Exploring Generative Design for Assistive Devices

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Abstract: This paper discusses the potential of the application of generative design to assistive devices. The concept of a cyber-physical human system is presented. An example case of generative design to explore innovative design solutions with novel features is presented. Outstanding challenges and gaps in research are discussed.

1 Introduction

Users of assistive devices represent a continuum of abilities (Cook and Polgar, 2008), from those with slight to moderate disabilities with more general needs to those with more severe disabilities with very unique and specific needs. An assistive device (defined by the federal Individuals with Disabilities Education Act of 1990) may therefore function well for one group of users but poorly for another group. Further adding to the challenge is that the capabilities will vary not only across. different populations but also change for individuals as their needs evolve over time.

This makes design of assistive devices to fit particular needs a special challenge. User centered methods that involved users at various stages of the design process are common to help get the right mix of features and function as well as testing. These approaches are used for unique and specialized conditions as well as more general ones where a more universal solution appropriate for a wider variety of users can be found.

The process from beginning to final product can be lengthy yielding a product that must find success in a segmented, niche market. Further, as new technologies and innovations become available, they can be slow to be widely integrated into new designs. Innovations with large changes are riskier and can take more time to develop with unpredictable impact on user acceptance.

Assistive devices often then go through an elaborate but mature process of matching a user to an available device that matches the needs and capabilities of a user. It generally follows eight main steps (Kairalla et al., 2016): Referral and Appointment; Prescription; Product Preparation; User Training; Assessment; Funding and Ordering; Fitting; Maintenance, Repairs and Follow-Up. There are also many actors involved at different stages, including providers (physicians, physical/occupational therapists), payors (public/private insurers, government), suppliers (device manufacturers, resellers), and the clients (patient, caregivers or employers).

While the process seeks to find a good match, abandonment is still common. This can result from a functional match that is not ideal, to other complex issues of perceived stigma, aesthetics or other preferences (Sugawara, et.al. 2018, Dos Santos, et. al. 2022). All of the complexity leads to opportunities for improvements and efficiencies in the process of design and delivery, especially for transformative design innovations or incremental incorporation of new technologies such as smart devices, assistive robotics and novel human/machine interfaces (such as brain-computer interfaces, eye tracking and facial gesture recognition) (Schmeler et al., 2019), wearable computing devices, or "Internet of Things" (IoT) devices and applications (de Domingo, 2013; Rosen and Choi, 2021).

The rest of this paper discusses proposals for meeting some of the opportunities and challenges. In particular we explore the potential of leveraging generative design for novel, customized engineering solutions for assistive products based on its foundations in product service system and cyber physical human systems (CPHS). We also discuss the significant challenges of maintaining the voice of the user in such systems to evaluate the likely usability and appropriateness of generated designs.

2. CPHS, Generative Design and Assistive Devices

The starting point here for generating design solutions is founded in the field of Cyber-physical-social systems (CPSS). These 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 (Yilma 2021). We can identify a subset of CPSS as cyber-physical-human systems (CPHS) as smart products that offer 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.

Generative design of CPHS refers to the generation of many alternative designs that designers or customers can consider during early design stages (Autodesk 2022). The term "generative design" takes its meaning from the current geometrical design generators that resemble topology optimization solvers (Bendsoe 1995). Applied to CPHS, generative design has an expanded meaning that generates product configurations and layouts; software, computation, and communications systems; and user interfaces and interactions.

"Human" in CPHS refers to the goal of designing user/customer experiences, user interfaces, ensure user acceptance, and, overall, to ensure 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. Service design can be included under user/customer experiences and value gained. The motivation is the idea 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.

Generative design is used currently for topology optimization based software that synthesizes part shapes given structural design requirements. The software explores the design space to generate many potential solutions through which designers can browse and select designs to engineer and optimize further. These software systems incorporate some manufacturing constraints or allow the designer to specify a target manufacturing process. Outputs from generative design software 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 CPHS design. However, for CPHS design, or even the design of assemblies, a different foundation is needed, one that reasons about product architectures, including function-form relationships. Additionally, design entities (components) should denote software modules, service elements, physical components, modules, and other constituent elements that comprise CPHS.

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 (Siddique and Rosen, 2001, Hansen and Rosen, 2019). 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).

To get a sense of the structure of such design spaces, consider the combinatorial space defined by selecting collections of constituents from a set of 5 components. That is, each design space element is a subset of the 5 components. This collection of sets of subsets can be arranged hierarchically in a subset-superset lattice as shown in Figure 1. This type of hierarchy is a partially ordered set, ordered by the subset relationship. More generally, elements of design spaces can be considered as graphs, where the relationships between constituents are modeled as edges of a graph, and the ordering relation is by subgraph.

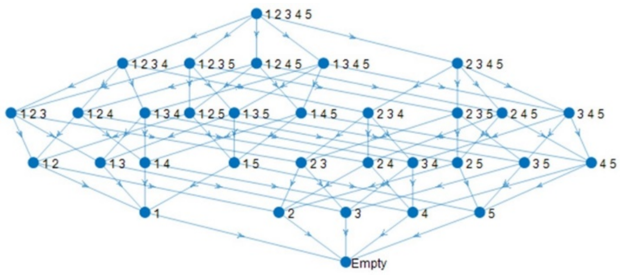

Figure 1. Partially order set of all subsets of [1, 2, 3, 4, 5].

These combinatorial mixed-discrete design spaces are presented here to highlight the importance of defining the design space before developing methods to search for design solutions. Discrete mathematics, including set theory and graph theory, can be applied. Combinatorics can estimate design space size. Further, design requirements should be modeled such that feasible regions of the design space can be identified and distinguished from infeasible regions. Search and sampling methods should be guided by the underlying mathematical structure of the design space, and should avoid infeasible regions. Generative design of CPH systems incorporates much beyond configuration design as outlined here. But, configuration design serves as a significant element of the larger design challenge.

These ideas can be applied to an example of a wheelchair (WC) CPHS family design. This starts with an identification of the highest level functions that the proposed WC family will perform. These include Transport Patient, Monitor Patient, Diagnose Patient, Monitor WC, and Maintain WC. Of these, the primary function that will be common to all CPHS's in the family is (of course) Transport Patient. An example view model for this function is shown in Figure 2, with a top-level Receiver State Parameters (RSP, indicator of customer value) of Safe & Secure Mobility identified. Associated with each sub-function is either a more specific RSP or a Function Parameter (FP). To support design of a family of WC CPHS's, usage scenarios have been developed for WC maintenance, user health monitoring, health interventions, etc. with resources identified to provide requirements for the future WC CPHS family.

At present, companies offer services to select and fit a patient to a WC, maintain the WC, and upgrade the WC with new capabilities. These services are provided through phone calls, web-sites, and technician visits. By adding sensors to the WC, we believe that additional services can be provided. Furthermore, these services will be delivered through websites with considerable back-end information technology (IT) that collects sensor data, analyzes it, and notifies appropriate personnel when the need arises. The back-end IT infrastructure could take the form of a database that requires humans to periodically check sensor readings, digital twins of each WC and patient to keep their states up-to-date, along with some decision making capabilities to notify technicians, physical therapists, occupational therapists, caregivers, or physicians, as appropriate.

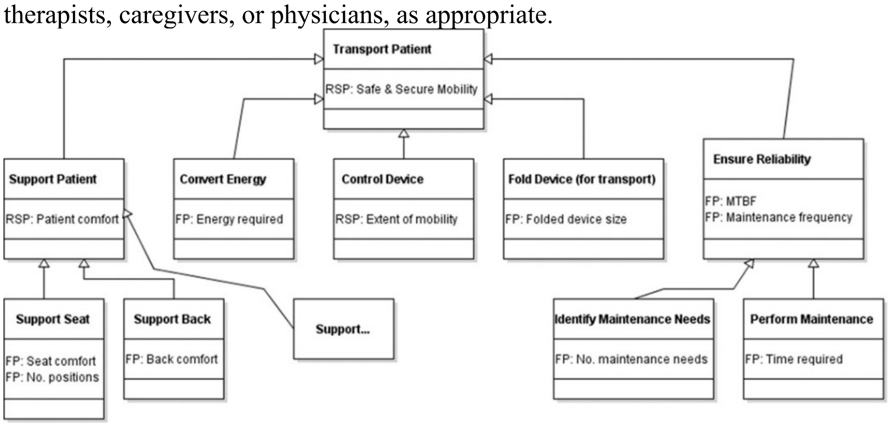

Figure 2. Function hierarchy for transport patient service, with functional parameters.

Further, patient needs can be analyzed, and some service scenarios proposed. While these service scenarios are developed, corresponding WC components should be identified as resources that enable those services. A basic service could include periodically notifying the patient's caregiver that the WC should be inspected, where the notification could be a phone call or text message. An alternative is to monitor WC status through sensors on the WC and identify maintenance needs through condition-based monitoring. Then, either the caregiver could be notified or a repair technician could be notified to arrange a visit to fix the WC. Services related to the patient could be similar; sensors on the WC could monitor patient vital signs (e.g., pulse-oxygen sensor) or their operation of the WC. If their ability to operate the WC seems to be degrading, then messages could be sent to their occupational therapist, physical therapist, or physician, as appropriate.

3 Research Gaps and Proposed Approaches

While there are many potential benefits, there are also many gaps that span multiple disciplines. Imagine a generative design system that provides an interface that allows a user (business, care provider, patient) to define a device by selecting various features. These can be mechanical (materials, load tolerances, etc), physical features/functions (interfaces, controllers, sensors, etc) or services (monitoring features, communications, etc). The system takes the specifications and searches through all of the potential combinations and presents the user with possible customized solutions that fit the provided criteria from which to select.

3.1 Managing Design Evolution and Complexity

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. The likelihood of missing emergent behaviors in the second or third CPHS generation, for example, rises significantly at the design stage of the first CPHS generation. 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.

A large variety of designs presents other issues. How can the system intelligently sort through thousands upon thousands of potential combinations and know which to present as potential solutions? In particular, the system will need some way to assess the likely usability of a generated design and be able to discard solutions which would not be acceptable.

From a broad perspective, analysis of CPHS and their cyber-physical subsystems is straightforward since these are technical constructs. Cyber systems can be designed and analyzed using the principles of computer science and software engineering. Physical products can be analyzed using engineering principles. However, human subsystems are not easily analyzed before prototypes are available.

3.2 Human voice and assessing usability

New knowledge is needed related to assessing usability and human responses of CPHS during their design. This is particularly critical when designing assistive devices. It is not good enough that they simply function. A look into the topic of abandonment will quickly surface examples of devices that seem to be designed 'well' but are rejected at high rates because they are institutional looking, generate stigma because they draw unwanted attention, or that might be desirable and functional but simply make tasks a hassle to perform. Without addressing these types of issues a generative system is likely to perpetuate similar problems with all of the same associated costs to users, insurers and providers.

Decades of research on user-centered design and human-computer interaction have been augmented recently by human-robot interaction research. There has been some progress in the area of automated usability evaluation. However, most of the work in 'automated' testing has been focused on streamlining and automating 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) are collected via a standardized instrument, such as the System Usability Scale (SUS) (Brooke 1996, 2013; Lewis, 2018). Most work focuses on automated collection, management and analysis of this data, but still requires engaging users to test each design.

There has been sparse research into methods of programmatically assessing usability using existing data sets, guidelines or heuristics without the direct involvement of users. There is a need to identify methods that are able to quickly assess hundreds or thousands of design possibilities and rank them similarly to how they would be with a human data driven tool such as SUS.

Some work in this direction has been done within very specific contexts, such as usability evaluation of new interfaces for image segmentation systems, such as those used to identify anomalies in medical scans (Amrehn, et. al. 2019). 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 (Ponce et.al. 2018).

A generalized approach for fully automated usability assessments is yet to be explored. Other fields may contribute to CPHS design, including behavioral psychology and behavioral economics. Both fields 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 agent-based or based on system dynamics and ideally simulate interactions between the CPHS being designed and each persona that has been defined. Another direction is in the application of machine learning methods. Methods such as Convolutional Neural Networks (LeCun 1995) could perform well at identifying usability problems based on heuristics or structured rules. 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.

3.3 Generative design alternatives

To illustrate some aspects of generative design, we can consider alternative WC designs that result from selections of different materials and manufacturing processes. If 3D printing in metal was considered, then complex, optimized frame geometry could be generated, such as shown in Figure 3a. On the other hand, 3D printing in polymer could be used to generate different designs. Two alternative concept sketches are shown in Figures 3b-d, which show a bulky structure (plastics are not as stiff as metal) for the frame in the operating (3b) and folded configuration (3c), assuming conventional joints among the parts. In contrast, Figure 3d shows an alternative with compliant (bending) hinges. Large configuration design spaces with various frame, joint, and other WC components may be defined in a straightforward manner.

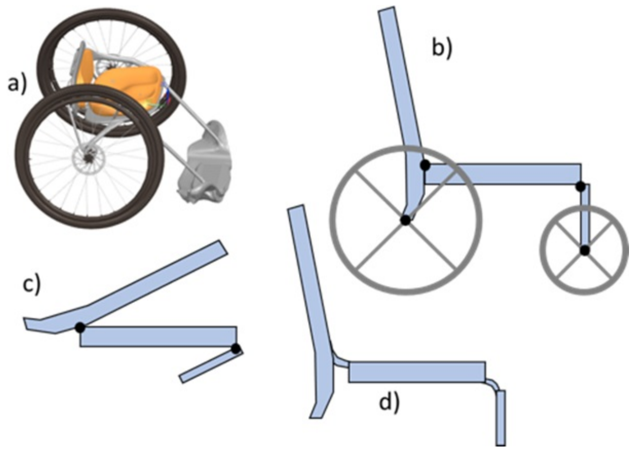

Figure 3. Wheelchair design concepts, including a) metal 3D printed optimized frame, b) plastic frame with pin joints among parts, c) plastic frame in folded configuration, d) plastic frame with compliant joints among frame segments.

Another design consideration is the need to provide customized control designs for specific patient conditions such as joysticks, tongue-drives, etc to control speed and direction. Other components with different features may be added in order to allow the generation of designs to included them. They just need to be added to the system such that all of the inputs, outputs, physical relationships and other required criteria (power requirements, physical connections, available materials, etc) are defined in relation to other possible components. With a catalog of available components many alternative designs that use one or more of these devices.

The process of generating the design alternatives is conceptually straight forward. Only the desired functional attributes need to be specified for the product output. The system then can consider all of the possible combinations based on the available library. There may be multiple control schemes that are most desirable. Each might have different input/output requirements and each option result in different possible combinations of other supporting components. The more available components and more requested features can result in exponentially larger combinations of design possibilities (in both components as well as in physical arrangement of those components).

This huge selection of alternatives is one of the chief barriers to such a system. On one hand, a generative system can consider far more possibilities, and very different combinations, than a human designer ever would be able to. Many of these designs could potentially be quite innovative or radical since the relative speed of the system can consider paths that are outside of the realm of more comfortable incremental changes. On the other hand, if the system generates millions of possibilities there is little chance that anyone would see it and select it as a potential design. This is part of the issue described in section 3.1. The other related issue is emergent behaviors. When many components are integrated together, the way that they work together can collectively lead to features and functionality that are not directly provided by any single component but emerge as a result of how they operate in relation to each other. These features can be very (un)desirable. Current generative systems can easily check that components satisfy all inputs, outputs or physical requirements between individual components, but they are not currently able to understand function that can arise from the collective operation.

The other critical barrier is in the area of user acceptance and usability. The same issue of millions of choices is at play here. Ideally, if a potential design is functionally feasible, the next step would be to get an idea of how likely it is to be usable and acceptable. Unlike an automated functional assessment, there are currently no good alternatives for automatically assessing usability. This kind of evaluation should implement checks to ensure that any design conforms to known good practice design heuristics, such as rules for human-computer interaction or proper arrangement of physical controls and displays. This way designs that very likely violate known human factors considerations can be ruled out.

It is important to note that automated usability assessment described here would not be a replacement for actual testing. However, some system would be needed in order to ensure human requirements are considered since it would be impossible to mockup and test all of the generated possibilities. An automated usability assessment would serve as an effective filter. Compared to a technical assessment, a method for assessing the possible usability or acceptability of a generated concept does not yet exist.

4 Conclusions

The system described is still an idea, yet many of the prerequisite technologies and systems already exist. Work is ongoing to explore solutions to the barriers. If these issues can be solved, it will be possible to imagine benefits to AT producers (not only of wheelchairs), better provisioning, higher satisfaction and possibly better function. A further integration into so called Industry 4.0 processes can be imagined encompassing many technologies from internet of things, cloud computing, additive manufacturing and other technologies that have an impact on manufacturing. If the components in the generative system are compatible with an automated manufacturing process, it might allow for the specification, ordering and manufacturing of bespoke assistive solutions to be integrated into the provisioning process, potentially bringing innovative solutions that are a better functional and preferential fit for users.

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