Development of a Generic Design Framework for Intelligent Adaptive Systems

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Abstract. A lack of established design guidelines for intelligent adaptive systems is a challenge in designing a human-machine performance maximization system. An extensive literature review was conducted to examine existing approaches in the design of intelligent adaptive systems. A unified framework to describe design approaches using consistent and unambiguous terminology was developed. Combining design methodologies from both Human Computer Interaction and Human Factors fields, conceptual and design frameworks were also developed to provide guidelines for the design and implementation of intelligent adaptive systems. A number of criteria for the selection of appropriate analytical techniques are recommended. The proposed frameworks will not only provide guidelines for designing intelligent adaptive systems in the military domain, but also broadly guide the design of other generic systems to optimize human-machine system performance.

Keywords: design guidance, design framework, intelligent adaptive interface, intelligent adaptive system.

1 Introduction

Computer-based systems assist operators in a myriad of mental and physical activities (e.g., decision support systems, automation, expert systems, and information fusion), to varying degrees of autonomy (e.g., tool, aid, associate, autonomous agent), and sophistication (e.g., assistant, associate or coach). There is a need to develop a unified framework to describe these conceptual approaches using consistent and unambiguous terminology. In addition, a lack of integration between the Human Factors (HF) and Human Computer Interaction (HCI) communities has increased the propensity for terminology to become ambiguous and misleading when applied globally. Furthermore, there are no established design guidelines for advanced operator interfaces used by decision-makers dynamically managing enormous amount of data and information in a complex and networked environment (e.g., World Wide Web or network centric warfare). In order to redefine the field in question, it is necessary to develop a framework of design guidelines encompassing both HF and HCI approaches. Defence Research & Development Canada (DRDC) has completed a project focused on developing theoretical concepts and preliminary guidelines for designing an agent-based interface system [1] [2]. The aim of this paper is to examine existing approaches in the

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design of intelligent adaptive systems. A unified framework to describe design approaches using consistent and unambiguous terminology was developed.

2 Methodology

Relevant literature was collected from scientific, defence, government, and internet-based sources pertaining to intelligent adaptive systems. The obtained literature was categorized into four topic areas: conceptual and project-related framework (68); analytical techniques (32); design principles and considerations (113); and psychological and behaviorally-based implementations (24). All articles were then classified in terms of Level of Experimentation, Peer Review, Domain Relevance and Literature Review Area. The literature was collated and reduced according to appropriate selection criteria. Table 1 details the number of articles classified according to the level of experimentation involved (i.e., conceptual study with no evaluation, single laboratory-based evaluation, single simulator- or field-based evaluation, and multiple laboratory-, field- or simulator-based evaluations), degree of peer review (i.e., none, conference proceedings and journal article), and proximity, and therefore relevance, to military domains (i.e., basic, business, industrial and military). These results demonstrate that the breadth of articles reviewed is sufficient, as a large number of articles have been used in all four topic areas.

Table 1. Number of references used in the literature review grouped by level of experimentation, peer review and domain relevance

	Level of Experimentation				Peer Review			Domain Relevance			
	Conceptual	Single Lab Evaluation	Single Sim/Field Evaluation	Multiple Evaluation	None	Conference	Journal	Basic	Business	Industrial	Military
Total	63	27	39	29	47	88	24	36	14	20	90

3 Intelligent Adaptive Systems

3.1 Automation and Interface

Traditionally, there have been two main thrusts of research and development addressing problems associated with operators working under conditions of excessive workload (e.g., sub-optimal task performance, error, and loss of situation awareness). The first body of research originated from the HF community, and was aimed at assessing the effects of adaptable automation on operator performance and workload within error-critical domains, such as aviation and industrial process control. The second approach originated from the HCI community, and consisted of research assessing the effects of adaptable operator machine interfaces (OMIs) on operator performance within relatively more harmless domains, such as word processing and web browsing.

Despite the obvious similarity between the HF and HCI research into intelligent adaptive systems, there is a paucity of research concerned with integrating these two research streams. This is an unfortunate oversight, as the lack of integration of these research streams creates potential for confusion over terminology.

3.2 Intelligent Adaptive Systems (IAS)

Capable of context-sensitive communication with the operator, intelligent adaptive systems (IAS) are a synergy of intelligent adaptive automation and intelligent adaptive interface technologies. IAS technologies currently under construction operate at the level of Assistant (e.g., Germany's CASSY/CAMMA programs [3], France's Co-pilote Electronique program [4]), Associate (e.g., USAF Pilots' Associate [5]) and US Army Rotorcraft Pilots' Associate programs [6], and Coach (e.g., the United Kingdom's Cognitive Cockpit program [7]).

Technological advances in both Artificial Intelligence and the physiological monitoring of human performance have the potential for enabling higher levels of intelligent support. Thus, in future, IAS will be considered fully integrated, intelligent systems that take on agent-like properties, rather than conventional systems with a discrete automation control centre. Future IAS will be able to: a) respond intelligently to operator commands, and provide pertinent information to operator requests; b) provide knowledge-based state assessments; c) provide execution assistance when authorized; d) engage in dialogue with the operator, either explicitly or implicitly, at a conceptual level of communication and understanding; and, e) provide the operator with a more useable and non-intrusive interface by managing the presentation of information in a manner appropriate to the content of the mission [8].

4 Generic Conceptual Framework for IAS

After reviewing the approaches concerned with the design of an intelligent adaptive system, a generic conceptual framework was developed. It has the following four components, which are common to all conceptual frameworks:

- *Situation Assessment and Support System.* Comprises functionality relating to real-time mission analysis, automation, and decision support in order to provide information about the objective state of the aircraft/vehicle/system within the context of a specific mission, and uses a knowledge-based system to provide assistance (e.g., automate tasks) and support to the operator.
- *Operator State Assessment.* Comprises functionality relating to real-time analysis of the psychological, physiological and/or behavioural state of the operator in order to provide information about the objective and subjective state of the operator within the context of a specific mission.
- *Adaptation Engine.* Utilizes the higher-order outputs from Operator State Assessment and Situation Assessment systems, as well as other relevant aircraft/vehicle/system data sources, to maximize the goodness of fit between aircraft/vehicle/system state, operator state, and the tactical assessments provided by the Situation Assessment system.

- *Operator Machine Interface (OMI)*. The means by which the operator interacts with the aircraft/vehicle/system in order to satisfy mission tasks and goals; also the means by which, if applicable, the operator interacts with the intelligent adaptive system.

All four components operate within the context of a *closed-loop* system: a feedback loop re-samples operator state and situation assessment following the adaptation of the OMI and/or automation (see Figure 1).

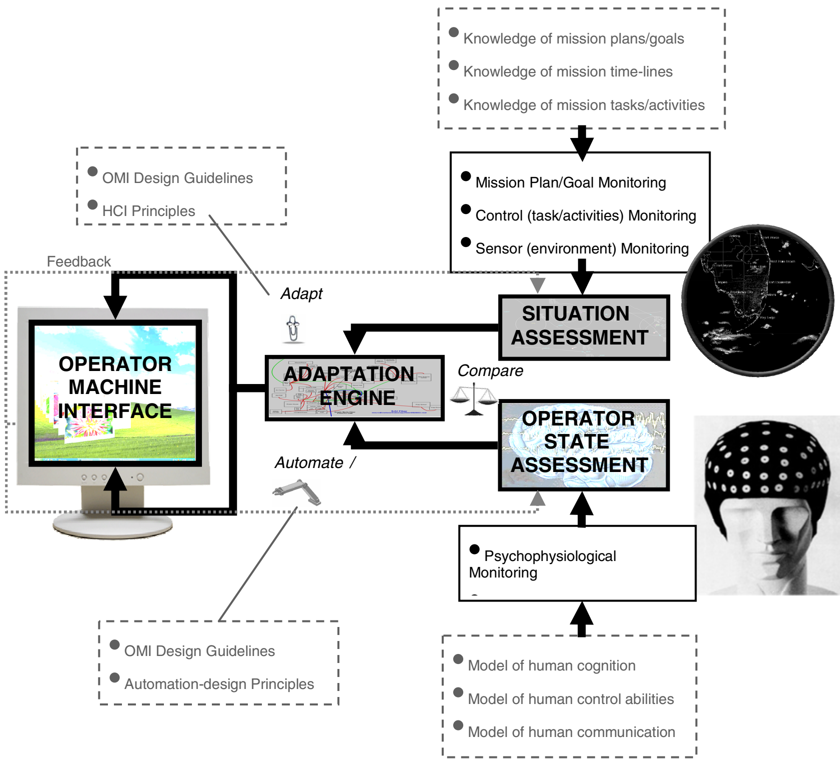

Fig. 1. Generic Conceptual Framework for Intelligent Adaptive Systems

5 Generic Framework for the Development of IAS

One of the most recent and comprehensive attempts to generate a design and development framework for intelligent adaptive systems was done by Edwards [9]. Edwards examined a variety of theoretical approaches to generate a generic, integrated and comprehensive framework for the development of an intelligent, adaptive, agent-based system for the control of Uninhabited Aerial Vehicles. These design approaches are CommonKADS (Knowledge Acquisition and Design Structuring) [10], IDEF (Integrated Computer Aided Manufacturing Definition) standards [11], Explicit Models Design (EMD) [12], Perceptual Control Theory (PCT) [13], and Ecological Interface Design (EID) [14].

The framework provides a comprehensive and efficient means of developing intelligent adaptive systems. The output of these processes is the construction and specification of a number of models that are used to construct an intelligent adaptive system:

- *Organization Model.* This model incorporates knowledge relating to the organizational context that the knowledge-based system is intended to operate in (e.g., command and control (C2) structures, Intelligence Surveillance, Target Requisition and Reconnaissance - ISTAR etc.);
- *Task Model.* This model incorporates knowledge relating to the tasks and functions undertaken by all agents, including the operator;
- *Agent Model.* This model incorporates knowledge relating to the participants of the system (i.e., computer and human agents), as well as their roles and responsibilities;
- *User Model.* This model incorporates knowledge of the human operator's abilities, needs and preferences;
- *System Model.* This model incorporates knowledge of the system's abilities, needs, and the means by which it can assist the human operator (e.g., advice, automation, interface adaptation);
- *World Model.* This model incorporates knowledge of the external world, such as physical (e.g., principles of flight controls), psychological (e.g., principles of human behaviour under stress), or cultural (e.g., rules associated with tactics adopted by hostile forces);
- *Dialogue/Communication Model.* This model incorporates knowledge of the manner in which communication takes place between the human operator and the system, and between the system agents themselves;
- *Knowledge Model.* This model incorporates a detailed record of the knowledge required to perform the tasks that the system will be performing; and,
- *Design Model.* This model comprises the hardware and software requirements related to the construction of the intelligent adaptive system. This model also specifies the means by which operator state is monitored.

Operationally, Edwards' framework illustrates the sequential process by which the models described above are created (see Figure 2). Indeed, common to all approaches reviewed in this document are the following system functions:

- Modified OMI to handle the interaction and dialogue between the operator and the systems agents (e.g., tasking interface manager);
- Tracking of operator goals/plans/intent (and progress towards them);
- Monitoring of operator state;
- Monitoring of world state; and,
- Knowledge of the effects of system advice, automation and/or adaptation on operator and world state (i.e., closed-loop feedback).

Furthermore, the models described here can also be mapped onto the generic conceptual framework described in Section 4 (see Figure 1). The association of Figures 1 and 2 indicates that: the User Model enables physiological monitoring of the operator; the Task, System, and World Models enable the monitoring of mission plan/goal completion, tasks/activities, as well as entities and objects in the external environment; the Knowledge Model enables the system to provide advice to the operator, automate tasks, or adapt the OMI; and that the Dialogue Model enables the interaction between the system and the operator. This shows the implementation of the generic conceptual framework. Figure 2 also illustrates each of the models with the relevant tools/methods/techniques relating to the design of intelligent adaptive systems, specifically:

- *Cognitive Analysis Methodologies*. Contribute to the construction of the Task, Agent and User Models;
- *Task Analysis Methodologies.* Contribute to the construction of the Task, Agent and System and World Models;
- *Human-Machine Function Allocation and Agent-based Design Principles*. Contribute to the construction of the Agent, Dialogue and Communication Models;
- *Human-Machine Interaction and Organization Principles*. Contribute to the construction of the Dialogue and Communication Models;

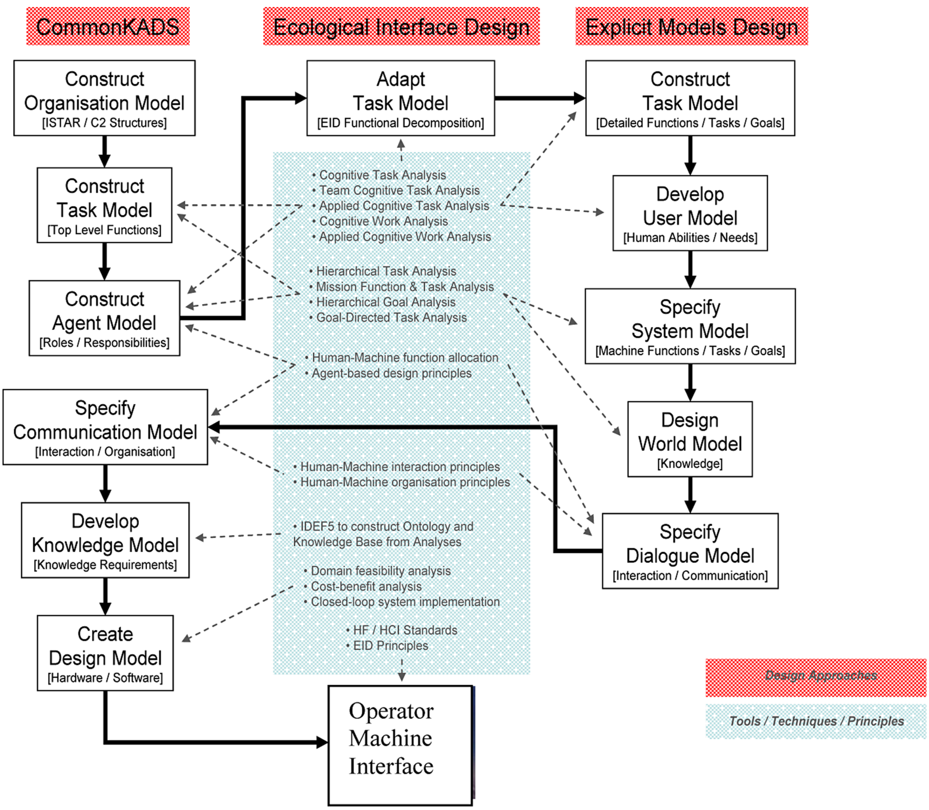

Fig. 2. Generic Framework for the Development of Intelligent Adaptive Systems

- *IDEF5 Guidelines*. Contribute to the construction of the ontology and knowledge base. This is then used to enumerate the knowledge captured by the analysis process;
- *Domain Feasibility, Cost-Benefit Analysis and Principles for Closed-Loop Implementation*. Contribute to the construction of the Design Model, including the means by which operator state is monitored; and,
- *Human Factors and Human Computer Interaction Principles.* Contribute to the construction of the OMI and related systems. The design process might also include principles from Ecological Interface Design.

Most of the tools/techniques/methodologies are generic (i.e. context independent) and scalable. The selection of the analysis tools is less critical as they are for the most part adjustable, and can be (and sometimes must be) modified to suit the domain. In addition, approaches can be combined to play to their strengths and mitigate weaknesses. There are a number of criteria that can be used to determine which of the analysis and design tools, techniques and methodologies described can be used for the design and development of a specific intelligent adaptive system. These criteria are:

- Project constraints: schedule and budget.
- Domain: complexity, criticality, uncertainty, and environmental constraints (particularly relevant to the choice of operator state monitoring systems).
- Operator: consequences of error and overload, what kind and quantity of support is needed, who needs to be in control (particularly relevant in combat domains).
- Tasks: suitability for adaptation, assistance or automation.

6 Conclusion

An extensive literature review has been conducted to examine approaches related to the design of intelligent adaptive systems. A unified framework to describe these approaches using consistent and unambiguous terminology was developed. It integrates design methodologies from both HCI and HF fields and provides generic conceptual guidance for the design of intelligent adaptive systems including human-machine interfaces. In addition, generic design guidance for the implementation of the conceptual framework was also generated to guide detailed analyses of system component models with associated analytical tools. A number of criteria for the selection of appropriate analytical techniques were also recommended. The proposed frameworks will not only provide guidance for designing intelligent adaptive systems in military domain, but also guide other generic systems to optimize human-machine system performance.

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