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Since the 1960s, the rapid growth of information systems has led to the wide development of research on human – computer interaction (HCI) that aims at the designing of human – computer interfaces presenting ergonomic properties, such as friendliness, usability, transparency, etc. Various work situations have been covered—clerical work, computer programming, design, etc. However, they were mainly static in the sense that the user fully controls the computer. More recently, public and private organizations have engaged themselves in the enterprise of managing more and more complex and coupled systems by the means of automation. Modern machines not only process information, but also act on dynamic situations as humans have done in the past, managing stock exchange, industrial plants, aircraft, etc. These dynamic situations are not fully controlled and are affected by uncertain factors. Hence, degrees of freedom must be maintained to allow the humans and the machine to adapt to unforeseen contingencies. A human – machine cooperation (HMC) approach is necessary to address the new stakes introduced by this trend. This paper describes the possible improvement of HCI by HMC, the need for a new conception of function allocation between humans and machines, and the main problems encountered within the new forms of human – machine relationship. It proposes a conceptual framework to study HMC from a cognitive point of view in highly dynamic situations like aircraft piloting or air-traffic control, and concludes on the design of 'cooperative' machines.

1. Introduction

If the abbreviation HCI (human – computer interaction) can be maintained to cover every form of human – machine relationship, it should be considerably extended to cover the ergonomics challenges presented by the contemporary, highly complex and dynamic human – machine systems. The notion of a human – computer interface remains a key point with its properties of friendliness, usability, transparency, etc. However, cognitive ergonomics has developed a large number of studies on human – automation relationship failures, which concern what is behind the interface (Billings

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1991, Parasuraman and Mouloua 1996). From the front line human operators' point of view, machines are not only tools, but also possibly autonomous agents, and some coherence must be maintained between humans' and machines' actions on the environment, whatever the interface is. That is why introducing the framework of cooperation into the study of human–machine relationship is attractive.

This paper focuses on human–machine cooperation (HMC) in dynamic situations like aircraft piloting, air-traffic control (ATC), industrial process control or anaesthesiology. As opposed to static situations fully controlled by the human–machine systems, dynamic situations can change autonomously. As far as human operators are concerned, control is partial in two senses. First, the situation has its own dynamics with which the operator's actions and the machine's actions are combined to produce effects. Second, automation introduces autonomous actions of machines on the situation. That is why the human activity integrates control and supervision. The sources of complexity and difficulty of this kind of situation have been largely described in the literature and will not be detailed here (Hollnagel *et al.* 1988, Woods 1988, Hoc 1993, Hoc *et al.* 1995b). For the purpose of this paper, only two sources of complexity will be stressed—uncertainty and risk.

Dynamic situations are uncertain since they are partially controlled. Unexpected factors can modify the dynamics of the process under supervision and internal incidents or breakdowns can affect the process itself. Such an uncertainty cannot be only managed by probabilistic models. It implies implementing adaptive mechanisms in real-time to face to events unforeseen beforehand by the designer of machines, regulations or work procedures. Moreover, action effects are often submitted to response delays, so that diagnosis, decision-making and planning must be performed before accessing all the necessary information. Dynamic situations are also risky. The cost of errors can be very high in terms of accident or money. Hence, human operators must manage risks (associated with costs and probabilities) when implementing a decision. For them, the major risk is the loss of control of the situation, acting too late, although comprehension can reach a high level by this time. Consequently, their main objective is to maintain the situation between acceptable limits, including their own cognitive limits, accepting partially to understand what is going on (Hoc *et al.* 1995a, Amalberti 1999).

Uncertainty and risk management implies keeping some degrees of freedom available in the system for adaptation and for calibrating an acceptable compromise between comprehension and maintenance of the situation under control. For these reasons, it is very dangerous to close the human–machine system into too rigid strategies, procedures and function allocation between humans and machines. For two decades human–machine communication and cooperation have progressively enriched the human–machine interaction research trends. Communication and cooperation require the introduction of more aspects of the human–human into the human–machine relationships. The notion of 'joint cognitive systems' applied to human–machine systems was a decisive step towards this conception (Hollnagel and Woods 1983, Rasmussen *et al.* 1994, Woods and Roth 1995). This notion revealed the fact that the human–machine system's task can have no sense if one considers the human or the machine as units in isolation. On the contrary, there is an overall task, dynamically decomposed into subtasks, to be integrated and distributed among human and artificial agents. New approaches to system design following the ecological perspective (Vicente 1999) or, more generally, the cognitive engineering methodology (Dowell and Long 1998) have translated this theoretical approach into practical methods of human–machine system design. Their main principle consists in describing the work domain constraints, postponing activity analysis or prescription as late as possible to avoid introducing unnecessary constraints that could reduce the degrees of freedom for adaptation.

Function allocation between humans and machines is a key question for the study or design of human–machine cooperation (HMC). The second section of this paper will be devoted to the evolution of its conception during the past two or three decades. In parallel, the third section will propose a short review of the main difficulties humans encounter with automation in highly dynamic situations as they have been mainly identified in aviation. Then, these two approaches to the human–machine relationship will lead to the fourth section, which proposes an attempt to apply the cooperation paradigm to this relationship.

2. Function allocation between humans and machines

The allocation of function between humans and machines is a very old topic in human engineering. The first type of solution to the allocation problem was an attempt to decompose an activity on a general basis into elementary functions and to allocate each one to the best efficient device (human or machine) for that function (Fitts 1951). For example, machines are considered as very good at calculating complex formulas, whereas humans are the best for facing unexpected or unknown situations. Such an approach has been repeatedly criticized (Bainbridge 1987, Older *et al.* 1997).

First, functions are rarely defined as such to avoid the need for frequent cooperation during task execution when tasks explode into several functions, so that tasks (including several functions) rather than functions are allocated. For example, in ATC, it has long been known that aircraft conflict detection and resolution are two tightly related functions (Bisseret 1970). If conflict detection is defined as the identification of a type of conflict relevant to the choice of an appropriate solution, the allocation of the detection function to a machine and of the resolution function to the human is not very efficient. If one considers that the machine can not resolve the conflict, the reason lies in the machine's limitation in identifying the conflict type appropriately. Thus, some cooperation should be introduced between the two agents to integrate closely the two functions (and the two agents) during task execution. In a recent study on ATC automation, control theorists have preferred the allocation of tasks (conflicts) rather than the allocation of functions between the human and the machine to avoid resolving this difficult cooperation problem (Vanderhaegen *et al.* 1994).

Second, human operators are finally (legally) responsible for the whole human–machine system's performance. How can they control a machine that operates very differently from them? Function allocation should integrate several levels of abstraction and not only a single one. Allocating a low-level function to a machine does not alleviate the human workload of supervising the overall task execution and the 'human-out-of-the-loop' syndrome has very often been stressed. That is probably one of the reasons why human air-traffic controllers rejected an automatic mode of conflict allocation between the human and the machine in the study of Vanderhaegen *et al.* (1994).

Third, the definition of functions is very determined by cognitive theories, which are various and concurrent. More often than not the decomposition is based on inefficient 'common sense' cognitive science. Thus, any decomposition should be considered as temporary and regularly updated, taking advantage of the progress made in cognitive psychology and technology. For example, Sheridan and Verplanck

(1978) or Endsley and Kaber (1999) have proposed taxonomies largely influenced by recent technologies, that is decompositions used in actual human – machine systems, for example manual control, action support, shared control, decision support, supervisory control, etc.

The argument here is not to say that decomposing human – machine systems into elementary functions is useless. When designing operator training or machines this is an inescapable problem. However, it is unclear whether the objects to be allocated are functions or tasks. In single-task situations, probably the consideration of functions is the right one, provided that some cooperative mechanisms are introduced between human and machine to allow the human to recompose the whole task. In multitask situations, like ATC, the case is very different because the human operators must share their time between several tasks (e.g. several and simultaneous aircraft conflicts in ATC). From the human point of view, each task corresponds to an intention to be protected. When task planning or execution is again split into several functions, the management of working memory can become overloading. Nevertheless, whatever what should be allocated—functions or tasks—the criterion of efficiency is not the only one to consider, especially in dynamic situations where the precise conditions of the actual performance are not known beforehand. For example, Rasmussen *et al.* (1994) or Older *et al.* (1997) suggest several other criteria like organizational or financial constraints, instantaneous workload, resource requirements, access to data, etc. Hence, a dynamic allocation paradigm is needed (Rieger and Greenstein 1982, Lemoine *et al.* 1996) that can take advantage of the access to instantaneous evaluation of the situations to choose the best allocation.

Several studies on ATC have explored the dynamic allocation problem on the basis of workload regulation using an automated aircraft conflict detection and resolution device. Vanderhaegen *et al.* (1994) showed that performance and reliability are better within an implicit allocation paradigm, where allocation of conflicts is fully automated, than within an explicit allocation paradigm, where allocation is decided by the human controllers. However, expert controllers preferred the explicit allocation principle, in spite of an increase in workload due to task allocation. Hoc and Lemoine (1998) explored the benefit of further assistance within the explicit paradigm and showed an improvement in reliability by the means of more planned strategies. However, the well-known phenomenon of complacency (see below) was observed in the more assisted situation where the human controllers could not decide the allocation by themselves but validated the decision of the automated system (with a possibility of veto). In this situation, they were more willing to let the system act without their supervision and to adopt conflict resolution strategies that did not interfere with the system strategies. These studies raise the question of the compatibility between an overall plan to manage the traffic (in charge of the controllers) and the plans elaborated to perform the subtasks. Task or function allocation should consider the overall organization of the human – machine system's task under the human responsibility.

3. Failures in the human – machine relationship

Many studies have been devoted to the failures in coupling human and automation, especially within the aviation domain where such failures have obvious consequences on reliability (for an overview, see Parasuraman and Mouloua 1996). As far as human error is considered, that is those cases where humans contribute to the multicausality of the accident, inquiry boards have analysed some poor ergonomic properties of the cockpit. However, on a more general basis including industrial process control, anaesthesiology, etc., four main kinds of failure can be summed up that not only have implications on human–machine interface design, but also have something to do with HMC.

3.1. *Loss of expertise*

Human loss of expertise is the consequence of designing machines that play autonomous roles, either performing low-level functions (decision implementation) or high-level functions (diagnosis, decision-making). Bainbridge (1987) stressed these 'ironies of automation' at the same time as consisting in assisting the operators and reducing the occasions for maintaining their skills. The effect of this phenomenon has often be described as resulting in a loss of vigilance, the operators becoming 'passive' (Endsley 1996). Some studies of dynamic task allocation have adopted this point of view, defining the allocation to the machine in relation to the human operator's workload (Millot and Mandiau 1995). However, the main problem of the loss of expertise is the loss of the necessary conditions to allow the operators to exert their responsibility over the entire human–machine system (Jones and Mitchell 1994). In addition, when operators again must take up manual control, they are likely to reach a poor performance. If this operators' role within the human–machine system is taken seriously, the loss of expertise leads to the loss of a particularly important kind of agent in the system who will can not cooperate with automation when the latter is out of its depth.

3.2. *Complacency*

Several times, human complacency or over-reliance as regards automation has been described, especially in relation to 'intelligent' machines performing high level functions (Layton *et al.* 1994, Endsley 1996, Smith *et al.* 1997, Mosier *et al.* 1998). Even when operators are sufficiently expert and can be reasonably aware of the limitations of the machines, which can not find optimal solutions in certain circumstances where they cannot consider some important factors, operators take the solutions for granted without questioning them. For example, Layton *et al.* (1994) and Smith *et al.* (1997) studied the use of an automatic replanner during air cruise. In a particular scenario, it was obvious that the system could not find the optimal re-routing. However, expert pilots did not question the proposed solution. This phenomenon poses the difficult problem of shared supervision. More often than not, automation aims at reducing the operators' workload when they are confronted with increasing requirements. The automation process does not alleviate the workload in terms of operators' supervision of the overall human–machine system activity. A possible reason for complacency could be a division of the supervision field into two independent fields, the operator's field and the machine's field (as shown for example in ATC automation; Hoc and Lemoine 1998). From the HMC point of view, the benefits of mutual control of the operator over the machine have been demonstrated (e.g. in trouble-shooting with the assistance of an expert system; Roth *et al.* 1988) or suggested (Clark and Smyth 1993). In response to complacency, Smith *et al.* (1997) suggested that the machine proposes several solutions instead of only one. However, this mutual control attitude is not easy to induce (Mosier *et al.* 1998, Endsley and Kaber 1999).

3.3. *Trust and self-confidence*

The seminal studies of Muir (1988) and Lee and Moray (1992, 1994) have drawn the attention to an important factor of the operators' utilization of automation when they have the choice between an automatic and a manual mode. In the experiments (control of a pasteurizer) the latter was designed to be more efficient than the former. These studies have shown that the shifts between the two modes can be predicted by the ratio between trust (in the machine) and self-confidence. More importantly, Muir described trust as a dynamic phenomenon in relation to the operators' experience of the machine, going through three steps. At first, without any precise model of the machine, only faith or doubt can develop, as described in cockpit automation for example (Amalberti 1992). First confronted with an automatic system for landing, pilots either used the system blindly (faith) or shortcut it (doubt). As experience increases, operators can reach a feeling of dependability and then of predictability. In terms of HMC, such a development is related to the elaboration of a model of oneself (self-confidence) and of a model of the other agent (trust) qualified by Castelfranchi (1998) as 'mind reading' within cooperation situations.

3.4. *Loss of adaptability*

Cognition is the way by which systems can adapt to the variety of their environments, relying on knowledge represented in their memories. 'Intelligent' machines are designed to increase the machines' adaptive power. However, they cannot equal operators in adaptive skill. Beyond the loss of expertise, automation has also been considered as reducing the adaptability of the human – machine system (Ephrath and Young 1981, Mosier 1997, Parasuraman 1997). The main reason for this drawback is the lack of feedback to the operator when the machine performs a task. This results in the well-known 'human-out-of-the-loop' syndrome (Ephrath and Young 1981, Endsley and Kaber 1999) leading the operators, when necessary, to take again the control in hand without any clear situation awareness. Moreover, to put it in HMC terms, the lack of feedback does not allow operators to anticipate possible interference between their own tasks and the machines' tasks. Finally, operators are compelled to adopt reactive strategies instead of anticipative strategies insuring long-term adaptation (Cellier *et al.* 1997). More generally, the various reasons for all these HMC failures reduces the dynamic cooperation between humans and machines in real-time to adapt the human – machine system to situations unforeseen by the designers. HMC is an important ingredient of the adaptive power of the human – machine system.

4. A minimal conception of cognitive cooperation to apply to human – machine cooperation

As many other concepts such as communication or intelligence, cooperation refers to the human (human – human cooperation) and HMC can be seen as a chimera, trying to introduce a human-like relationship between two very different entities. Nevertheless, the implication of a human into this kind of relationship, even if it integrates a machine, may be justified to contribute to resolve part of the automation failures in terms of human – machine relationships. Decisive progress has been made in introducing 'know-how' into machines and it is time to provide them with some 'know-how-to-cooperate' at the same time distributed artificial intelligence is developing (Castelfranchi 1998, Millot and Lemoine 1998). Certainly one cannot imagine building machines capable of generating all the complexity of the human's cooperation skill. However, a restriction of this skill to its cognitive aspects appears to be a reasonable medium term aim. Highly dynamic situations have been selected that imply small human and machine teams, very goal-oriented to elaborate on cognitive cooperation modelling (e.g. in ATC, Hoc and Lemoine 1998, Carlier and Hoc 1999; or in fighter aircraft piloting, Loiselet and Hoc 1999). In this kind of situation, cognitive aspects of cooperation are major and are limited by time constraints, and they can result in manageable models. The main objective for a fighter aircraft crew is returning to the base and the social aspects of cooperation, for example, are minor.

In the line with Piaget (1965), one considers cooperation from a functional point of view—that of the cooperative activities performed in real-time by individuals within a team, which are not performed when working alone—as opposed to a structural point of view (e.g. network organization). One considers that two agents are in a cooperative situation if they meet two minimal conditions:

- Each strives towards goals and can *interfere* with the others on goals, resources, procedures, etc. Interference can take several forms, for example precondition (an agent's action being a precondition for another agent's action), mutual control (contributing to correct the others' mistakes), redundancy (replacing another agent for diverse reasons), etc. If there is no interference, coordination is prebuilt and is not questioned during task execution; thus, the agents' activities are independent.
- And each tries to manage interference to *facilitate* the individual activities or/ and the common task when it exists (e.g. cooperation on resource utilization does not imply a common task). Cooperation is very closed to competition, the sole difference being that in competition interference is managed so that the others' activities are made more difficult.

The symmetric nature of this definition may be only partly satisfied. Even in human–human cooperation, only one agent can be in charge of managing interference due to the others' workload (e.g. in ATC, the planning controller in charge of coordination with adjacent sectors is mainly facilitating the radar controller's task consisting in controlling the sector). Consequently, it is possible to improve HMC, although the machine has a limited cooperation skill. A minimal solution is to help the human to identify human–machine interference.

From a cognitive point of view, interference management to facilitate collective tasks is performed by the means of cooperative activities that are part of those described in the human–human cooperation literature, which integrates leadership, engagement, etc. (Militello *et al.* 1999). Following this restrictive view, cooperative activities can be organized into three levels, at the same time implying an increase in abstraction and an enlargement of the time span referred to:

- *Cooperation in action* groups together activities that have direct implications on the short-term and that can rely on a local analysis of the situation. This level includes local interference creation (e.g. mutual control), detection, and resolution. It also integrates interference anticipation by identifying the other agents' goals in the short-term.
- *Cooperation in planning* consists in maintaining or/and elaborating a common frame of reference (COFOR; De Terssac and Chabaud 1990).

COFOR includes not only a shared situation awareness (Salas *et al*. 1995) in the sense of a common representation of the environment, but also a representation of the team considered as a resource. COFOR maintenance and elaboration concern common goals, common plans, role allocation, action monitoring and evaluation, and common representations of the environment. These activities need a certain abstraction to develop and determine the team's activity in the medium term.
- *Meta-cooperation*, situated at a much higher abstraction level, allow the agents to improve the cooperative activities described above by elaborating long-term constructs, such as a common code to communicate easily and shortly, compatible representations formats, and above all models of oneself and of the other agents.

Studies of human–human cooperation in the highly dynamic situations referred to (ATC, sharing aircraft in the same sector between two radar controllers, and two-seated fighter aircraft piloting, with a pilot and a weapon system officer) have stressed three main facts:

- COFOR management represents at least half of the cooperative activities. Communications on plans, goals and roles are very efficient in reducing most of the local interference management.
- COFOR management is more concerned by the team's process control activity in itself (plans, goals, role allocation, etc.) than by the process under control ('situation awareness', strictly speaking).
- COFOR maintenance activities are almost as frequent as COFOR elaboration activities. Thus, a large part of the activities at the planning level consists in maintaining a common representation without needing a long and tedious elaboration.

5. Conclusion

The result of this application of a general framework for cooperative activities to highly dynamic situations can allow one to be quite optimistic as regards the design of 'cooperative machines'. Some engineering studies already aim at designing machines capable of performing some of the cooperative activities described here, for example identification of the human agent's goals, cooperative plan generation, etc. (Castelfranchi 1998, Millot and Lemoine 1998). Certainly, 'meta-cooperative' machines are still not attainable, but the designer can introduce some operator's models into machines. Some of the activities described at the two first levels can be implemented, at least in specific situations. The development of this kind of enterprise is crucial to improve the human–machine systems' adaptability and reliability by introducing a flexible cooperation in real-time.

However, even if the cooperative skills of the machines are very restricted, machines can at least help the operators to perform the HMC activities in better conditions than the current ones. The development of tools to maintain a COFOR between humans and machines is probably a first and important step towards such an improvement (e.g. in the line of Lemoine *et al*. 1996 or Jones and Jasek 1997). Nevertheless, there remain serious problems to be solved in terms of alleviation of the human workload of informing the machine of the operator's activity. Currently, these problems in ATC are trying to be solved with a very simple machine capable of implementing controllers' schematic plans for subtasks, but of communicating with the controllers through a COFOR-like interface. Such an interface aims at supporting the controllers' problem-space, updating it regularly.

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