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A function-to-task process model for adaptive automation system design☆,☆☆

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ABSTRACT

Adaptive automation systems allow the user to complete a task seamlessly with a computer performing tasks at which the human operator struggles. Unlike traditional systems that allocate functions to either the human or the machine, adaptive automation varies the allocation of functions during system operation. Creating these systems requires designers to consider issues not present during static system development. To assist in adaptive automation system design, this paper presents the concept of inherent tasks and takes advantage of this concept to create the *function-to-task design process model*. This process model helps the designer determine how to allocate functions to the human, machine, or dynamically between the two. An illustration of the process demonstrates the potential complexity within adaptive automation systems and how the process model aids in understanding this complexity during early stage design.

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1. Introduction and definitions

Consumer, commercial, and government systems increasingly apply automation, particularly in systems which involve time critical decisions and actions. These systems include manufacturing plant process control (Itoh et al., 1999; Valente et al., 2010; Valente and Carpanzano, 2011), aircrew and air traffic control (Prevot et al., 2008), and remotely piloted or controlled vehicles (Parasuraman and Wickens, 2008; Parasuraman et al., 2009; Kidwell et al., 2012). Automation can improve the performance of systems without increasing manpower requirements by allocating routine tasks to automated aids, improving safety through the use of automated monitoring aids, and reducing the overall cost or improving productivity of systems (Rouse, 1981). Additionally, automation can permit removal of the operator from particularly undesirable or dangerous environments (Nakazawa, 1993), increasing the safety and reducing stressors placed upon the operator.

Unfortunately, automation system designers have limited ability to project future events, and are often unable to adapt when unforeseen circumstances occur. As such, utilization of a human operator who can adapt to these unforeseen circumstances to provide system resilience is desirable (Woods and Cook, 2006). With the inclusion of a human operator, other problems arise. Some include over-reliance on automation (Itoh, 2011), placing inappropriate levels of trust in the automation (Dzindolet et al., 2003; Lee and See, 2004; Merritt et al., 2012), or losing situation awareness to preclude appropriate recovery from automation failures (Itoh, 2011). Further, as operators are not performing active control of the system, they may not practice the knowledge necessary to operate the system and can suffer from skill atrophy (Kirwan, 2005). As a result, practitioners developed adaptive automation systems to maintain user engagement, without overloading operators (Rouse, 1977).

Automation is the capability "to have a computer carry out certain functions that the human operator would normally perform" (Parasuraman et al., 2000). Knowing which entity will perform a given task helps determine whether to automate a task or not. There are many types of tasks, and consequently, several forms of automation. The categories of automation can include "the mechanization and integration of the sensing of environmental variables; data processing and decision making; mechanical action; and 'information action' by communication of processed information to people" (Sheridan and Parasuraman, 2005).

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Since Rouse proposed a dynamic approach to automated decision-making (Rouse, 1977, 1981), the field has adopted the terms *adaptive automation* and *adaptive systems* to define the idea of an automated system that can adapt to a changing environment. Within research, the definition of adaptive automation has been subject to debate. Most authors would agree that levels or types of automation change in an adaptive system. For example, Dorneich et al. (2012) define adaptive systems as those "allowing the system to invoke varying levels of automation support in real time during task execution, often on the basis of its assessment of the current context... invoking them only as needed". This view of adaptive automation places the onus of determining the current automation state on the system. However, others have shown that even the determination of who 'adapts' the system (e.g., the system and the operator) can fall on a sliding scale (Parasuraman and Wickens, 2008).

Within the current context, a *system* is a combination of hardware, software, and human operators that work together to accomplish one or more goals. As a focus of the paper is system design, the term *machine* refers to the combination of all hardware and software within the system with which the human operator interacts.

Although the terms *function* and *task* are sometimes applied interchangeably (Bye et al., 1999), clear differentiation of these terms leads to a better understanding of the proposed process model. Here, we define a *function* as an action that an element of a system performs to accomplish the desired goals or to provide the desired capability. A function is delineated from a task as the function is not allocated to an entity. A *task* is a function allocated to a specific entity, and represents the actions necessary for the entity to perform the function.

A task's allocation can be either explicit or inherent. An *explicit* task is one that is directly indicated by a previously defined function. Alternatively, an *inherent* task arises only once a function is allocated to a specific entity. An inherent task is not required by the function, but is necessary to enable the allocated entity to perform the function. For example, the system might require an operator to make a selection, requiring an explicit action. However, to make this selection, the operator will need to gather appropriate information from the system or environment and make decisions, each of which an inherent task. *Task load* then describes the number and difficulty of tasks assigned to human operators, to which they must respond.

Workload refers to the impact of the task demand placed upon the operator's mental or physical resources. The variability in the task load imposed upon an operator (and the workload the operator experiences) originates from a number of sources. In addition to the variance of performance due to explicitly defined workload, the performance of the human operator may vary due to individual factors such as fatigue, stress level, motivation, and training level (MacDonald, 2003; Reid and Nygren, 1988).

This research presents a function-to-task design process model to aid the conceptual design of adaptive automation systems. The function-to-task design process model creates a set of visual diagrams enabling designers to better allocate tasks between human and machine. This is achieved through a set of five analysis tools allowing designers to identify points within a function network where the transitions between human and machine entities can facilitate adaptive automation. This paper proceeds as follows. Section 2 reviews the design processes currently in place for adaptive automation systems. Section 3 presents the function-to-task design process model. Section 4 illustrates the function-to-task design process model through a system design iteration. Section 5 presents conclusions summarizing the information presented.

2. Designing adaptive automation systems

Discussions on the design of manned systems as a tool to aid allocation of functions or tasks between a human operator and a machine often cite Fitts' List (Fitts et al., 1951) of tasks that machines tend to perform "better" than humans and those that humans perform "better" than machines. Fitts et al. discussed tasking the machine to perform routine tasks that require high speed and force, computational power, short-term storage, or simultaneous activities; and further propose leveraging the human's flexibility, judgment, selective recall, and inductive reasoning to improve system robustness to unforeseen circumstances. They also acknowledge the limitation of humans to correctly employ these capabilities when overloaded due to excessive task demands or to maintain alertness and employ these capabilities when not actively participating in system control.

One may consider the allocation of functions between man and machine within a system as a multi-objective optimization, wherein designers optimize some combination of performance, safety, and robustness as a function of the tasks allocated to each component. The limitations of system and human capability shape this optimization, with a significant component of human capability quantified in terms of human workload. Adaptive automation system design assumes that the number and difficulty of tasks performed will vary over time, and the tasks allocated to the human or machine need to vary to provide the human operator with an appropriate workload.

Fig. 1 illustrates this concept, which depicts a two-dimensional space which arranges tasks, T1–T9, based on how well a human operator or the machine can perform them under reasonable task load. As shown, performance by either system can range from unsatisfactory through excellent (Price, 1985). We should allocate tasks, such as T1 or T8 – which one entity (human or machine) can perform more satisfactorily – to the better performing entity. However, any task that either entity can perform beyond the point of satisfactory performance, we can reasonably allocate to either human or machine.

If there was no constraint on resources, one could maximize performance of the overall system by allocating tasks below the 45° line to the human and tasks above to the machine. However, resource constraints force a shift in the location of this line. For instance, assuming workload limits on human performance and unbounded machine resources might induce the designer to shift the dividing line lower in the plot, decreasing human workload and allocating additional tasks to the machine. On the other hand, if users' performances improve by increasing their engagement with the system, raising the dividing line allocates more tasks to the human. Therefore, adaptive automation effectively requires the system to permit this allocation line to shift up and down

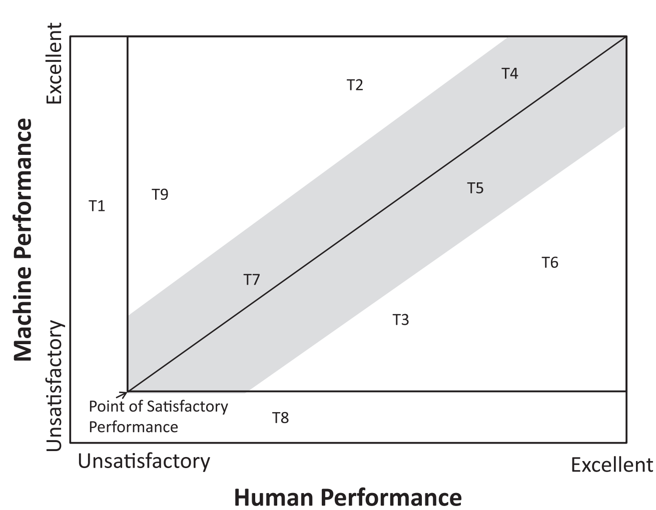

Fig. 1. Diagram for task allocation in adaptive automation, adapted from Price (1985).