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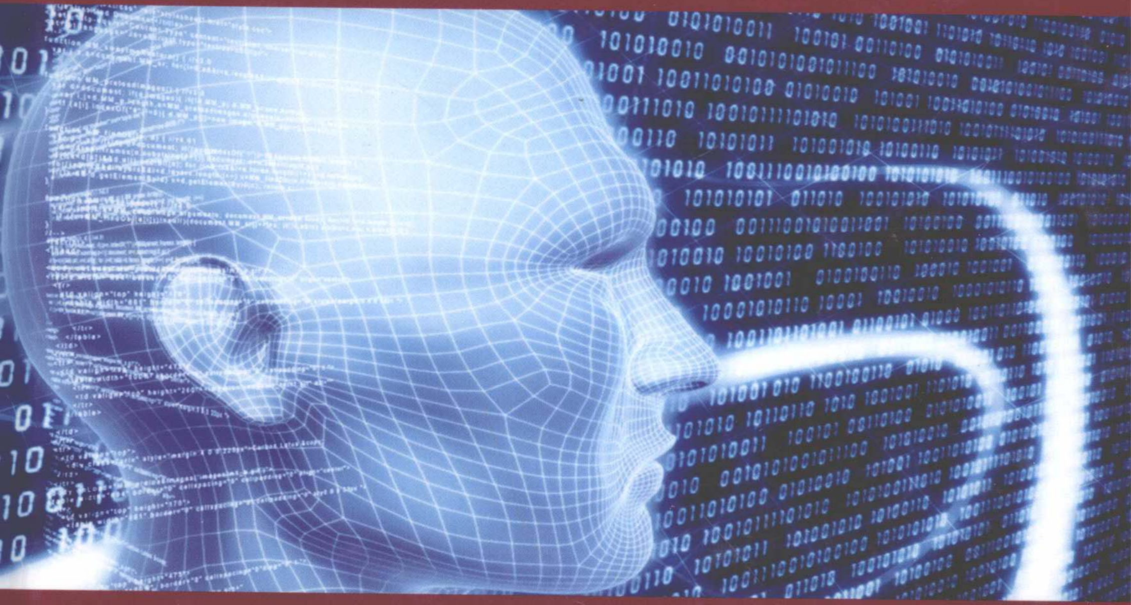

Designing Human–Machine Cooperation Systems

Edited by Patrick Millot

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Foreword

There are three central words to this book: "ergonomics", "human being" and "machine". This book is not a book on ergonomics, although the topic is duly covered; neither is it a book on human science, even though human beings play a key role in it. This book is what I like to call a book of interfaces, a book that is the result of research at the junctions of various topics. Topics encompass the scientific domains that research – in France, and elsewhere – consists of. Classically, one belongs to a single topic, and one conducts research *within* this single topic. However, this categorization does not enable a true rendition of all the problems of research, including those found at the boundary between several topics.

Separation into different topics satisfies a certain element of Cartesianism in its presentation, but can cause confusion with regard to the work of researchers focusing on these interfaces. Indeed, they are not focused on the difficult problems of topic A or topic B; they are rather focused on the difficult problems that involve both topics A and B. This structure therefore presents shortcomings in appreciating the quality of much important research. Simply by looking at the history of scientific progress, it would appear that a lot of breakthroughs happen at these interfaces.

For this reason, among others, some countries (the number of which is always on the increase) have called upon the help of research organized into projects through agencies (such as the National Science Foundation (NSF), the Defense Advanced Research Projects Agency (DARPA), etc., in the United States, and the National Funding Agency for Research (ANR) in France, etc.). A project is presented as a scientific objective and, therefore, is not restricted by topic. It is run by a consortium consisting of members of the different topics required to reach this research objective over a certain timescale. The evaluation of a project allows us to determine the quality of the research conducted, and this evaluation is no longer limited to one topic. This organization into projects allows for a greater focus on various difficult problems, which the one-topic limit did not.

To conclude this point, this does not mean that research must only be conducted through various projects: actually, depending on the goal of the planned research, two types of presentation may be necessary, and these must therefore coexist. However, this also means that research at interfaces is just as important as purely topic-based research and that both must be evaluated using relevant scientific criteria.

The work put together by Patrick Millot sits at the junction of several topics, since it covers work on human–machine systems and their conception. It can therefore be defined as a project whose objective is to assemble the results of the most recent research in this field; this project is run by a consortium of acclaimed scientists from a variety of different backgrounds. Let us not mention the timescale of this project, as it equates to the maturing time of a book: a time that is usually underestimated.

Human–machine systems are as present in our working world and everyday life as they are in the technological world. These systems are therefore very important, as poor choices during conception can have very big consequences, especially in terms of safety, as recent examples have certainly shown. I have chosen one example in particular, as it is universally known. One system, the automobile, is itself linked to another, the road system and the other drivers and one pilot: the driver of the vehicle itself. To this collective, a significant limitation must be added: the driver is not a professional. The human–machine systems must therefore be simple (the driver has not received any specialized training other than that required for the obtainment of a driving license) but very informative, without being overbearing (there is also a lot of information coming from outside the vehicle), with the goal of making driving as safe and enjoyable as possible. We can see the difficulty and complexity of such a human–machine system and therefore the necessity of permanent research on this topic. The proposed work will offer solid lines of thought and solutions, especially as it comes at the topic from an original angle: putting the person at the center of human–machine systems.

From this point of view, the book is organized into three complementary parts that enable the different aspects of the problem to be addressed: part 1 focuses on the methods of conception, part 2 focuses on the methods of evaluation and, finally, part 3 focuses on human–machine cooperation. Undoubtedly, the readers will find in this book an idea of the state of research in this area, and hopefully the answers to many of their questions.

Finally, this book introduces us to a selection of authors from very different disciplines: specialists in "human engineering", cognitive psychology, artificial intelligence, etc. This fits in well with the requirement of uniting acclaimed specialists from different topics so as to conduct or even understand research at the interfaces.

To conclude, I will reiterate something that I often say, which is that one cannot be precise at the interface of topics: in other words, one cannot be a specialist in inter-disciplinarity. On the contrary we can be excellent in our discipline and know how to cooperate with other specialists, and from this cooperation new advances arise from knowledge. However, this cooperation is only fruitful if the different players are excellent in their respective domains.

This book is the perfect illustration of this concept, and I am convinced that the readers will take great pleasure and interest in reading a book that offers a complete vision of the conception of a human–machine system that is centered on the "human fully involved in the loop".

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University of Technology of Compiègne

Introduction: Human–Machine Systems and Ergonomics

I.1. What has ergonomics got to do with human–machine systems?

This book on the ergonomics of *human*–machine[1] systems is aimed at engineers specializing in informatics, automation, production or robotics, and who are confronted with an important dilemma during the conception of human–machine systems:

– on the one hand, the human operator guarantees the reliability of the system and he has been known to salvage numerous critical situations through reasoning abilities in unplanned, imprecise and uncertain situations: the Apollo 13 space mission is a mythical example of this[2], where the three astronauts owed their survival to their own genius, their innovative capabilities, as well as to those of the engineers on the ground;

Introduction written by Patrick MILLOT.

1 The word *human* used here without prejudice as a synonym for a human being, or a human operator. For this reason, the masculine form *he* is used throughout the text to avoid weighing down the syntax of the text with the form *he/she*.

2 Apollo 13 (April 11, 1970, 13.13 CST – April 17, 1970) was a manned moon mission of the Apollo program that was cut short following the explosion of an oxygen tank in the Apollo service module during the flight to the Moon. As the vessel could not be turned around, the crew was forced to pursue their trajectory toward the Moon, and harness its gravitational pull during orbit so as to return to Earth. As the service module had become uninhabitable, the crew took refuge in the lunar module, Aquarius. Occupation of this module by the entire crew for an extended period of time had obviously not been anticipated. The astronauts and the control center on Earth had to find ways of recuperating energy, saving enough oxygen and getting rid of carbon dioxide. The crew eventually made it safely back to Earth. See http://fr.wikipedia.org/wiki/Apollo_13.

– on the other hand, the human operator can be unpredictable and create disturbances in the automated system; the nuclear industry is an "interesting"[3] example of this in that it gave three dramatic examples in a little over 30 years: Three Mile Island in 1979, Chernobyl in 1986 and Fukushima in 2011. The Mont Sainte Odile accident is another significant example, from the aeronautic field.

At the beginning of the 1990s, a well-known researcher in the French control community said to me: "human-machine systems are interesting, but I don't see what they've got to do with automation!" On the contrary, the three nuclear incidents mentioned show what the consequences of badly designed human–machine interaction can be. Kara Schmitt accurately summarizes the problems that can be encountered with human–machine interaction. The Three Mile Island accident was the result of *automation misunderstanding* in that the operators did not understand the function of the automatic safety system that would have avoided the accident, and unplugged it. The major Chernobyl accident was characterized by a *lack of confidence in automation* associated with poor understanding of nuclear physics, and the lack of a culture of automated safety in Eastern European countries at the time. These combined factors caused the operators to conduct tests that pushed the reactors to their limits after having turned off the safety systems. Finally, the Fukushima accident, which took place after a tsunami that damaged the nuclear station, was the result of a *lack of appropriate automation* associated with an under-estimate of the risks during conception: the height of the anti-tsunami chamber was only 5.7 m while the waves reached 10 m, the emergency generators in the underground were flooded, their batteries no longer having enough power to feed the cooling systems and to secure the reactors after they had stopped. Moreover, the several emergency stop systems were not automated and the security principles were passive and not active, and therefore required energy to operate [SCH 12].

As a matter of fact, automation does not rival a human remaining in the control loops and supervising the systems, but the human operator must not be reduced to an emergency device to control non-automated activities. On the contrary, the teams of human operators must be fully integrated in the

3 More than the terrible impact of the accidents, importance lies in the lessons learned that could lead to increased safety levels.

command, control and supervisory loops of human–machine systems, so as to get as much as possible out of their capabilities, without suffering from the disadvantages. So, this book focuses on these problems of human-centered *automation* and the factors it addresses.

The approaches of different solutions lie in models, in the sense of a "greater understanding" of human operators, as much as for the systems themselves and their environment. Human modeling has united the *human factors* community over the last 70 years, since the end of World War II. Considering the limitations of the systems of that time, which had relatively low levels of automation, and therefore required a human presence in piloting, control and regulating tasks, researchers tried out unique approaches between the modeling (for the command) of the technical component of the human–machine system and the modeling of the human component. These approaches were inspired by theories of "engineering", first of all the information theory, and then the control theory [SHE 74]. Human engineering research belongs to this movement and was mainly brought to France by Noel Malvache [MAL 73]. The reader can find a history of the approaches used in the human factors research field in [MIL 03] and [SHE 85].

Since the end of the 1990s, the application domains studied have strongly evolved toward large, complex systems, whether they are discrete continuous or hybrid. These are designated as systems of systems, network systems and multi-agents. The *automation level* has greatly increased, which has brought about an increase in the *performance* of the production or service system.

Nevertheless, other objectives must be taken into account, particularly *safety* and *security*. The interest in *life critical systems has increased increasingly*. At the beginning of the 2000s, Amalberti came up with the following categories of *risky systems* [AMA 05]:

– the riskiest systems involve amateur individuals, alpine mountaineering for example, with a risk level around 10^{-2};

– next, he places systems available to the public in which the safety culture is poorly developed (or not consistent) and the choice of operators is not very discriminative, such as car driving, with a level of 10^{-3};

– the chemical industry is next, with a risk level of 10^{-4};

– charter flights with a level of 10^{-5};

– finally come systems that are said to be ultra-safe, such as commercial aviation, the nuclear industry and transport by train, with a risk level of 10^{-6}.

In these systems, the human is seen as an unreliable factor: in 1950, for a hundred accidents, seventy were due to a technical problem, and humans caused thirty. Since 2000, globally this proportion has been reversed, with seventy human causes for thirty technical causes. This is particularly due to a great increase in technical reliability, while human causes have not changed. This explains a natural reflex in the designer to minimize the role of the human in systems by increasing the level of automation. Aside from the technical difficulties surrounding complete automation, increasing automation levels is not actually that simple, in that it involves aspects other than ergonomics, i.e. contextual and organizational. This book attempts to show all the dimensions relating to this problem.

I.2. Increasing level of automation?

The level of automation determines the role and the involvement of human operators to guarantee these objectives: *performance, safety and security*. In highly automated systems, operators have migrated toward control rooms to carry out *supervisory* functions, i.e. *monitoring* and managing failures: *diagnosis* for *re-use*, the *accommodation* or the *reconfiguration* of the automated system. Human tasks become decision based, at the expense of action tasks (reactive), the outcomes of which can be very important for the integrity of the system, but also for its security. In these systems, operators are usually professionals, trained and supervised in an *organization* that is often hierarchical, where they must follow *procedures* to respond to known situations, whether they are normal or part of an incident. However, the main difficulties relate to unexpected and new situations, for which the operators are not prepared and where they must "invent" a solution. The *designer's dilemma* can here be summarized as follows: on the one hand, he can be tempted to aid, or even limit, human activity in the known situations so as to avoid possible mistakes; on the other hand, he can only rely on human inventiveness to deal with the unexpected. However, to try to understand these unexpected situations, the human operator needs information of the system operation in known situations, the very information that is being taken away from him!

These problem-solving tasks are cognitive in nature, and theories that support their modeling can mainly be found in the vast spectrum of cognitive sciences, which include artificial intelligence, cognitive psychology, sociology and ergonomics. These approaches are multi-disciplinary and participative where each discipline contributes to the model and to the proposing of solutions. This book develops these different multi-disciplinary approaches of analysis and modeling for the design of modern human–machine systems and attempts to give an answer to the *designer's dilemma* mentioned above.

In the large transport systems (airplanes, high-speed trains, metro), the operators can still remain directly involved in the driving or piloting loop, all the while carrying out a supervisory role. However, the domain of automobile driving is atypical. It is currently the object of considerable effort to increase its safety, but the problem is difficult because the population of car drivers possesses very heterogeneous capabilities, practice and training, and the organization is hardly controlled, except in an open manner by traffic laws, and with some "sampling" in a closed manner through police controls. Its level of automation is low and efforts are focused on the automation of certain security features, rather than driving in general [INA 06]. Several chapters of this book are focused on this field of research.

Organization itself plays an important role. From an informatics point of view, Guy Boy provides a diagram for a human–machine system using a pyramid, made up of five summits and of their relations which he names AUTOS: A for artifact, U for user, T for task, O for organization and S for situation (see Figure I.1) [BOY 11]. Transposed onto the dynamic systems, the artifact becomes the system and the user becomes the operator.

This figure therefore shows the well-known classic triangle of the *human engineer* O–S–T, as the operator has been formed in the system, carrying out tasks depending on the needs of the system by applying *procedures* (or by trying to innovate in the case of a new problem), these tasks needing to be helped by the *ergonomic quality* of human–machine interaction but also of the interface.

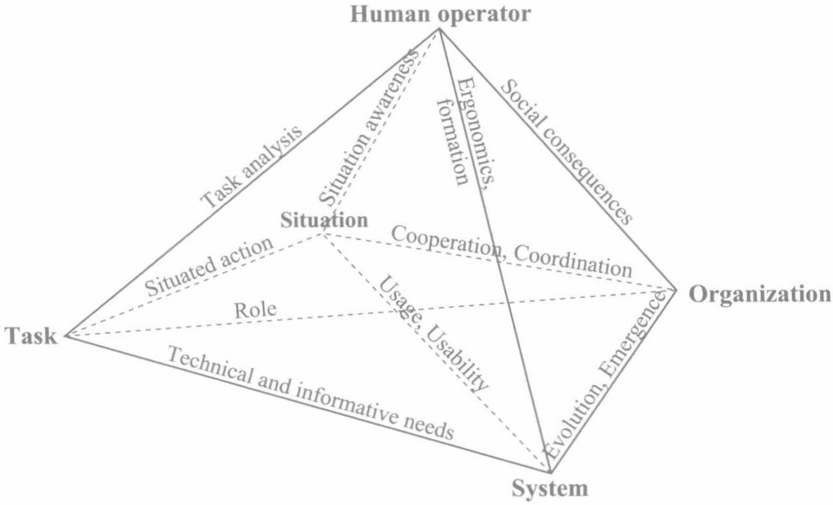

Figure I.1. *Human–machine system environment (adapted from [BOY 11])*

The fourth summit, organization, introduces the *level of automation* involving the *role of the operator* and *task sharing* (and function sharing) between humans within the control or supervision team, but also between humans and automatic systems (of control or of decision). *Task sharing* (or function sharing) between humans and machines gives humans a *level of responsibility* regarding the management of performance and of the risks and a *level of authority* that determines this responsibility. The socio-organizational context of the systems must then make compatible these two levels of authority and responsibility: this is part of the *designer's dilemma* mentioned above. To this effect, human–human and human–machine task sharing cannot be static and defined from the earliest design, but instead must evolve dynamically according to criteria that integrate the performance of the global system and/or the human workload [MIL 88]. It can go even further by establishing a cooperation between human and machine. These advanced aspects will be covered in the last part of this book.

The fifth summit concerns the situation of the task that can introduce new limitations requiring an evolution of the *situation awareness* of the human operator to detect an unusual situation, an evolution of decisions, of the competences being used of even a dynamic evolution of the organization as mentioned previously.

The connection of these five dimensions shows that the successful automation of a system goes well beyond the problem of making it automatic, and that it needs to be a part of a process of *human-centered design of the human–machine system.* Indeed, this approach is developed in this book, in three parts.

Part 1 is dedicated to the methods of human-centered design, from three points of view:

– Chapter 1, written by Patrick Millot, presents the models developed by human engineers and bases itself on functional models to explain human behavior in his environment. It looks at the approaches for positioning levels of automation, notably through principles of task and/or function distribution between human and machine, and extends these to the sharing of authority and responsibility. To attempt to resolve the apparent ambiguity of the role of the operator, this chapter also introduces the mastering of the *situation awareness* of operators, widely studied today.

– Chapter 2 by Christine Chauvin and Jean-Michel Hoc develops models of cognitive psychology and proposes a methodology of design derived from the works of Rasmussen and Vicente called *Cognitive Work Analysis* [VIC 99].

– Chapter 3, written by Gilles Malaterre, Hélène Fontaine and Marine Millot, can be situated in the domain of automobile driving, which unfortunately is the victim of numerous real accidents. The approach the authors use is to analyze these cases to deduce the need for adjustments or assistance tools for the design of new vehicles and the improvement of infrastructure.

Part 2 develops the methods of evaluation of human–machine systems:

– Chapter 4, by Jean-Christophe Popieul, Pierre Loslever and Philippe Simon, evaluates the activity of the human operator at work using methods of automatic classification to define different classes of behavior. The data come from sensors that give the parameters of the task and of its environment, but also from sensors placed on the human body which record characteristic signals of the human state such as the electroencephalograph (EEG) or characteristics of the person's decision and action strategies through eye movements. The methods are illustrated by experimental examples obtained in an automobile driving simulator during studies on the detection of hypo-vigilance.

– Chapter 5, written by Frédéric Vanderhaegen, Pietro Carlo Cacciabue and Peter Wieringa, presents human error analysis methods that are inspired by and adapted from technical reliability analysis methods and which in a sense form the dual approach of modeling methods based on "normal" human behavior. This chapter concludes with the results of the integration of such methods in the design process of human–machine systems.

Finally, Part 3 is dedicated to *human–machine cooperation* through four complementary (between themselves) chapters. We shall see that a cooperative agent comprises a *know-how* and a so-called *know-how-to-cooperate*. The organization of the *cooperative system* is defined according to a structure in which the inputs and the outputs of each of the agents are connected to their environment and to the system that they must control or manage. The functioning of cooperation is related to more functional aspects. Finally, operational aspects such as parameters called cooperation catalysts play a role:

– Chapter 6 by Jacky Montmain contributes to the *know-how* of the cooperative agent. It develops the *causal reasoning* that permits a human–machine cooperation by creating tools founded on artificial intelligence (AI), to support the operator in the control room confronted with situations requiring complex decisions. The author moves from the observation that human reasoning is neither based on a mathematical model of the process, nor on the detailing of the numerical data that are presented, but on the symbolic interpretation of these, which is the key to the explanations that a support system should give. The principal quality expected of the models is no longer precision, but pertinence and compatibility between the representation in use and the cognitive modes of the operator. Examples from the supervision of a chemical process in a nuclear reprocessing plant illustrate these principles.

– Chapter 7, written by Jean-Michel Hoc, contributes to the functional aspects of cooperation. In particular, it presents the models of cooperative activity, the concept of the *COmmon Frame Of Reference* (COFOR) and draws up the lessons for the design of the cooperative human–machine systems. It then describes cooperative activities according to the three levels of abstraction corresponding to the three temporal horizons, by deriving some implications for the design: *cooperation in action*, where the agents manage the interferences between their goals, *cooperation in planning*, where the agents negotiate to come up with a common plan or to maintain a common reference and *meta-cooperation*, which establishes the structures of knowledge of cooperation, such as models of partners or models of oneself.

– Chapter 8 by Serge Debenard, Bernard Riera and Thierry Poulain, describes the development of the human–machine cooperation through the definition of the cooperative structures and through the definition of the *cooperative forms* between human and machine and the implication that they have on human activities. They introduce the concept of "common work space" (CWS), which is very import to encourage cooperation between the agents. Two examples of application processes are detailed, each having different levels of automation, the first application process is low and is concerned with air traffic control (ATC), the second application process is high and concerns a nuclear waste reprocessing plant.

– Finally, Chapter 9, by Patrick Millot and Marie-Pierre Pacaux-Lemoine, widens the notion of the dynamic sharing of tasks or functions between the human and machine toward human–machine cooperation by integrating two dimensions: the structural and organizational dimension and the functional dimension linked to the know-how of the human and automated agents, but also (and especially) their know-how-to-cooperate. The CWS is shown as a way to make the COFOR concrete. Indeed, COFOR is mandatory for any cooperation. Three examples are given to illustrate these ideas: human–machine cooperation in the cockpit of a fighter aircraft, cooperation between a human and a robot in a recognition task and human machine cooperation in the ATC. Finally, we show that more than just being a useful tool facilitating cooperation, the CWS improves the situation awareness of the team. This is of major interest for holding humans in the loop.

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Contents