system consists of all the computational assets in the product and in a back-end system that may be cloud-based. It can control the operation of the physical system, make decisions about which actions to take and when, and learn over time to improve its performance. The human system is shown surrounding the physical and cyber subsystems since it interacts with both. This subsystem consists of software that provides the user interface between the human and the cyber and physical subsystems, as well as providing services to the human that are delivered through the physical subsystem. As part of the human subsystem, we propose a "human digital twin" that maintains a model of user's behavior (their interactions with the CPHS) over time to monitor how their behavior may evolve. Users interact with these subsystems through user interfaces that are constructed as elements of the CP systems. Services are delivered to the user/customer through the product and user interface. The human learns over time to improve their utilization of the other systems, similarly to how the cyber system can learn about how the user uses the system. Other humans are shown around the CPHS; these people have other roles in maintenance or management of the system, or providing services to the CPHS (and ultimately to the user). The CPHS should be designed to facilitate the interactions with all these types of people. However, we assume that these people do not interact with each other; hence, we do not consider this a CPSS.

In this paper, we propose an initial approach for CPHS family design that incorporates concepts of systems engineering, generative design, product families, and user experience design. We believe this is a novel approach. The long term objective of this work is to develop a design methodology for CPHS families, which are groups of related CPH systems that share cyber, physical, and human components, modules, or technologies. Design methods should enable the generation of a wide range of alternative solutions, while considering interactions among the cyber, physical, and human subsystems and human responses to the proposed alternatives.

Some additional comments are warranted related to the "human" subsystem of CPHS. Our goal is to design user/customer experiences, user interfaces, ensure user acceptance, and to ensure that users gain value from the CPHS. This is consistent with the objectives of product-service-system (PSS) design [12] but, we believe, encompasses the explicit considerations of the three subsystems and their interactions.

1. Design Framework

The proposed design framework for CPHS design, shown schematically in Figure 2, consists of three primary fields:

- Model-Based Systems Engineering (MBSE)
- User eXperience design (UX)
- Systems Family Design (SFD)

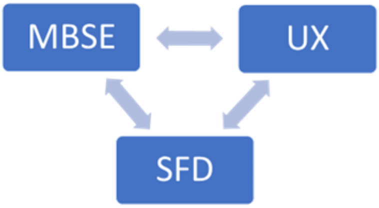


Figure 2. Overview of design framework.

This combination indicates the intent to integrate the rigor of engineering design with the broad structure of systems engineering and the more subjective approaches of user experience design. Such a combination represents a transdisciplinary approach to CPHS design. Each field will be described briefly.

Model-based systems engineering evolved over the past 20 years to inject additional rigor into the top-down management approach of systems engineering. Developed largely in the aerospace and defense fields, systems engineering introduced structure into the conception, development, and operation of large, sophisticated systems like aircraft, military weapons, satellites, etc. over their life-times. From the NASA Systems Engineering Handbook [13], systems engineering "…consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals." MBSE takes this further by incorporating models of system components and their interactions into the systems engineering process. Models evolve as the system development process proceeds, becoming more advanced and detailed over time. Interestingly, some groups are proposing that systems engineering be viewed as an emerging transdiscipline [14].

In CPHS, humans are part of the system. Their behavior when interacting with the system should be simulated and evaluated. As a general statement, engineering disciplines do not have adequate models of human behavior and decisions making, so it is necessary to explore other disciplines that do. User experience design is such a discipline, but is also meant here as a broad “umbrella” term that incorporates fields including user-centered design, customer experience design, usability, universal design, and industrial design [15]. The UX field defines UX as the process of defining the experience a user would have when interacting with a product or system [16]. As a consequence, UX can be used to evaluate system concepts during design when physical prototypes are not available.

System family design builds on the product family design field in engineering design. Further, it is again an umbrella term for incorporating rigorous engineering design methods, such as design exploration and exploitation, design decision making, and design optimization. In product family design, the focus is on developing a family of related products, where typically the products in the family share a common platform [17]. If properly engineered, the use of the platform saves significant time, cost, and effort when developing each product in the family. Typically, the same production line manufactures the products in the family, again saving considerable time, cost, and effort compared to separate lines for each product. The role SFD plays in CPHS design is the same as for product family design: a strategy for sharing and leveraging development resources.

A more detailed look at the proposed CPHS design framework is offered in Figure 3. The systems engineering process is typically presented as a “V” diagram that emphasizes a top-down approach to system development, starting with requirements analysis and progressing from system-level to subsystem-level to component development stages. In MBSE, models are used for analysis at each stage. The right side of the V shows integration of the various elements at each stage and their testing and validation.

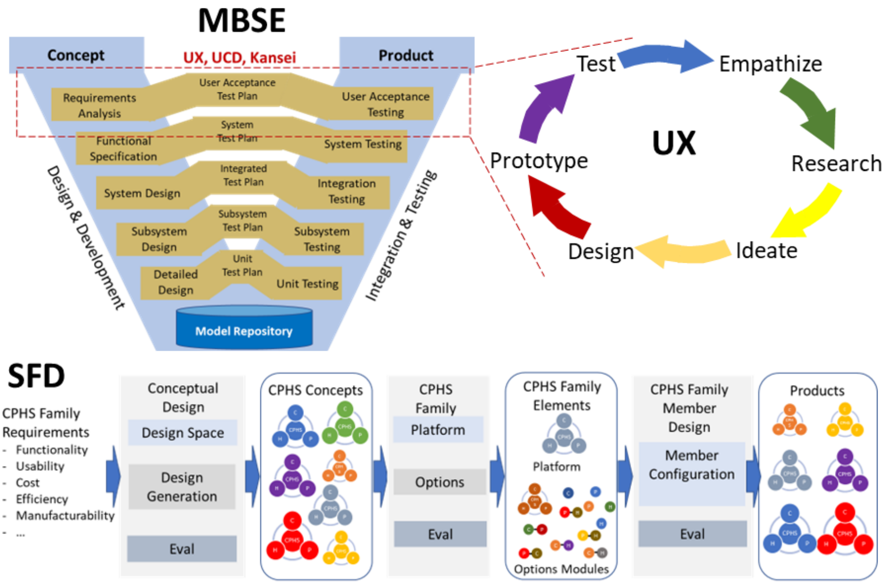


Figure 3. CPHS design framework.

A typical UX process is illustrated in the top right of Figure 3, which starts with “empathize” and “research,” indicating the need to carefully understand users and their motivations, interaction behaviors, and decision processes. From that understanding, system concepts can be ideated, designed in more detail, prototyped, and tested. Results and insights from user testing are then fed back into another cycle, as needed. UX can play a vital role in the early stages of systems engineering where requirements associated with users of all kinds are determined. Additionally, UX is critical for system testing after development. Not shown, but implied, is further user testing at subsystem and component levels.

A SFD process is shown at the bottom of Fig. 3 that illustrates a straightforward adaptation of product family design methods [11]. The conceptual design stage seeks to generate a wide range of system concepts that corresponds to the “System Design” and “Subsystem Design” steps in the MBSE “V” diagram. A filtering step identifies those concepts of sufficient merit to warrant further development. Rather than narrow down to one system design, multiple designs of varying scale and capability are kept since they indicate the variety desired in the final system family. From these identified concepts, a common platform is identified that could be used throughout the family. The platform will consist of shared technologies and capabilities, and may include common (physical) components and subsystems. From there, further development will lead to complete system designs that comprise the final family.

Application of this CPHS design framework is illustrated in the next section.

2. Example

2.1. Application Domain

Assistive Mobility (AM) devices provide a plethora of opportunities to explore CPHS design issues. AM devices, such as manual wheelchairs, powered wheelchairs, and walkers are critically important to many people worldwide. Currently, the process of designing and provisioning mobility devices is very product-centric [18]. Wheeled mobility devices have the potential to be much more innovative, for example, by combining the device with integrated services to better meet the user's needs with the device.

Figure 4. Panasonic Resyone bed-chair system.

We will use reconfigurable bed-chair systems as the domain to investigate. Such systems are wheelchairs that allow the patient to transition from a sitting position to lying flat. One commercial example is shown in Figure 4 that integrates with a hospital bed [19]. For this example, an additional function, enabling the patient to stand, can be added. Finally, an exoskeleton attachment can be added that, after attaching to the patient’s legs, allows the patient to walk short distances. These four patient functions, *sit*, *lie*, *stand*, and *walk*, can be combined in several ways to generate different systems.

We propose to augment these devices to deliver customized services tailored to an individual patient's conditions. Services such as monitoring the patient and the wheelchair could be offered. Patient monitoring could include typical health readings (pulse, blood-oxygen level, etc.) or more sophisticated analyses could track the patient's activities and note any degradation in their activity level or ability to control the bed-chair. Bed-chair monitoring would detect deteriorations in its physical condition and anomalies in its performance. Other services include notifying caregivers, occupational therapists (OT), physical therapists (PT), or doctors about the patient status.

2.2. Requirements Development

The systems engineering process begins with establishment of system requirements. For the AM domain, this will entail discussions among systems engineers and UX designers. Top level system functions as well as target user profiles and personas should be identified. Usage scenarios of various system configurations should be developed for the various users and stakeholders, including the patient, primary caregivers, nursing staff, etc. Measures of value added by the system should be identified that will help in quantitatively evaluating system alternatives [12]. Various categories of requirements should be identified through continued interactions among the various personnel.

For this proposed system family of AM devices, the top level functions, combinations of functions, and services should be developed. For the purposes of this example, these functions and services are shown in Table 1. All combinations of primary functions include *sit*. Services are split into basic and advanced, where basic services are mostly passive, while the advanced services take actions.

Table 1. Primary functions and services for the bed-chair system.

Functions	Services (basic)	Services (advanced)
Sit	Automated transitions	Track patient
Sit-stand	Monitor patient health	Notify caregiver/OT/PT/doctor
Sit-sleep	Monitor patient usage	Notify maintenance
Sleep-sit-stand	Monitor device condition	Remote operation
Sit-stand-walk		
Sleep-sit-stand-walk		

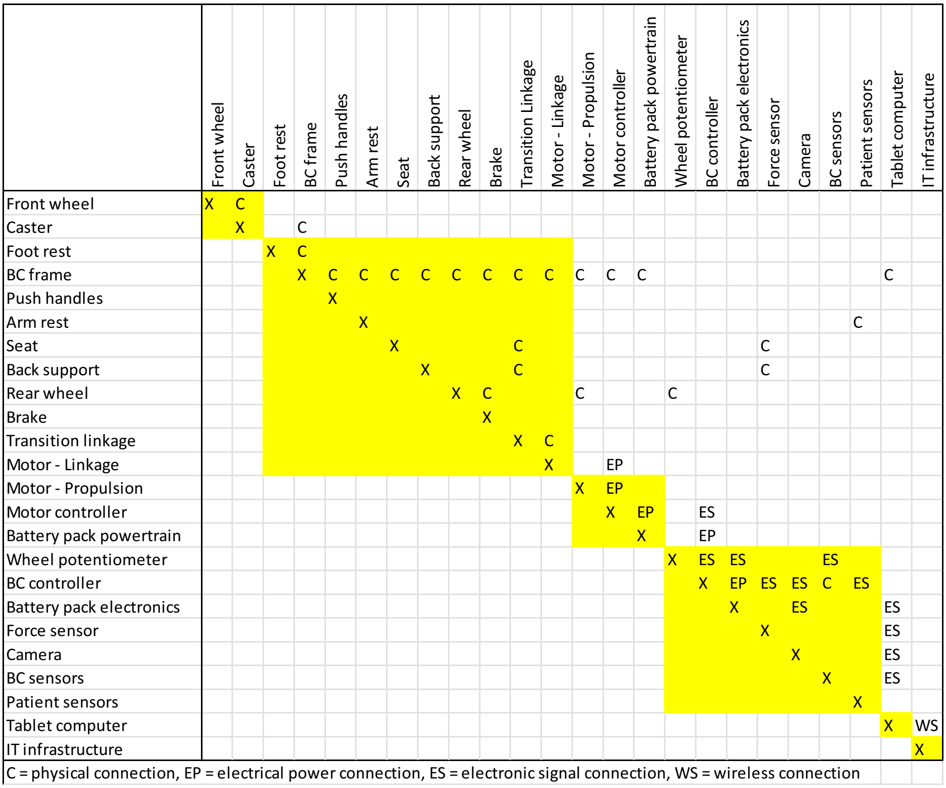
Based on the identified usage scenarios and services, a user test plan should be developed. That is, plans are needed for testing the services, system usability, and user acceptance across all potential system configurations [20]. These test plans should encompass all potential interactions between various users and the systems.

2.3. Application of MBSE

After developing system requirements, the first set of high level system models should be developed. One type is a state transition model that captures the primary functions and states of the bed-chair system. Another model type utilizes mock ups of user interfaces to explore usability characteristics. Then, integration of the state-transition and user interface models enables services to be modeled and explored.

Over time, the system becomes better defined as design decisions are made. System models evolve to incorporate results of those decisions. Subsystem concepts and configurations are explored and subsystem models become defined. More specifically, separate cyber, physical, and human usability subsystem models will be developed. Upon integration, system performance can be tested.

As system and subsystem design progress, more detailed decisions will be needed on the structure of the physical and cyber subsystems as well as the user interface. Additionally, the platform for the system family needs to be identified. A useful tool in identifying modules for the structures and platforms is the Design Structure Matrix (DSM) [21]. For this example, we will apply basic DSM analysis of connections, both physical and electronic, among components to identify modules. An example set of modules, based on typical wheelchair components and the enhancements described, is shown in Figure 5. Note that DSM matrices are symmetric so only the connections in the upper matrix region are shown. The large module in the upper left consists of the frame and standard components connected to the frame. Since these designs are powered bed-chairs (BC), the 3-component module in the middle includes the propulsion motor, controller, and battery. To support the various services, a large module was defined to include the sensors and BC controller. A tablet computer is used as the primary interface and communication device, and is a separate module. IT infrastructure exists but is not bundled with any other components. Note that four types of connections were used for DSM analysis: C for a physical connection between components, EP for electrical power, ES for an electronic signal, and WS for a wireless signal. Based on this analysis, and other family design considerations, a system platform can be identified.



	Front wheel	Caster	Foot rest	BC frame	Push handles	Arm rest	Seat	Back support	Rear wheel	Brake	Transition Linkage	Motor - Linkage	Motor - Propulsion	Motor controller	Battery pack powertrain	Wheel potentiometer	BC controller	Battery pack electronics	Force sensor	Camera	BC sensors	Patient sensors	Tablet computer	IT infrastructure
Front wheel	X	C																						
Caster		X		C																				
Foot rest			X	C																				
BC frame				X	C	C	C	C	C	C	C	C	C	C	C								C	
Push handles					X																			
Arm rest						X																C		
Seat							X				C								C					
Back support								X			C								C					
Rear wheel									X	C			C			C								
Brake										X														
Transition linkage											X	C												
Motor - Linkage												X		EP										
Motor - Propulsion													X	EP										
Motor controller														X	EP		ES							
Battery pack powertrain															X		EP							
Wheel potentiometer																X	ES	ES			ES			
BC controller																	X	EP	ES	ES	C	ES		
Battery pack electronics																		X		ES			ES	
Force sensor																			X				ES	
Camera																				X			ES	
BC sensors																					X		ES	
Patient sensors																						X		
Tablet computer																							X	WS
IT infrastructure																								X

C = physical connection, EP = electrical power connection, ES = electronic signal connection, WS = wireless connection

Figure 5. Design structure matrix for the physical subsystem, with one set of possible bed-chair modules.

2.4. System Family

After detailing cyber, physical, and human subsystems and identifying platforms, system designers should develop specific systems to comprise the system family. At a high level, one can think of this as investigating combinations of the functions and services in Table 1, but the system descriptions must be more detailed. This system family configuration task is part of the “integration and testing” (left) of the MBSE “V” in Fig. 3.

For the physical subsystem, the first 3 modules in Fig. 5 will comprise the physical platform. We can assume that suitable cyber and service platforms have been defined as well. Various optional modules should be developed that can be used to generate other system designs that can comprise the family.

From the platform and optional modules, designers can generate many candidate system family members. Further analysis, including cost and market studies, should lead to the identification of a suitable collection of family members that covers the market segment of most interest. For our purposes, four system designs were selected as shown in Table 2: one low-end bed-chair system with basic maintenance and health diagnosis, two mid-range BC models that offer one additional service, and a high-end BC that include the option of having a physician perform health diagnosis. These choices cover the low and high ends of the market and provide two intermediate choices with different levels of service. Of course, these 4 designs are merely a sampling of the entire set of possible system configurations.

Table 2. Selected BC System Family.

Model	Services	Functions	Product Modules
Low-end BC	BC maintenance caregiver OT health diagnosis PT health diagnosis	Sit-sleep-stand	BC frame Basic electronics module
Mid-range BC1	BC maintenance technician OT health diagnosis PT health diagnosis OT training diagnosis	Sit-sleep-stand	BC frame Basic electronics module Pulse-ox sensor
Mid-range BC2	BC maintenance caregiver OT health diagnosis PT health diagnosis OT training and diagnosis	Sit-sleep-stand	BC frame Advanced electronics module Advanced patient sensors Patient tracking
High-end BC	BC maintenance technician OT health diagnosis PT health diagnosis OT training diagnosis Physician health diagnosis	Sit-sleep-stand-walk	BC frame Advanced electronics module Advanced patient sensors Patient tracking Remote operation

This example was intended to give a flavor of the application of the proposed CPHS family design framework, including snapshots of design activities and outputs. It is important to realize the many design steps and interactions among design personnel will be necessary to design successful CPHS families, but could not be included here for sake of brevity. It is also important to highlight the variety of test plans that were developed, at the different levels of detail, in the MBSE “V.” These plans validate component, subsystem, and system-level performance. Additionally, the test plans need to test human efficacy and efficiency in using the various systems. Usability and acceptability are critical considerations.

Another factor that was not included in the example is customization of systems to specific classes of patients, or even to individual patients. Decisions about platforms and options modules will impact the capability of a system to be customized to individuals who may have unique or rare needs. Hence, the level of customization desired should be an early consideration in the system family design process.

3. Conclusions

A design framework for cyber-physical-human systems (CPHS) was proposed in this paper that recognizes the importance of human interactions and usage with technical systems. Motivation for this work stems from two observations. First, the number and complexity of smart products and systems, product-service-systems, intelligent manufacturing systems, and similar developments is likely to grow over the coming years. Second, we believe that designers of such products and systems would benefit greatly from a comprehensive design methodology. CPHS consist of physical systems that offer services to their customers, supported by back-end systems (e.g., information, finance) and other infrastructure. Although the domain of cyber-physical systems relies on engineering and computer science as its foundations, the emerging field of CPHS does not have an underlying scientific foundation. Transdisciplinary teams of researchers are needed to integrate the engineering, computing, and human behavioral fields that are central to CPHS to develop new foundational theory and methodology. The proposed CPHS design framework recognizes the transdisciplinary nature of the field and highlights that human acceptability and usability considerations distinguish CPHS design from CPS design. An example in the domain of assistive and rehabilitation technology was used to outline the application of the design framework to an emerging class of smart devices that could benefit from the framework. Some discussion of research directions was offered with the hope that this paper stimulates research on the topic of CPHS design.

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