Research Issues in the Generative Design of Cyber-Physical-Human Systems

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ABSTRACT

Cyber-physical-human systems (CPHS) are smart products and systems that offer services to their customers, supported by back-end systems (e.g., information, finance) and other infrastructure. In this paper, initial concepts and research issues are presented regarding the generative design of CPHS and CPHS families. Significant research gaps are identified that should drive future research directions. The approach proposed here is a novel combination of generative and configuration design methods with product family design methodology and an explicit consideration of usability across all human stakeholders. The need for a new CHS transdiscipline is identified. With the proposed approach, a wide variety of CPHS, including customized CPHS, can be developed quickly by sharing technologies and modules across CPHS family members, while ensuring user acceptance. The domain of assistive technology is used in this paper to provide an example field of practice that could benefit from a systematic design methodology and opportunities to leverage technology solutions.

Keywords: cyber-physical-social systems, cyber-physical-human systems, product family, generative design, configuration design

1 Context and Design Domains

Cyber-physical-human systems (CPHS) are smart products or systems that offer services to their customers typically connected to back-end systems for access to centralized databases and computational resources. CPHS can be considered as subsets of cyber-physical-social systems that are scoped to the individual, rather than including social (human-human) interactions [1]. Conversely, CPHS can be considered as extensions of cyber-physical systems (CPS) that are generally defined as the integration of computation with physical processes [2]. Some provide more a more specific description, such as: CPS are "physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core," [3] typically with a real-time control aspect. Examples include smart transportation systems, smart buildings, and automated pilot avionics. As such, the extension from CPS to CPHS could be considered as adding the dynamics of human interactions into integrated computation-physical system such as robotic exoskeletons that help disabled people walk, and robot-human collaborative workcells for manufacturing. However, we consider the broader context of human usability, emotional response, and acceptance of the CPHS, not just the dynamics of the interactions in this work.

A schematic of a CPHS is shown in Fig. 1. 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. 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 generative and configuration design, product families, and usability analysis, as shown in Fig. 2. 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.

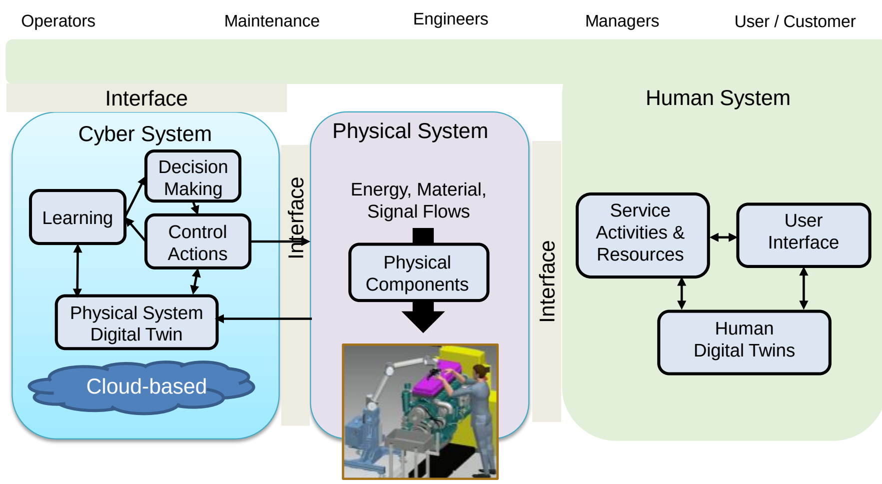

Fig. 1 Schematic of cyber-physical-human system.

In this approach, generative design methods are used to generate many design concepts for the CPHS. Shown schematically in Fig. 2 is a set of CPHS, with various cyber (C), physical (P), and human (H) subsystems. Variations are indicated with different sizes and colors. Key research issues are highlighted in the Generative Design box as design space representations, generation methods, and evaluation methods.

Some additional comments are warranted related to the "human" subsystem of CPHS. This deals with the design of user/customer experiences, services, and user interfaces that ensure usability, user acceptance, and that users gain value from the CPHS. This is consistent with the objectives of product-service-system (PSS) design but, we believe, encompasses additional considerations.

After generative design, the CPHS family will be configured using methods from the product family design domain in a two-step process. First, the set of generated CPHS concepts is analyzed to identify possible platforms for the CPHS family, as well as the individual C, P, and H subsystems. Simultaneously, options should be developed that enable a variety of CPHS family members to be produced. The final step is to configure the entire CPHS family by developing CPHS family members.

The scope of the proposed CPHS family design methodology is applicable to a wide variety of smart products and systems, including intelligent manufacturing systems. An example will be given from the assistive technologies domain that illustrates aspects of the configuration design of CPHS in the next section. Section 3 discusses the foundations for CPHS design with a wide ranging literature review. In Section 4, research issues are identified and the potential impact of addressing them is outlined in Section 5.

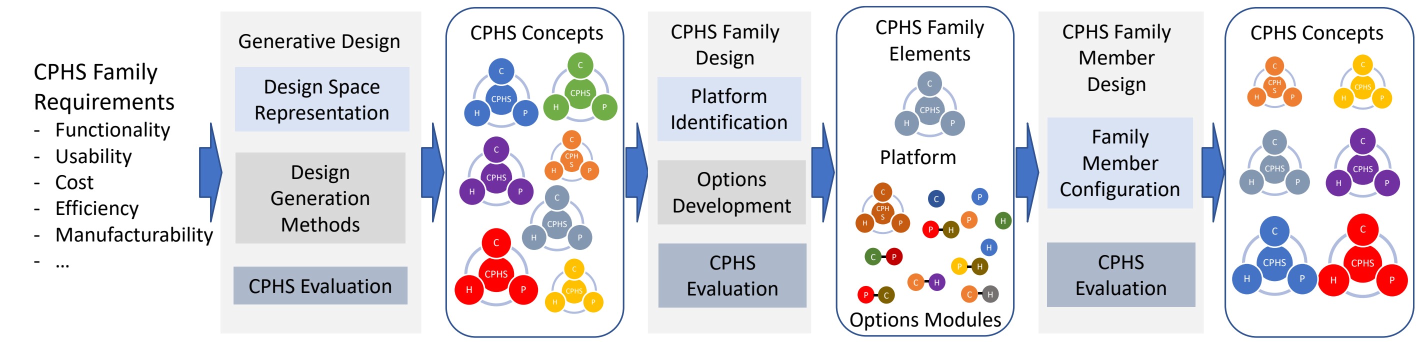

Fig. 2 Proposed CPHS family design approach.

2 Motivating Example

The domain of Assistive Technology (AT) or, more specifically, Assistive Mobility (AM) will be chosen to explore CPHS design issues. The specific devices to be considered are reconfigurable bed-chair systems, that is, wheelchairs that allow the patient to lie flat and optionally integrate with a hospital bed [4]. A commercially available example is shown in Fig. 3. AM devices, such as manual wheelchairs, powered wheelchairs, and walkers are critically important to many people worldwide.

Wheeled mobility devices could be much more innovative with useful integrated services that will make it easier to match the device to the user's needs. As a first step, the bed-chair can be enhanced to enable the patient to stand. As a final step, we can imagine that an exoskeleton attachment fits onto the wheelchair that, after attaching to the patient's legs, allows the patient to walk short distances. For the purposes of this example, we identify four patient functions (number labels used in Fig. 4): *sit* (0), *sleep* (1), *stand* (2), and *walk* (3).

Fig. 3. Panasonic Resyone bed-chair system.

These devices could be used to deliver customized services tailored to an individual patient's conditions. Sensors could be configured to enable communicating the basic status of the bed-chair system as a baseline service. Additional services could be added for system maintenance (detect wear, malfunctions, report to service provider, etc.). Additional sensors on the bed-chair could monitor the patient and send notifications to health care providers. Additionally, motion trackers could be installed in the room if extra patient monitoring is necessary. To support the services, communications with a back-end system enables collection, processing, and distribution of sensor readings to support decision making, control actions, and notifications. If suitable system controls are available, some level of patient autonomy could be provided (i.e., patient-controlled transitions from bed to chair to stand to walk, etc.). These four levels of service are denoted as *basic status* (4), *maintenance* (5), *patient status* (6), and *patient autonomy* (7). For this example, two underlying technologies could be used to power and control these systems: *pneumatics* (8) and *electronics* (9). One of these will be selected.

At the conceptual design stage, designers may want to consider various functions, services, and technologies. Forming, characterizing, and searching the design space will be important during conceptual design. For configuration design, this simple set of alternatives results in 128 ($= 2^3 \cdot 2^3 \cdot 2$) possible combinations of functions, technologies, and services. Even with only a few options, the designer will have difficulty keeping track of all alternatives, evaluating them, and comparing them.

Many products have hierarchies of options, that is, some options are only available with certain other options. If we impose some example restrictions, we can see the effects on the configuration design space. First, consider that the *walk* (3) function is only available if the *stand* (2) option has been selected. Further, *patient autonomy* (7) is only available with *patient status* (6). These two constraints reduce the number of possible combinations to 98 ($= (2^3 - 1) \cdot (2^3 - 1) \cdot 2$). The configuration design space can be visualized as a mathematical lattice, where each element is a string of numbers representing the options. Connections between levels in the lattice denote subset relationships; for example (1 2 3 6 7 8) is a subset of (1 2 3 5 6 7 8). The top three levels of the lattice are shown in Fig. 4 that encompass 22 of the 98 feasible combinations of options. The two constraints eliminate several of these alternatives; elements below the red dashed line are infeasible based on these constraints.

To continue the example, we choose the baseline configuration as a combination of the *sit* function with *basic status*, using pneumatics technology. Hence, the platform for the system family is [*sit*, *basic status*, *pneumatics*]. The cyber subsystem platform consists of computation and communication capabilities as well as the back-end system. Of course, each subsystem should be detailed with modules, components, and their connections and relationships in subsequent design stages. Further, individual patient needs should be considered when defining design spaces so that customized AM CPHS can be developed based on the CPHS family being defined. Note that this example ignores the significant control issues associated with the standing and walking functions that are in the domain of CPS, which rely on tightly integrated computation.

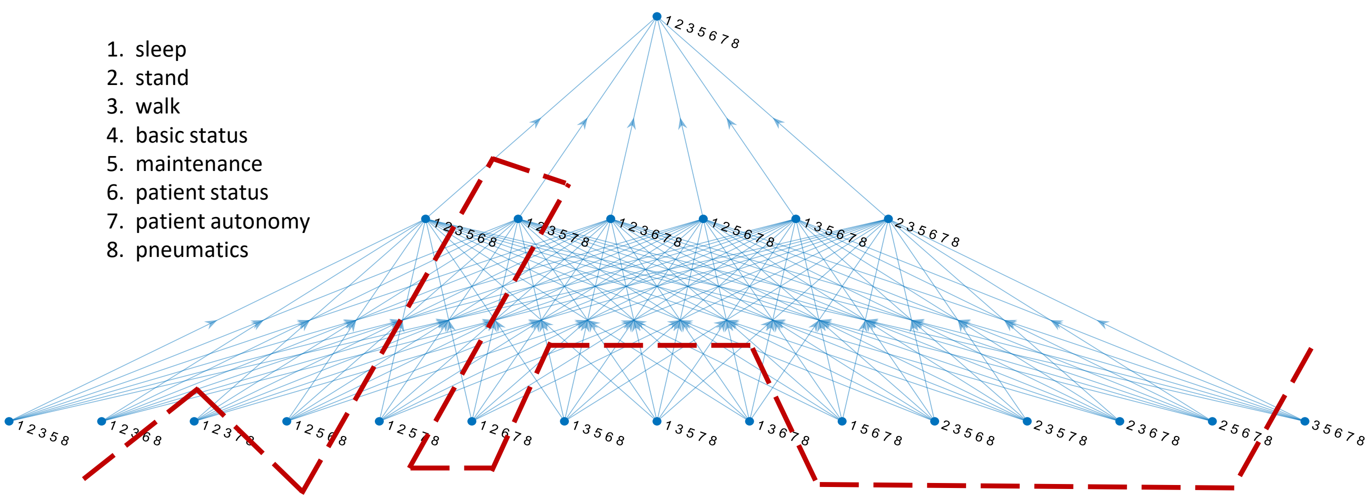

Fig. 4 Partial configuration design space for sit-sleep-stand-walk system with example constraint.

3 Foundations of CPHS Design

The overall foundations of CPHS design are explored, followed by considerations of supporting fields and disciplines.

3.1 Incomplete Foundations

Fundamentally, we believe that the intellectual foundation for CPHS design has not yet been developed. Ultimately, a new transdiscipline is needed to support CPHS design and life-cycle engineering, but it is the foundation for this transdiscipline that must be developed. Some evidence suggests that industry has developed their own transdisciplinary system development processes [5] and some transdisciplinary design education successes have been achieved [6]. But these advances need to be extended greatly to develop a CPHS transdiscipline that includes the various requirements of human interactions with these systems, including users, operators, maintainers, designers, managers, and others.

From the subsystem perspective, the intellectual foundation for each subsystem can be considered. Computer science and related fields provide the foundation for the cyber subsystem, while engineering science underlies the physical subsystem. Combined, the emerging transdiscipline of mechatronics, or embedded systems engineering [2] supports CPS engineering, although advances are still needed. No coherent discipline provides the foundation for the human subsystem, although many fields and subfields may contribute. This is a major research gap. Relationships among the subsystems and the supporting fields and disciplines are illustrated in Fig. 5a.

It is important to consider the foundations of a CPHS design theory and methodology, in addition to the intellectual foundation for the CPHS field. We believe that such a foundation will likely emerge from a combination of methodologies and theories. Engineering design, systems engineering, industrial design, and software design are well recognized theories and methodologies that can provide aspects of the foundation for CPHS design (Fig. 5b). User-centered design, user experience design, and Kansei engineering are fields that seek to integrate human usability, acceptance, and emotions into design methods. Decision theory contributes methods to model preferences and make rational design decision that are consistent with those preferences.

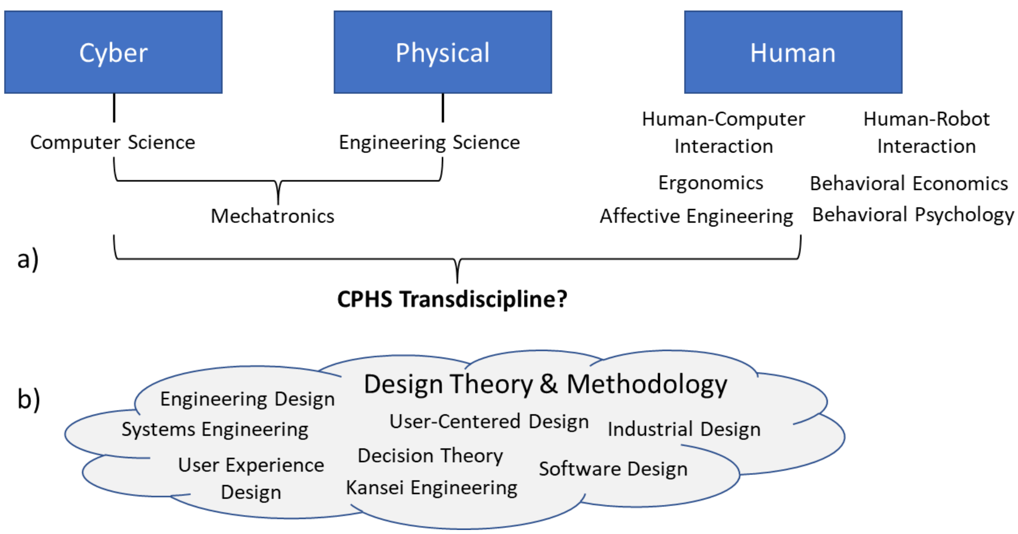

Fig. 5 Foundations of CPHS design viewed from the subsystem perspective (a) and from the design perspective (b).

3.2 Engineering Design Methodology

The ASME Design and Computers & Information in Engineering divisions have long histories of publishing computational design related research methods and results. Additionally, many other communities address computational design issues. These fields are too large to enumerate and survey for this paper, so only a few specific topics will be included here.

The field of systems engineering is large, but tends to focus more on descriptive methods, guidance, and metrics than on computational issues [7]. However, the subfield of model-based systems engineering (MBSE) is growing quickly that offers “a design process-agnostic, system development approach that places models at the center of system development” [8]. The intent is to develop a set of models from the beginning of system development that are comprehensive and evolve to reflect the state of system development. As such, they can be used to answer a wide variety of questions, explicitly address subsystem coupling, and help predict emergent phenomena [9]. Systems engineering has been proposed as an emerging transdiscipline [10] that could contribute significantly to a CPHS design methodology and transdiscipline.

The subfield of computational conceptual design started in the 1990's [11] and has relied on a variety of discretized knowledge representations, such as sets and graphs [12], and computational approaches, such as function-based and analogy-based [13]. A wide variety of computational methods has been explored to generate designs including graph grammars, evolutionary algorithms such as genetic algorithms [14], and other optimization strategies.

The final topic to be summarized here is generative design, which typically refers to a topology optimization based method that synthesizes part shapes given structural design requirements [15-16]. Software for generative design explores the design space to generate many potential solutions through which designers can browse and select designs to continue developing. Outputs from generative design are one or more geometric part models.

We believe that a broader perspective on generative design enables the solution of a much wider range of design problems, specifically for CPHS design [17]. However, for CPHS design, a different foundation is needed, one that reasons about collections of components, hierarchies of components and modules, and connections and other relationships between components. Additionally, "components" must have a more general meaning than simply a physical part; it should also denote software modules, service elements, and other constituent elements that comprise CPHS. Further, the behaviors and dynamics of these generated designs must be understood to support CPHS design [18].

One aspect of this broader perspective on generative design is the capability to generate design configurations. That is, configuration design encompasses the selection of constituent elements, their connections and logical and spatial relationships, and their hierarchical organization. While conventional optimization explores design spaces that are subsets of $\mathbf{R}^n$ (i.e., design variables are real-valued dimensions and attributes), configuration design operates in large combinatorial design spaces where the analogs of design variables are discrete choices of constituents or relationships between constituents. Each element of such design spaces is a design configuration, that is, a collection of elements with relationships that may represent a partial or complete design solution. These design spaces have been described and utilized for product family design in our earlier work [19-21]. Since each design space element can have associated attributes and/or dimensions, each element represents its own continuous design space (subset of $\mathbf{R}^n$). As a consequence, configuration design spaces are large-scale mixed discrete-continuous spaces (called mixed-discrete). The bed-chair example from Section 2 is an example of configuration design reasoning in a discrete design space.

3.3 CPHS Family Design

Design of CPHS families is highly related to, and inspired by, the topic of product family design which has a long, rich research history [22,23]. A foundational concept is the development of a product platform from which all members of the product family will be generated. The platform embodies the common aspects across the family, including technologies, parts or modules, manufacturing processes, corporate investments, etc. Product family members are generated by adding options (components, modules) to the platform or scaling up/down the platform, or both. Product families with customized family members have been researched [24]. Research on product service system (PSS) families has also been reported recently [25,26].

Similarly, a CPHS family is an extension of a product or PSS family that includes cyber and human elements. More specifically, we can define a CPHS platform consisting of physical, cyber, and human platforms. CPHS family members include the platform and optional modules, functions, services, and capabilities. Platforms for the UI, services, product, and software should be determined. But the highly coupled nature of CPHSs means that they cannot be determined independently. For example, a desired service may require specific product modules, user interface capabilities, and computing resources for its realization. If that service is incorporated into the service platform, then the related items must also be included in the platforms. Using these subsystem-level families, members of the CPHS family can be generated to comprise the CPHS family.

3.4 Human Subsystem

Several topics will be briefly covered including human centered design, human-robot interaction (HRI), and Kansei engineering. Decades of research and practice on user-centered design has led to a large body of knowledge on designing for human users. The ISO 9241-210 standard on "Human centred design processes for interactive systems" [27] defines human-centered design as "an approach to interactive system development that focuses specifically on making systems usable. It is a multi-disciplinary activity." Further, usability is defined as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use." Usability objectives typically include several aspects [28]. Usefulness relates to how the product or system enables users to achieve their goals related to the tasks it was designed to perform. Effectiveness, or ease of use, is qualitatively related to intuitiveness, enabling rapid and error-free usage and quantitatively related to speed of performance and error rate. Learnability is the user's ability to operate the system to some defined level of competence after some period of training. Likeability relates to the user's perceptions, feelings, and opinions of the product, also their satisfaction with the product. The updated term of user experience design emphasizes not just users and usability but user's experiences, and how they perceive their experiences, using the product or system [29]. It is important to highlight the various related groups of users of a CPH product or system.

Decades of research on user-centered design and human-computer interaction have been augmented recently by HRI research. A good survey paper on the topic [30] identifies four main levels of HRI where the human and robot share the workspace: assistance without shared tasks, cooperation with shared but sequential tasks, collaboration with shared and simultaneous tasks, and fully autonomous where the human participates in decision making but provides no physical assistance. A variety of human input modes have been studied including hand gestures, voice, gaze, and emotions through facial expressions, leading to semantic understanding of their environment. Most of the research surveyed focused on developing technologies and applications of machine learning for the robot to learn from human interactions. The papers, for the most part, do not directly address the considerations of usability or perceptions of human collaborators.

Some progress has been made in automated usability evaluation. However, most of the work in 'automated' testing has focused on evaluation of end products to streamline and automate the collection of data from testers. Generally, usability testing involves recruiting users to use a prototype to perform a task. Information related to the level of usability (effectiveness, efficiency, satisfaction) is collected via a standardized instrument, such as the System Usability Scale (SUS) [28,29,31]. Most work focuses on automated collection, management and analysis of this data, but still requires engaging users to test each design. Some work in this direction has been done within very specific contexts, such as usability evaluation of new interfaces for software to identify anomalies in medical scans [32]. Another example is the use of a specialized system that uses computer vision to identify elements of a physical interface (a thermostat), infer the function of each element, and apply heuristic rules to assess the likely level of usability [33].

For consumer products it will important to identiy a method for automatically assessing the usability of generated designs. This will enable condideration of solutions that might otherwise go unconsidered in more traditional design environments due to time, cost, experiential bias, or other factors. A search method that can approximate both objective and subjective user response to different design options must be defined. These in turn must feed back and inform selection of technical components and attributes. Generally the constructs needed to evaluate usability are deterministic, heuristic or approximate in nature.

Attributes such as the size and arrangement of interface items can be evaluated for their deterministic impact on efficiency by employing tests such as a Fitt's Law analysis [34] to select optimal size and spacing for a given set of controls and features. To determine the proper types of controls and their arrangements, Efficiency and effectiveness can be evaluated by analyzing the arrangement or conrol components and display elements against well defined human factors and HCI heuristic design rules [35]. Satisfaction might be estimated by leveraging sets of data that have been collected from users for known use cases who represent a variety of demographics or levels of ability in the case of assistive products. Together the goal of these operations is to examine a large variety of options and suggest configurations that are most likely to be acceptable based not on technical requirements but on human capabilities and preferences. The most likely candidate designs can then be selected for user validation via traditional methods.

The field of Kansei engineering, or affective engineering, deals directly with human responses to products. Kansei engineering can be defined concisely as translating user's feelings into concrete product parameters [36] and is related to the impression somebody gets from a certain artifact, environment, or situation using all their senses as well as cognition [37]. A commonly cited example of applying Kansei concepts is the development of the Mazda Miata sports car in the 1990s. The Miata was supposed to be fun to drive which, in part, was translated into feeling faster than it is [38]. The objective of Kansei and affective engineering is to anticipate customers' responses to products to ensure the products are attractive, have characteristics that distinguish a company's products from competitors), and maximize value to the customer. This approach to engineering has been applied to a wide range of products and services, including industrial products such as construction equipment [38] and CPHS such as social and service robots [39].

4 RESEARCH GAPS

A set of research gaps is offered from the system and family design perspectives. These gaps are in addition to the significant issues associated with CPS and extensions to include humans in CPS dynamics and controls challenges.

1) What are the requirements for the CPHS family design methodology? Formulations of CPHS design and CPHS family design remain open research issues. The CPHS schematic in Fig. 1 and the approach to CPHS family design in Fig. 2 are untested proposals. That said, product family design and PSS design literature provide a solid foundation for these ideas. However, these areas of literature do not address the user interface requirements, the richness of the interface between the cyber and physical systems, or the integration across cyber, physical, and human systems. Development of a CPHS design methodology suggests the need for developing a CPHS transdiscipline.

2) How to efficiently represent and search large, combinatorial mixed-discrete design spaces for CPHS? As discussed in Section 2, new math models of mixed-discrete design spaces are needed that capture the salient characteristics of CPHS. Compared to product and product family design, CPHSshave another layer of hierarchy (i.e., combination of cyber, physical, and human subsystems) that adds complexity to the modeling challenge. Representations of these CPHS design spaces that support efficient computation also need to be investigated. Search and sampling methods are needed that enable designers to identify promising regions of these large combinatorial design spaces. These spaces are highly hierarchical. At what level in this hierarchy should search and sampling occur such that designers have enough insights into CPHS properties to make decisions? New methodology is needed to answer this and related questions.

3) How to identify cost effective cyber, physical, and service platforms for CPHS families? Significant research is needed to extend the platform development methods from product family design literature to CPHS family design, to consider the coupling among cyber, physical, and human systems, to include service family design, and to consider the need for back-end and cloud-based computing infrastructure.

4) In a quickly evolving market, when should new platforms be designed to support next-generation products? Two primary issues arise. First, CPHS should be designed to evolve with the changing needs of its user(s). The design challenge is balancing the needs to satisfy identified current requirements and user

needs with needs that may arise in the future. To the extent that it is feasible, platforms should be developed that provide a good foundation for the variety of systems that have been identified, while not precluding changes necessitated by evolving needs.

Second, at some point, the platform may not be able to support evolving needs and should be redesigned. Although technology considerations are involved, this is largely a business and market question. New market prediction, cost, and revenue models are needed to support the new platform development decision. Detailed cost and revenue models have been developed for technology diffusion and new product introduction [40] in the management literature. These should be extensible to CPHS. Customer acceptance of new technology-based products and systems remains a question that may continue to confound revenue estimate models.

5) Given platforms and options modules, how should customized CPH products be designed? What variety can be generated? Methods for generating variety and customizing products are available in the product family design literature. They need to be extended to address the complexities inherent in CPHS. One specific issue to be addressed is which subsystem should support the most granular customization capabilities. Typically, it is easiest to customize software (i.e., the cyber subsystem), but this may not lead to the most usable products for certain types of customers who may require customized physical subsystems.

An interesting issue arises when we consider a CPHS learning over time, or further, how a CPHS family may evolve over time. Considerations of CPHS variety during the design stage may greatly underpredict the range of behaviors that individual CPH products may learn after long usage by a customer. Designers may foresee some emergent behaviors among CPHS and their users, but not others. Significant research is needed to understand the issues surrounding emergent behaviors of CPHS, particularly as they evolve. Such understanding is a prerequisite to research on methods to predict these behaviors and to design to enhance or mitigate them.

6) How to analyze product usability, human responses to services, and human acceptance during CPHS design when prototypes are not yet available? As discussed in Section 3.1, analysis of CPS and their subsystems relies on technical solutions. However, human subsystems are not easily analyzed before prototypes are available. New knowledge is needed related to assessing usability and human responses of CPHS during their design. Usability is strongly linked to product success and is one of the most important measures [41,42]. Usability is more than just functional performance; it is the quality of a user's experience when interacting with a system when using it to perform a task or action. More specifically it is the effectiveness, efficiency, and satisfaction with the system when used to achieve a specific goal within a given environment [27]. These basic components are a combination of factors such as the intuitiveness of the design, ease of learning to accomplish basic tasks, efficiency of use in accomplishing tasks, the frequency and severity of errors when using the system, and the user's level of overall subjective satisfaction with the system (Usability.gov).

A generalized approach for fully automated usability assessments is yet to be explored, as presented in Section 3.4. The fields of behavioral psychology and behavioral economics seek to understand how humans behave and make decisions under various circumstances. One research direction may be to develop behavioral simulators based on defined personas and existing pools of user collected data that capture shared characteristics of specific user groups. These simulators could be based on system dynamics and ideally simulate interactions between the CPHS and each defined persona. Another direction is in the application of machine learning methods for detecting changes in customer usage, deteriorating patient behaviors or conditions, and identifying equipment malfunctions. Machine learning methods are also ideal for evaluating decisions based on well defined heuristic rulesets [43]. Another direction may be assessments based on Monte-Carlo type simulations to generate distributions of likely behaviors, from which higher level assessments of usability, acceptance, and value could be ascertained.

5 POTENTIAL IMPACT

If the research gaps can be addressed, potential impacts include contributions to the research field as well as impacts on broader society. These potential impacts are as follows.

We believe that a common design methodology can be developed for CPHS that include smart products, products through which extensive services are delivered, and even intelligent manufacturing systems. This methodology should be extensible to CPHS families through the incorporation of product family design methods. Leveraging the product (CPHS) platform enables the rapid design of products or systems within the family, enabling a company to respond to market changes more quickly than if the entire product or system had to be developed from scratch.

Generative exploration has the advantage of being able to consider vast unexplored design spaces to find options that are acceptable or even radically innovative. This generative approach promises to explore far more design options than designers could using traditional methods. The number of product/service combinations increases with complexity. It allows the increasing numbers of viable design paths to be explored that may not otherwise be considered.

Design consistency may also be improved. Designers can often encounter problems following best practices or common standards. This is due to human bias, which might prioritize aesthetic features or sub-optimal configurations based on experiential preferences as to what will work best. The rules governing the design generation or selection can ensure that all configurations conform to selected guidelines.

Better CPHS performance, robustness, and resilience should result. The design methodology should include consideration of emergent behaviors, performance variations due to market and environment changes, capability to respond to various faults and disruptions, and similar issues impacting robustness and resilience.

Broader impacts on society include the potential to discover end products which are much more usable and deliver higher customer value. This can be realized through the ability to automatically assess the usability of generated designs to highlight solutions that might otherwise go unconsidered in more traditional design environments due to time, cost, experiential bias, or other factors.

In assistive products and services, level of usability is even more critical. If a device is unwanted, difficult, or annoying to use, or brings unwanted attention to a disability, it is likely to be abandoned and go unused [44,45]. The product/service may function perfectly well and may be replacing a critical ability to perform activities of daily living, but if the usability is low a preferrable option for the user is simply not use it.

Improved customer/patient quality of life should be achievable based on a design methodology that encompasses products and systems, services, and user responses, particularly for assistive technologies and other health-tech systems. Uniform service quality can become independent of geographic location.

6 CLOSURE

This paper proposed some initial thoughts on the design of Cyber-Physical-Human Systems and CPHS families. A CPHS is a smart product or manufacturing systems that offers services through a physical device to its customer or user, supported by back-end systems (e.g., information, finance) and possibly other infrastructure. In this paper, initial concepts and research issues were presented regarding the design of CPHS families and generations of these families. Significant research gaps were identified including requirements for a CPHS family design methodology, representations for CPHS design spaces and methods for their exploration, CPHS family platform identification, identification of needs for a new platform, customized CPHS, and CPHS usability. A combinatorial mixed-discrete design space for CPHS was proposed and corresponding generative and configuration design methods were described. A brief assistive technologies example illustrated some research issues and design opportunities. Potential impacts of filling those gaps provide motivation for the development of a design methodology for CPHS. With this paper, we presented tentative ideas with the hope of interest in fostering discussion and continuing the dialog.

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