Integrating Human Factors and Artificial Intelligence in the Development of Human-Machine Cooperation

Peter-Paul van Maanen*‡, Jasper Lindenberg*, and Mark A. Neerincx*†

* Department of Information Processing, TNO Human Factors
P.O. Box 23, 3769 ZG Soesterberg, The Netherlands
Email: {peter-paul.vanmaanen, jasper.lindenberg, mark.neerincx}@tno.nl
† Man-Machine Interaction Group, Delft University of Technology
Mekelweg 4, 2628 CD Delft, The Netherlands
‡ Department of Artificial Intelligence, Vrije Universiteit Amsterdam
De Boelelaan 1081a, 1081 HV Amsterdam, The Netherlands

***Abstract*— Increasing machine intelligence leads to a shift from a mere interactive to a much more complex cooperative human-machine relation requiring a multidisciplinary development approach. This paper presents a generic multidisciplinary cognitive engineering method CE+ for the integration of human factors and artificial intelligence in the development of human-machine cooperation. Four case-studies are presented which contain a description of the developed human-machine cooperation and the adjusted CE+ method used. For each case-study the method supported research and development activities in such a way that sound knowledge bases, methodologies, and user interfaces for human-machine cooperation could be established. However, the method always needed to be tailored to the specific goals and circumstances, such as the available time, novelty, and required integration.**

***Index Terms*— Human-machine cooperation, integrated system design, cognitive engineering, human factors, intelligent user-interfaces.**

I. Introduction

Living, travel and working environments contain a growing number of networked information compilations and electronic services (e.g., health-care and security services), which are accessible to an increasing number of diverse user groups. In current human-computer interaction (HCI) research, personalization, adaptive interfaces and electronic assistants are proposed to enable easy access to the proliferating functions and services in such environments for both the consumer and professional domain (e.g., [1]–[3]). The increasing intelligence of machines leads to a shift from HCI to human-machine *cooperation* (HMC) [4]. Future machines will either be designed to cooperate, or designed to learn how to cooperate, with humans. They will be able to assess and adapt to human goals [5]. It was only first mentioned in [6] that there is a growing need for humans and machines to comprehend each other's reasoning and behavior. And since the last decade or so, one is beginning to realise that exactly this really requires researchers with different backgrounds to believe in a more multidisciplinary approach.

For HMC the aim is to customize support by accommodating individual user characteristics, tasks and contexts in order to establish HMC in which the computer provides the "right" information and functionality at the "right" time and in the "right" way [7].

The customization that one encounters today at work, during travel or at home is rather limited, appearing as static user interfaces with simple or "local" adaptations [8], [9]. The possibilities for HMC are extensive, however knowledge is lacking on both the specific human factors (HF), the artificial intelligence (AI) prospects and on ways of successfully integrating both HF and AI during development. This paper focuses on the latter, the integration of HF and AI during research and development (R&D) of HMC. An extensive and diverse set of HF methods and tools are distinguished and proposed for the design of tasks and user interfaces, for instance from the perspective of (cognitive) task analysis (e.g., [10]–[12]), HCI (e.g., [13], [14]) and usability engineering (e.g., [15]–[17]). Furthermore, there is an extensive and diverse set of guidelines and standards for HCI in general (e.g., [18]), and for specific application domains (e.g., [19]). A major challenge for the development of complex and dynamic human-machine systems — such as industrial process control, aerospace and traffic control — is to develop HMC and realize concrete design practices in the near future. A suitable candidate for this activity is cognitive engineering with its roots in both principal contributors HF and AI. Other available development methods are too heavily focused on their own origin (human or technology), and have a blind spot for the other domain. Methods focused on integration such as MUSE [20] or even ISO 13407 are not well suited for innovation. An extended generic cognitive engineering method CE+ is presented and four case-studies illustrate the use of this method and the required adjustments based on specific project requirements and circumstances.

II. The Cognitive Engineering Method CE+

Cognitive engineering (CE) approaches originated in the 1980s to improve computer-supported task performance (e.g., [21], [22]) and emerged from the fields of cognitive science and AI. CE aims at generating new or enhanced

HCI by increasing insight in the cognitive factors of human performance [23]. Furthermore, CE guides the iterative process of development in which an artifact is specified in more-and-more detail and specifications are assessed more or less regularly to refine the specification, to test it, and to adjust or extend it. The original CE methodology was extended with an explicit technology input thus creating the CE+ method. This extension was primarily made because of two reasons. First, the technological design space sets a focus in the process of specification and generation of ideas. Second, the reciprocal effects of technology and HF are made explicit and are integrated in the developent process. In Figure 1 the development process of the extended method CE+ is shown. The HF knowledge provides relevant expertise (i.e., guidelines and support concepts) and techniques for the specification and assessment of HMC. The technological design space sets the technological and operational requirements for HMC. In the specification both the guidelines and the technological design space must be addressed concurrently. In the assessment it is checked whether the specifications agree with these guidelines and the technological design space. An assessment will provide qualitative or quantitative results in terms of effectiveness, efficiency, satisfaction and user experience which are used to refine, adjust or extend the specification. Eventually, the process of iteration stops when the assessment shows that the HMC satisfies all requirements [24]. The above thus suggests dynamic integration of knowledge into the design process rather than *a priori* specification of guidelines.

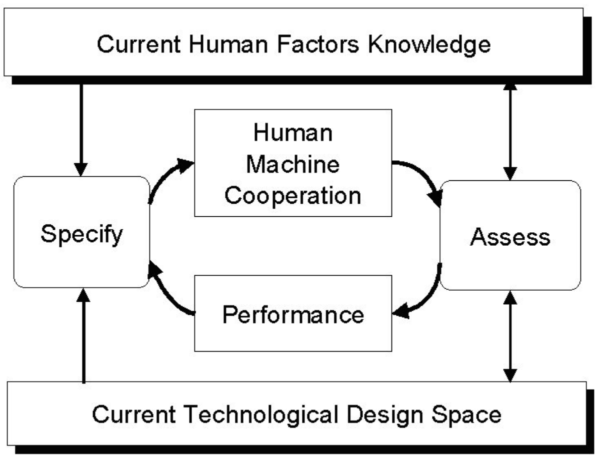

Fig. 1. The development process of the CE+ method.

III. Case-studies

A. Personal Assistant for onLine Services

The Personal Assistant for onLine Services (PALS) project was aimed at substantially improving the user experience of mobile internet services [25]. It focused on a generic solution: a personal assistant, which attunes the interaction to the momentary user needs and use context (e.g., adjusting the information, presentation and navigation support to the current context, device and interests of the user).

The PALS project was carried out using CE+. The method was adjusted to fit the specific needs of the PALS project. The goal of the project was not only to realize an effective and efficient PALS but also to generate fundamental HF and AI knowledge. Therefore, three research lines can be distinguished within the adjusted method for the PALS project (Figure 2):

1) PALS creation: using a cognitive engineering approach.
2) Basic HF research: extending the HF knowledge base.
3) Basic technological research: extending the AI knowledge and engineering base

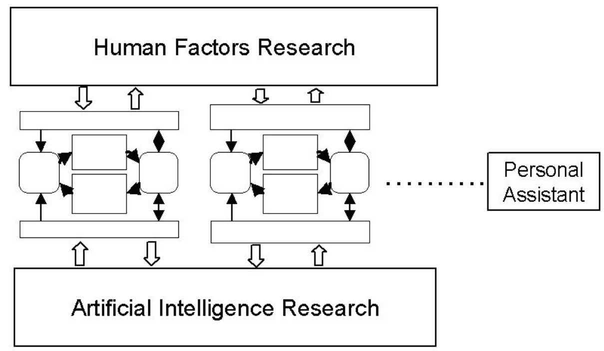

Fig. 2. The CE+ development process in the PALS project.

The first research line focused on the actual realisation of a PALS demonstrator guided by the cognitive engineering process (Figure 3). In different stages knowledge and/or technology was needed that was not available at that time. This knowledge was developed within the two, discipline focused, research lines of PALS, both enabling the realization of an effective PALS and extending the HF and AI knowledge base. For example, the influence of attention on mobile user interaction, and the AI techniques to attune the interaction to the users attentional state. These issues were examined by developing a rule-based in-car system that predicted the momentary mental load caused by the driving task and attuned the dialogue accordingly to prevent overload. In addition to the CE+ generated questions that "fed" the basic research, autonomous processes within the basic research line "fed" the CE+ process by providing new interaction concepts. The specific circumstances of this project such as the combination of fundamental research with prototype development, the relatively long running time, and the physical distance between the participating partners gave rise to the specific method that was used. The integration of HF and AI technology in PALS resulted for example in a Point of Return indicator, an Interactive Suspension Point and a Tailored Information View, based on mining and (graph) modeling of user behaviour data and the identification of HF bottlenecks in mobile environments.

B. Context Aware Communication Terminal and USer

The Context Aware Communication Terminal and USer (CACTUS) project aimed at researching technological and usability aspects of human-machine and machine-network

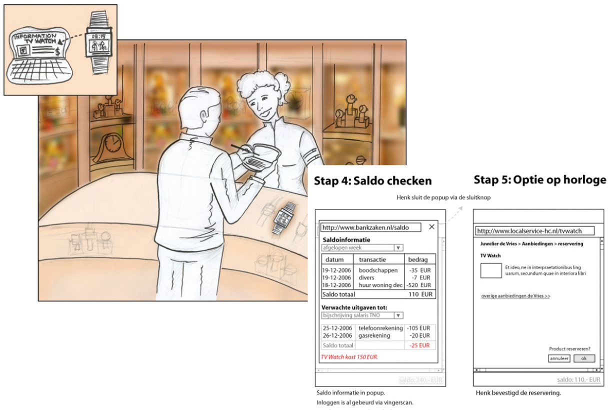

Fig. 3. Scenario based design was used to specify the interaction.

interaction with personalized, intelligent and context-aware wearable devices in ad-hoc wireless environments such as the future home, office, or university campus. In this paper we will focus on a part of the project which was concerned with the selection and identification of agents in an ubiquitous computing environment. Future AI and HF problems were identified by a technology assessment early on in the project. It turned out that current techniques for identification and selection of agents in ubicom environments were not scalable leading to all types of HF and AI performance problems. This instigated a research program containing both an AI and HF challenge: create a scalable decentralized agent system which enables users to identify and select the best service to obtain their goals. The CE+ method described in the previous section contained two separate, domain specific, research lines which are integrated by a third development line. That particular set-up was not suited for CACTUS because of the limited amount of time that was available and the strict interactions between the AI and HF challenge. Therefore, both domains were studied in an integrated manner. A realistic technological solution for the predicted HF problems was conceived and implemented within a limited environment. This technology enabled the user to simply express his goal, in a decentralized manner each agent decided whether or not it was capable. The most capable agents would rise to the surface and offer their services to the user. Early on in the development the technology was empirically tested with a realistic mock-up in which the actual behavior of the technology was simulated by a human operator (Wizard of Oz) (see [26] and Figure 4). Because experiment showed a significant increase in user performance the decision was made to extend the implementation to a larger environment. The data that was gained during the experiment was actually used as excellent training data for the final implementation providing another argument for joint HF and AI research [27].

The development process of the method that was used is shown in Figure 5. The assessment in the final iteration of the development showed that both AI and HF challenges for agent selection in a dynamic, large and ad-hoc agent environment were met.

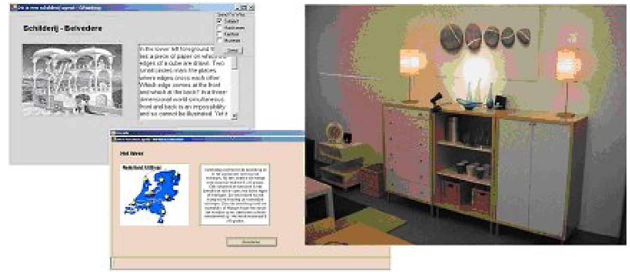

Fig. 4. Early empirical testing of ubicomp agent archtecture with end-users.

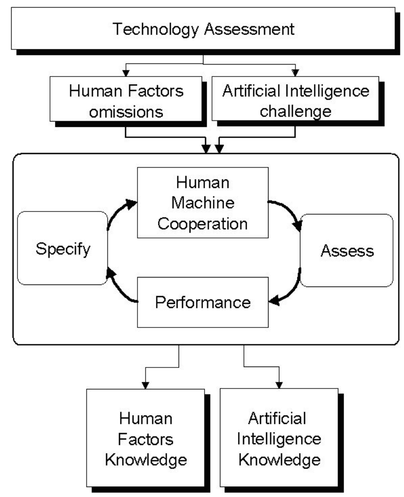

Fig. 5. The CE+ development process in the CACTUS project.

C. Situated Usability engineering for Interactive Task Environments

Intelligent operation support is crucial for human-machine performance in space laboratories. A tool kit for "Situated Usability engineering for Interactive Task Environments" (SUITE) was developed to guide the design of such operation support, in order to harmonize the activities of diverse stakeholders who implement various applications (platform systems and so-called payloads), apply specific design techniques and focus on the development of either (intelligent) task support or displays [28]. SUITE consists of a usability engineering handbook that provides context- and user-tailored views on the recommended HF method, guidelines and best practices. Furthermore, it provides a generic task support and dialogue framework, called Supporting Crew OPErations (SCOPE), as both an implementation of these methods and guidelines, and an instance of current interaction and AI technology for HMC. This framework defines a common multi-modal interaction with a system, including the integrated provision of context-specific task support for nominal and off-nominal situations. Furthermore, SCOPE detects system failures, guides the isolation of the root causes of failures, and presents the relevant repair procedures in textual, graphical and multimedia formats (see [29]). The diagnosis is a joint astronaut-SCOPE activity. Taken HF into account, the tasks of the human and machine actors, and their interactions, were specified and assessed as a joint activity. When needed, SCOPE asks the astronaut to perform additional measurements in order to help resolve uncertainties, ambiguities or conflicts in the current machine status model. SCOPE will ask the user to supply values to input variables it has no sensors for measuring by itself. Each new question is chosen on the basis of an evaluation function that can incorporate both a cost factor (choose the variable with the lowest cost) and a usefulness factor (choose the variable that will provide the largest amount of new information to the diagnosis engine). After each answer, the diagnosis re-evaluates the possible fault modes of the system on the basis of the additional values (and new samples for the ones that can be measured). As soon as SCOPE has determined the likeliest health state(s) of the system with sufficient probability, it presents these states to the user, possibly with suggestions for appropriate repair procedures that can be added to the todo list and executed. As soon as the machine has been repaired, SCOPE will detect and reflect this.

SCOPE was applied for the Cardiopres, a portable payload for medical experimentation (see Figure 6). In the evaluations

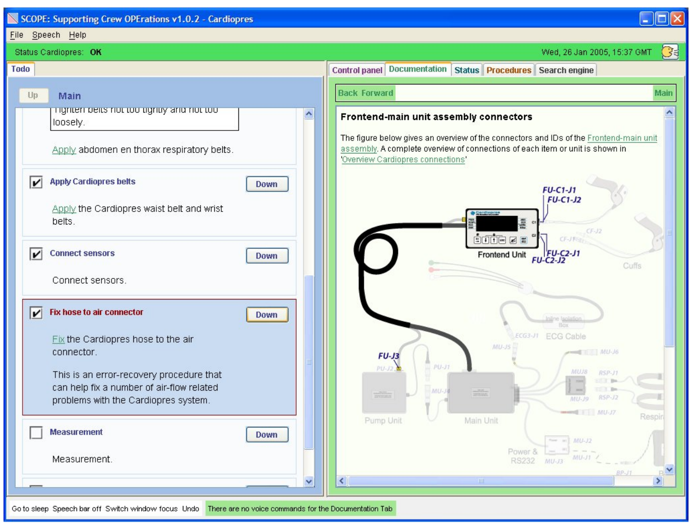

Fig. 6. SCOPE showing a successful completion of a diagnosis process (green status bar at top), procedure generation (left), and reference documentation (right).

of the SCOPE system for the Cardiopres, the user interface and AI-based task support functions proved to be effective, efficient and easy to learn, and astronauts were very satisfied with the system [28].

The development of the SUITE tool kit is an iterative process in itself, and new experiences with its application (e.g. currently for a new payload) will improve it. Currently, the SCOPE framework is being applied for the development of an intelligent user interface for the Pulmonary Function System (PFS) payload. Its task support functions will be improved to deal with dependencies of actions with each other and the usage context. Assessments will help to establish adequate performance and user experience of this component (see Figure 7). In general, the SUITE toolkit reduces the

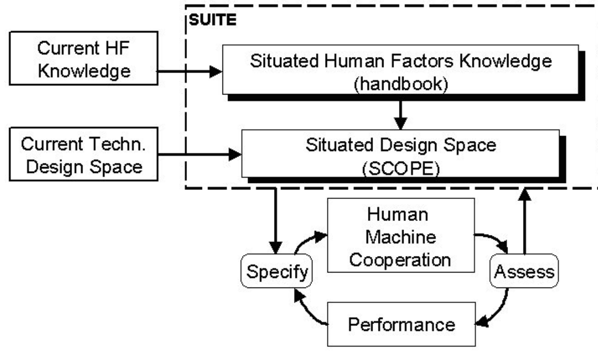

Fig. 7. The CE+ development process implemented as design guidance for intelligent user interfaces of space missions.

time and cost of development efforts, whereas it improves the usability of intelligent interfaces. Embedded in a HF engineering process, user interfaces and the underlying AI methods are systematically and coherently specified, implemented and assessed from early development phases on, which is in itself efficient and prevents the need for late harmonisation efforts between user requirements and technological constraints.

D. Human-Machine Task Integration

In contrast with the previous subsections, this last sub-section describes the analysis of the CE+ applicability on an *ongoing* programme. Resultingly, this case-study is based on expectation resulting from previous cases rather than on plain results. In the "Human-Machine Task Integration" (HMTI) programme human-machine task integration concepts are developed, tested, and evaluated in order to come to a recommended methodology to considerably improve performance with respect to HMC on future navy platforms, based on non-fixed HF and AI knowledge. Those scenarios are considered that contain dynamic, unreliable, and ambiguous environments, and systems that operate under time pressure, and with less resources (e.g. manning). Notably, these situational aspects are nowadays repeatedly mentioned as typical for what we can expect already in the near future. Exactly these (should) motivate governments to fund research on the integration of tasks through HMC systems. In Figure 8 an implementation of early HMTI for future navy platforms is shown.

Adaptive HMC (AHMC) systems attempt to adapt to the human-machine relation complexity. AHMC is an approach to design where tasks are dynamically allocated over time between humans and machines for the purpose of optimizing overall system performance. The apparent underpinnings of AHMC consisted of, among others, loss of expertise, automation-induced complacency, over- and undertrust, and loss of adaptivity (e.g., [30]–[32]). To overcome these problems, future HMC systems should detect and adapt to those situations that cause them.

mental load, boredom, emotion, skill, experience, stress, self-confidence, trust, and commitment (to name but a few), and determine their characteristics in terms of for example demand for transparency, machine autonomy, responsibility, "out of the loop"-ness, task switching, and delegation strategy. These models may depend on specific task, environment, machine, user, or organization characteristics. Further research also applies to the *formalization*, *verification*, and *validation* of these models. This is for the reason that well-balanced models should be consistent when combined, refrain from under- as well as overfitting instances of reality, and result in implementations that are *application valid*. The latter may imply theories with low construct validity, as is discussed recently in [37].

Fig. 8. Early HMTI for future navy platforms.

Research in HMTI can be divided into two main foci. The first focus is on when specific types of cooperation should be changed (triggering or invocation strategy), and the second one is on what and how it should be changed (response or allocation strategy). Guided by HF and AI research, these together span the whole AHMC system design space. In general, invocation strategies are based on the characteristics of, and changes in, the human-machine system, its environment, and estimated future performance models. After this, chosen allocation strategies cause new characteristics and changes. In complex, ambiguous, and dynamic environments this choice must be made *a posteriori*, i.e. real-time.

What can be determined *a priori*, i.e. during design, is everything that constitutes the design purpose, such as the choice that the allocation strategy is based on a left-over, economic, or comparison method [33]. Another choice a designer can make is what type of support HMC should provide and more specifically what type of sharing of control. The type of sharing of control designates in what way agents (machine or human) cooperate to achieve the system's goals. There are three sharing of control strategies, namely extension, relief, and partitioning [34]. It is clear that these control strategies require different intelligence of the cooperating partner. In many cases extension simply requires precompiled tools, whereas partitioning sometimes needs an agent to be even more intelligent than the subject. Also, in partitioning cooperation will require the cooperating agents to perform additional meta-operations [4], which are to be relieved by means of a well-equipped AHMC design methodology.

Given the research aims of the area of integrated system design, we can definitely claim that there is still a lot of work to be done. With respect to AHMC design, in spite of its popularity in the past decades, there is very little formal research to be found that can improve the design of large complex systems (e.g., [35], [36]). There are few usable models for predicting the dynamics of human or machine state, performance, and environment. Therefore more research on its theoretical framework is needed. Models need to be developed that can closely predict situation awareness, vigilance, mode awareness, automation-induced complacency,

As an important first result of the HMTI programme the above clearly implies that HF and AI research are thoroughly intertwined into the HMC system design process. This suggests the applicability of the CE+ method and this is why the HMTI programme has adopted it. In Figure 9 the proposed CE+ development process is shown. The initial knowledge helps in setting system constraints and show important gaps that indicate a need for further research. After an experimental phase, results are reflected upon the initial theory by means of comparing desired and resulting perfomance. This gains new knowledge and new concepts are further studied. Important

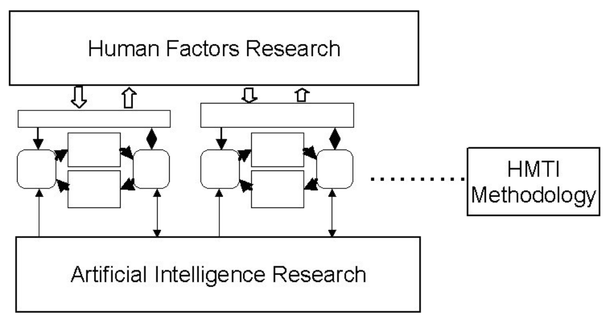

Fig. 9. The proposed CE+ development process in the HMTI programme.

here is that after several of such iterations the resulting methodology is not technology driven, but rather realistic for future navy platform scenarios in a generic sense. This is why the current technological design space is missing in this diagram and AI research is directly integrated in the specification and assessment processes. Indeed, few gaps will be identified when not using any CE+ method. Eventually the resulting AHMC system design methodology will be useable without first going through phases of trial and error.

IV. Conclusion

Increasing machine intelligence leads to a shift from a mere interactive to a much more complex cooperative human-machine relation. Exactly this really requires researchers and engineers to believe in a more multidisciplinary approach. This paper stressed validity and therefore usability of a generic multidisciplinary cognitive engineering method CE+ in human-machine cooperation system design by means of four case-studies. For each case-study the method supported research and development activities in such a way that sound knowledge bases and user interfaces for human-machine cooperation could be established. This was done for example by deriving artificial intelligence and human factors requirements for the attention driven dialogue (PALS), for the hypotheses generation, approval or falsification (SUITE, [29]), for adaptivity of automated decision support (HMTI), and agent selection in large ad-hoc environments (CACTUS, [27], [38]). However, the method always needed to be tailored to the specific goals and circumstances, such as the available time, novelty, and required integration. We can conclude that due to the complexity of system design processes, their success depends upon integration of human factors and artificial intelligence research early on in the development process.

ACKNOWLEDGMENT

The PALS project is partly funded by the IOP MMI program of SenterNovem. The Human-Machine Task Integration programme is funded by the Dutch Ministry of Defense (programme nr. V206). The CACTUS project was supported by the Towards Freeband Communication Impulse of the CIC programme of the Ministry of Economic Affairs in The Netherlands. The SUITE tool-kit was developed for the European Space Agency (contract C16472/02/NL/JA) in cooperation with Science & Technology (The Netherlands). Gratitude goes to Jan Maarten Schraagen and Egon van den Broek for their helpful comments.

REFERENCES

[1] E. Aarts, R. Harwig, and M. Schuurman, "Ambient intelligence," in *The Invisible Future*, P. Denning, Ed. New York: McGraw Hill, 2001, pp. 235–250.

[2] G. D. Abowd, E. D. Mynatt, and T. Rodden, "The human experience," in *Pervasive Computing*, Jan-March 2002, pp. 48–57.

[3] M. Satyanarayanan, "Pervasive computing: Vision and challenges," *IEEE Personal Communications*, pp. 10–17, August 2001.

[4] J.-M. Hoc, "Towards a cognitive approach to human-machine cooperation in dynamic situations," *International Journal of Human-Computer Studies*, vol. 54, no. 4, pp. 509–540, 2001.

[5] C. Castelfranchi, "Modelling social action for agents," *Artificial Intelligence*, vol. 103, pp. 157–182, 1998.

[6] E. Hollnagel and D. D. Woods, "Cognitive systems engineering: New wine in new bottles," *International Journal of Man-Machine Studies*, vol. 18, no. 6, pp. 583–600, 1983.

[7] G. Fischer, "User modeling in human-computer interaction," *User Modeling and User-Adapted Interaction*, vol. 11, pp. 65–68, 2001.

[8] M. Schneider-Hufschmidt, T. Kühme, and U. Malinowski, "Adaptive user interfaces: principles and practices," in *Human factors in information technology*, 10th ed. Amsterdam: North-Holland, 1993.

[9] E. Aarts, R. Collier, E. van Loenen, and B. de Ruyter, Eds., *Ambient Intelligence: EUSAI 2003. Lecture Notes in Computer Science*. Berlin: Springer, 2003.

[10] B. Kirwan and L. K. Ainsworth, Eds., *A guide to task analysis*. London, UK/Washington, DC: Taylor & Francis, 1992.

[11] J. M. C. Schraagen, S. E. Chipman, and V. L. Shalin, Eds., *Cognitive Task Analysis*. Mahwah, NJ: Lawrence Erlbaum Associates, 2000.

[12] E. Hollnagel, Ed., *Handbook of cognitive task design*. Mahwah, NJ: Lawrence Erlbaum Associates, 2003.

[13] M. Helander, T. K. Landauer, and P. V. Prabhu, Eds., *Handbook of Human-Computer Interaction*, 2nd ed. Amsterdam, The Netherlands: North-Holland, 1997.

[14] T. A. Jacko and A. Sears, Eds., *The Human-Computer Interaction Handbook: Fundamentals, evolving technologies and emerging applications*. Mahwah, NJ: Lawrence Erlbaum Associates, 2003.

[15] D. J. Mayhew, *The usability engineering lifecycle: A practitioner's handbook for user interface design*. San Fransisco, CA: Morgan Kaufman, 1999.

[16] M. Maguire, "Methods to support human-centered design," *International journal of human-computer studies*, vol. 55, pp. 587–634, 2001.

[17] M. B. Rosson and J. M. Carroll, Eds., *Usability engineering: Scenario-based development of human-computer interaction*. San Fransisco, CA: Morgan Kaufman, 2001.

[18] N. Bevan, "International standards for hci and usability," *International journal of human-computer studies*, vol. 55, pp. 533–552, 2001.

[19] NASA standards, *Payload Display Developers Guide. Annex 6 of the International Space Station, United States Payload Operations, Data File Management Plan*, National Aeronautics and Space Administration Std. MSFC-PLAN-2886, September 1998, *Appendix H - Payload displays of the document DGCS (Display and Graphics Commonality Standards)*, International Space Station program document (SSP) 530313; *Appendix I - Payload displays of the document DGCS (Display and Graphics Commonality Standards)*, International Space Station program document (SSP) 530313, Revised Draft.

[20] K. Y. Lim and J. B. Long, *The Muse Method for Usability Engineering*. UK: Cambridge University Press, 1995.

[21] J. Rasmussen, *Information processing and human-machine interaction: an approach to cognitive engineering*. Amsterdam, The Netherlands: Elsevier, 1986.

[22] D. A. Norman, "Cognitive engineering," in *User-Centered System Design: New perspectives on human-computer interaction*, D. A. Norman and S. W. Draper, Eds. Hillsdale, NJ: Erlbaum, 1986.

[23] M. A. Neerincx, "Cognitive task load design: model, methods and examples," in *Handbook of Cognitive Task Design*, E. Hollnagel, Ed. Mahwah, NJ: Lawrence Erlbaum Associates, 2003, ch. 13, pp. 283–305.

[24] M. A. Neerincx, S. Pemberton, and J. Lindenberg, "U-wish web usabilty: methods, guidelines and support interfaces," TNO Human Factors, Soesterberg, The Netherlands, Tech. Rep. TM-99-D005, 1999.

[25] J. Lindenberg, S. F. Nagata, and M. A. Neerincx, "Personal assistant for online services: Addressing human factors," in *Human-Centred Computing: Cognitive, Social and Ergonomic Aspects*, D. Harris, V. Duffy, M. Smith, and C. Stephanides, Eds. London: Lawrence Erlbaum Associates, 2003, pp. 497–501.

[26] J. Lindenberg, W. Pasman, K. Kranenborg, J. Stegeman, and M. A. Neerincx, "Improving service matching and selection in ubiquitous computing environments: A user study," *Personal and Ubiquitous Computing*, submitted for publication.

[27] W. Pasman and J. Lindenberg, "Human-agent service matching using natural language queries: System test and training," *Personal and Ubiquitous Computing*, submitted for publication.

[28] M. A. Neerincx, A. H. M. Cremers, A. Bos, and M. Ruijsendaal, "A tool kit for the design of crew procedures and user interfaces in space stations," TNO Human Factors, Soesterberg, The Netherlands, Tech. Rep. TM-04-C026, 2004.

[29] A. Bos, L. Breebaart, M. A. Neerincx, and M. Wolff, "SCOPE: An intelligent maintenance system for supporting crew operations," in *Proceedings of IEEE Autotestcon 2004*, 2004, pp. 497–503.

[30] R. Parasuraman and V. A. Riley, "Humans and automation: Use, misuse, disuse, abuse," *Human Factors*, vol. 39, pp. 230–253, 1997.

[31] N. Moray, "Human factors in process control," in *Handbook of human factors and ergonomics*, G. Salvendy, Ed. New York: Wiley-Interscience, 1997, pp. 1944–1971.

[32] W. B. Rouse, "Twenty years of adaptive aiding: Origins of the concept and lessons learned," in *Human Performance in Automated Systems: Current Research and Trends*. Hillsdale, NJ: Lawrence Erlbaum Associates, 1994, pp. 28–32.

[33] ——, *Design for success: A human centered approach to designing successful products and systems*. New York: Wiley, 2001.

[34] T. B. Sheridan, *Telerobotics, Automation, and Human Supervisory Control*. Cambridge, MA: MIT Press, 1992.

[35] R. B. Fuld, "The fiction of function allocation," *Ergonomics in Design*, vol. 1, pp. 20–24, 1993.

[36] S. F. Scallen and P. A. Hancock, "Implementing adaptive function allocation," *International Journal of Aviation Psychology*, vol. 11, no. 2, pp. 197–221, 2001.

[37] G. E. Campbell and A. E. Bolton, “HBR validation: Integrating lessons learned from multiple academic disciplines, applied communities and the AMBR project,” in *Modeling Human Behavior with Integrated Cognitive Architectures: Comparison, Evaluation, and Validation*, R. W. Pew and K. Gluck, Eds. Lawrence Erlbaum, in press.

[38] W. Pasman, “Organizing ad hoc agents for human-agent service matching,” in *Proceedings of Mobiquitous 2004*, D. Harris, V. Duffy, M. Smith, and C. Stephanides, Eds., Boston, MA, August 22-25 2004, pp. 278–287.