Published in final edited form as:

Proc Hum Factors Ergon Soc Annu Meet. 2018 September ; 62(1): 450–454. doi:

10.1177/1541931218621103.

Elaborating the Human Aspect of the NIST Framework for Cyber-Physical Systems

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Abstract

The National Institute of Standards and Technology (NIST) has developed a Framework for Cyber-Physical Systems (CPS Framework) that supports system engineering analysis, design, development, operation, validation and assurance of CPS. Cyber-physical systems (CPS) comprise interacting digital, analog, physical, and human components engineered for function through integrated physics and logic. For instance, a city implementing an advanced traffic management system including real-time predictive analytics and adaptation/optimization must consider all aspects of such a CPS system of systems' functioning and integrations with other systems, including interactions with humans. One *Aspect* (or grouping of stakeholder concerns) of the CPS Framework is the *Human Aspect*. NIST is engaging HFES in a panel discussion to elaborate Human Aspect concerns, especially relevant constructs, measures, methods, and tools.

SUMMARY

Human Aspect Panel Discussion at the HFES Conference

The *Human Aspect* is one of the nine high level *aspects*, or grouping of concerns, of the NIST CPS Framework (Griffor, Greer, Wollman, & Burns, 2017), and one in need of further development. This will require contributions from existing research and industrial communities. This session discusses a “straw man” scenario used to elaborate Human Aspect concerns and their component sub-concerns (such as human performance). By providing a detailed articulation of the Human Aspect, CPS and Internet of Things (IoT) design-critical issues can be identified and addressed, and the concerns used for better understanding the associated engineering requirements, tools, and interactions between human concerns and the other systems concerns that drive the design, manufacturing, service, and retirement of CPS.

INTRODUCTION

The Challenges of Emerging Project Types

A challenge of technological change is that developers and users of emerging, complex systems types do not have adequate mental models of the systems that they develop, operate, maintain, and of operator needs for training. These challenges are being addressed for existing project types, including mechanical equipment, embedded systems, mechatronics, robotics, and (mostly closed) software systems. But recently, the difficulty of these development, operations, maintenance, and training challenges has increased as systems of open, complex, interactive systems are developed that must interact with other such systems to successfully execute their respective missions. Emerging project types that entail these challenges include: multi-scale systems (Kevrekidis, Gear, & Hummer, 2004), socio-technical systems (Fischer & Hermann, 2011), cyber-physical systems (Lee E. , 2008) (Xie, 2006), ultra-large-scale systems (Northrop, et al., 2006), and complex, large, integrated, open systems (Dodder, Sussman, & McConnell, 2004).

As a point of reference, in response to the U.S. Army’s need to manage operations so complex that they “take billions of lines of code to run,” the Software Engineering Institute identified the challenge of developing “ultra-large-scale systems,” and described it as developing the equivalent of functioning, “biological ecosystems.” (Northrop, et al., 2006) More recently, many of the concerns embodied by these emerging project types have received broader industry and public interest, especially through concepts like IoT (Xia, Yang, Wang, & Vinel, 2012), the Industrial Internet (Bruner, 2013), and Industry 4.0 (Lee, Bagheri, & Kao, 2015). In summary, challenges that have long been the concerns of the aerospace, defense, and (parts of) the software industries are now also becoming the concerns of all industries that incorporate ubiquitous and open software layers with extensive interconnectivity, integration, and operational autonomy.

Addressing the challenges of such systems requires the development of fundamentally new constructs, measures, methods, and tools (this work is ongoing), as well as developing consensus in professional communities regarding foundational concepts and best practices for use of such constructs, measures, methods, and tools. NIST has facilitated such

consensus-based processes regarding the concepts of CPS, IoT, and smart infrastructure, and the results include the CPS Framework (Griffor, Greer, Wollman, & Burns, 2017), the Internet of Things-Enabled Smart City Framework (IES-City Framework), and associated tools (National Institute of Standards and Technology, 2018). NIST recognized that the Human Aspect of the CPS Framework requires development, and this panel begins an elaboration of the Human Aspect to:

- a. capture existing constructs, measures, methods, and tools used to model human interaction with CPS/IoT, and
- b. identify new constructs, measures, methods, and tools that will be required to address these development, operations, maintenance, and training challenges in the future.

NIST Framework for Cyber-Physical Systems

CPS comprise interacting digital, analog, physical, and human components engineered for function through integrated physics and logic. The NIST CPS Framework provides, “an organized presentation of a CPS analysis methodology based on the CPS Framework core concepts of facets (modes of the system engineering process: conceptualization, realization and assurance) and aspects (clusters of concerns: functional, business, human, trustworthiness, timing, data, composition, boundaries, and lifecycle).” (Griffor, Greer, Wollman, & Burns, 2017) (See Figures 1-4)

Smart City Application of the CPS Framework

The IES-City Framework is an application of the CPS Framework that provides, “tools to enable stakeholders of smart city implementation projects to perform more and faster implementations through lowered barriers to interoperability.” (National Institute of Standards and Technology, 2018) Two primary constructs of the IES-City Framework are Pivotal Points of Interoperability (PPI) (consensus standardized interfaces of CPS composition) and Zones of Concerns (ZofC) (unique sets of concerns emphasizing specific PPI at the system interface architectures). (National Institute of Standards and Technology, 2018)

Elaborating the Human Aspect

The Human Aspect of the NIST Framework for CPS addresses “concerns about human interaction with and as a part of CPS” (Griffor, Greer, Wollman, & Burns, 2017). Aspects and Concerns of the CPS are represented as a tree structure, where branching represents the decomposition of a concern. System requirements are placed at the end of a branch as leaves to indicate addressing the concern.

Considering the Role & Methods of Human Factors at a New Frontier or Systems Representation and Analysis

In relation to designing, operating, and maintaining complex, interactive project types, the Human Factors and Ergonomics (HF/E) community has developed many useful constructs, measures, methods, and tools. The Skills, Rules, and Knowledge framework, Abstraction Hierarchy (Rasmussen, 1983), and Cognitive Task Analysis (Rasmussen, 1985) address the

challenge of designing control systems with integrated automated and human-controlled operations. Cognitive work analysis (Vicente, 1999), ecological interface design (Vicente & Rasmussen, 1992), neuroergonomics (Parasuraman & Wilson, 2008), embodied cognition (Robbins & Aydede, 2009), human-machine teaming (Chen & Barnes, 2014), and human performance modeling (John, Prevas, Salvucci, & Koedinger, 2004), among others, elaborate the constructs, measures, methods, and tools necessary to design, operate, and maintain integrated human-machine systems.

In relation to the Human Aspect of the NIST CPS Framework, the HF/E community can share current best practices and active areas of research on how to represent humans and organizations as systems, and how to represent their interactions with complex technical systems. The goal of this panel is to outline some fundamental and/or broadly applicable concepts and areas of focus that can be used to organize the ensuing, larger, more detailed conversation around this topic. A Smart City Traffic Accident Scenario is used to facilitate this initial discussion.

CPS and a Futuristic Smart City Traffic Accident Scenario

My great Aunt Edna gets around Pittsburgh on a new, battery-powered, semi-autonomous scooter (scooterbot). She just tells it where to go, and it takes her there. Yesterday, she crossed a busy intersection in downtown. A semi-autonomous city bus (busbot) was waiting to turn right. The busbot queried the scooterbot and verified its goal (to cross the street), trajectory, and speed, calculated when the scooterbot would pass, and began rolling forward as the scooterbot approached the curb. The driver of the manually driven car behind the bus noticed the busbot rolling forward and rolled forward, too.

But then the battery in Edna's scooterbot shorted out and her scooterbot stopped in the street just before reaching the curb. Normally, the scooterbot would broadcast a help signal to surrounding vehicles and alert Edna to switch to manual mode, but without power, it couldn't. The busbot's sensors noticed the scooter stop, so the busbot software slammed on the brakes and stopped, but not quickly enough for poor Aunt Edna, who sat terrified as the bus rolled toward her. The human driver of the car rolling forward behind the bus, who had glanced down to look at a GPS app, did not see the bus jam on its brakes, and rear-ended the bus as a result. Everyone on the bus was jolted forward in their seats. The busbot registered the event and notified the city's smart traffic management system and smart first responder management system, which dispatched the police and EMS to the scene. People began texting, calling, and capturing video.

PANEL PRESENTATIONS

Panel Discussion Overview

Panelists discuss representation of humans in relation to CPS via the Smart City Traffic Accident Scenario.

Human Error Modeling for Autonomous Systems

Ronald Laurids Boring, Idaho National Laboratory

Much research conducted within the U.S. Department of Energy national laboratories centers on critical infrastructure systems like baseload power plants. Many of these systems represent a balance of legacy technologies (e.g., manual operated power plants) coupled with autonomous systems (e.g., electrical grid, including early implementations of smart grids). Of interest in these systems is the opportunity for human error to influence the safety and performance of the system. The Aunt Edna Scenario demonstrates how this critical infrastructure emphasis applies in new systems and how it needs to be expanded for use in new systems.

Human error modeling, including human reliability analysis, was originally developed for nuclear power applications, which included manual operation by control room and field operators. The models have been generalized to other critical infrastructure systems. The Aunt Edna Scenario shows the applicability of the human in the loop in accident scenarios and the relevance of traditional human error modeling. The scenario also illustrates the increasing role of autonomy in infrastructure, here in terms of transportation systems. Traditional human error modeling must be adapted for human-automation contexts. The NIST framework does not eliminate the need for human error modeling, but rather establishes an approach by which human error modeling can better consider new, highly automated technological contexts.

Cognitive Engineering & Decision-Making

Stephen B. Gilbert, Iowa State University

The Aunt Edna Scenario combines multiple familiar concepts from cognitive engineering and decision making: mental models (even if held by agents), short timing, and critical decisions. Edna has a mental model that includes her current destination, her current status (ok, moving through crosswalk), and the status of her scooterbot (ok, doing what it should). The scooterbot and busbot have "mental" models of the intersection and vehicles moving through it. The driver of the trailing car also has a mental model that drives his or her actions. Each agent (human and autonomous) must make decisions quickly based on these models.

In the past, a root-cause analysis of an accident like this might have included factors like stopping distance, blame for close following, blame for distraction of human drivers by devices, etc. In this scenario, however, the cause stems in part from a traffic software developer not anticipating this situation. If the NIST CPS Framework Human Aspect concern were in place, perhaps the engineer would have included a heuristic like, "scooterbots can short out spontaneously; be extra cautious when reacting to one."

NIST Framework for CPS

Edward Griffor, National Institute of Standards and Technology

The City Traffic Accident Scenario contains many CPS, including the semi-autonomous busbot, as part of a potentially broader *traffic management system*, and Edna's *scooterbot*. Both vehicles are connected, i.e., able to send and receive information about their current status. There is a myriad of concerns from the CPS Framework involved here, some of

which have been addressed in the elements of the design of the systems as revealed in the narrative of the scenario. One such concern is *Software Safety*, that led the designers to provide for the transmission of a help message, though in this case there was no alternative source of power (additional *Functional Aspect* requirements needed). To apply the CPS Framework as a design or analysis tool, one applies a concern to obtain, or identify, requirements that meet the concern. In the software safety example for vehicles this involves the application of a *functional safety* standard practice such as the one described in ISO/IEC 26262 (International Organization for Standards, 2011). To apply a *human concern*, we would similarly need a practice associated with the concern that would provide guidance as to how to create or identify the requirements needed to address that concern. Examples of human concerns indicated by the accident scenario may include Human-Machine Interaction (HMI) with Cognition, Indications, and more as *sub-concerns*.

How Smart Do We Want Surface Transportation Systems to Be?

Yi-Ching Lee, George Mason University

Surface Transportation Technical Group recognizes that the human operator is an integral component of a CPS, just as a driver is an integral component of an automotive system. As components of CPS become more technologically advanced, we need to ensure that operators and the operating environments are properly supported and maintained while adhering to safety and efficiency standards.

Just how “smart” do we want the surface transportation systems to be? How do we know when we have reached a tipping point where safety, performance, efficiency and user satisfaction is the highest? Human operator and users’ perceptions and expectations, barriers to adoption, attitudes and willingness, and trust are important aspects and milestones to consider. Equally important are special populations, such as people with disabilities, the young and the elderly, subpopulations in social and demographic context, as they may have different needs and requirements for mobility.

As we design and define smart transportation systems in a broader context of smart cities and communities, a deeper understanding of the role human operators play as well as the benefits and costs and their influences on social ecosystems is critical (Chourabi, et al., 2012). The CPS framework is a useful reference as we develop directions and agendas for research, evaluation, and implementation of smart infrastructure, vehicles, and sensors in transportation systems.

Should My Smart Fridge Tattle to My Doctor After Reordering Cookie Dough For Me?

Dan Nathan-Roberts, San Jose State University, USA

Tomorrow’s CPS tantalize us with visions of the Jetsons tv show brought to our lives, however to get there will not only require a robust set of communication protocols, but also careful thoughts around the implementation, resilience, mechanisms for updates, and the ethics of our systems.

Sociotechnical Systems research from Macroergonomics and Systems Development scholars must be leveraged at each stage of an iterative cycle of analysis, design, testing, prototyping that includes all of the stakeholders and considers cradle-to-grave Life-Cycle Assessment and environmental impact analysis. These fields have repeatedly highlighted the importance of early stakeholder involvement to reduce overall system costs via a proactive approach (Taylor & Clark, 2017), however, less common is including a focus on the implementation process apart from the desired outcomes.

Fortunately, the US Federal Aviation Administration's (FAA)'s Aviation Safety Reporting System, Step Change in Safety's Human Factors Toolkit, healthcare's moves towards resilient systems and the Food and Drug Administration's Guidance on Applying Human Factors and Usability Engineering to Medical Devices can all be studied as means to implementing effective systems so that this author doesn't get in trouble from his refrigerator.

How Do We Prepare Human Factors and Ergonomics Professionals to Overcome Complex CPS Design Challenges?

Tonya Smith-Jackson, North Carolina A&T State University

Across centuries, research and design in the extant literature and embedded within our HF/E educational programs have been dominated by perspectives of majority group members, with few perspectives, mental models, or other relevant contributions from underrepresented minorities, those with disabilities, or individuals who have been ascribed less power and privilege within the larger culture. While these groups have been participants in research, they have not been equally represented at the level necessary to yield equity in benefits and outcomes of CPS, for example. In fact, such concepts as algorithmic fairness arose from scholars in engineering, computing, information science, and the social sciences who understood how traditional methods in science and engineering perpetuated inequities.

From the scenario of Aunt Edna, quite a few concepts emerge that raise the need to increase the rigor of the educational programs in HF/E to better understand and advocate for algorithmic fairness and design equity (Wachter-Boettcher, S., 2017). Some concepts might include accuracy equity and disparate impact (Binns, 2018) (Camp, 2012); Camp, 2012). An expansion of the knowledge base to include implicit bias in design, quantification, and evaluation would contribute to more effective preparation of HF/E professionals in IoT and CPS. These concepts will be discussed in the context of subject matter for classroom integration and research preparation using inclusive research excellence practices.

Future Work

Our aim to elaborate the *Human Aspect* of the CPS Framework, a fragment of which is represented by the CPS Framework concern tree in Fig. 4. The elements of this tree can be represented, for example, as we represent paths in a file system. Possible examples suggested by these panelists contributions are cognition/perception/situational awareness, decision-making/mental models, and ethics/fairness.

ACKNOWLEDGEMENTS AND REFERENCES

The organizers and panelists would like to thank the National Institute of Standards and Technology and the Human Factors and Ergonomics Society for supporting this discussion, as well as our respective organizations. This document includes official contributions of the National Institute of Standards and Technology; not subject to copyright in the United States.

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Figure 1.
NIST Process for Analysis/Development of CPS (Griffor, Greer, Wollman, & Burns, 2017)

Figure 2.
NIST Representation of Cyber-Physical Systems Concepts (Griffor, Greer, Wollman, & Burns, 2017)

Figure 3.
CPS Framework Concern Tree Example

Figure 4.
Relationship of Humans and CPS in NIST CPS Framework (Griffor, Greer, Wollman, & Burns, 2017)

Figure 5.
Smart City Traffic Accident Scenario