An Attempt for conceptual framework for Human-Machine Cooperation

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Abstract: As technical processes become more and more complex and the need to support human operators in supervision or control tasks becomes increasingly crucial, the nature of the interactions between human operators and Decision Support Systems (DSS) tends towards Human-Machine cooperation in which the DSS facilitates a partnership with the human operators. In this paper, we first recall a definition for cooperation from the field of psychology: Two agents are cooperating if 1) each one strives towards goals and can interfere with the other (e.g., in terms of goals, resources, procedures) and 2) each agent tries to detect and process such interferences to make the other’s activities easier. This definition, which was originally intended to describe human-human cooperation, can be extended to Human-Machine Cooperation if adjustments are made to compensate for the limitations of the machine’s capabilities. We then present the four basic elements needed to design a cooperative Decision Support System:

- sufficient know-how for solving problems autonomously,
- know-how-to-cooperate ability,
- an adequate organizational structure that integrates human and machine, and
- a need-to-cooperate.

Key studies in engineering have focused on know-how; others have concentrated on the ability to know-how-to-cooperate; still others, on the organizational structure of the Human-Machine partnership and the conditions that motivate human and artificial agents to cooperate to accomplish a task. Using a multi-disciplinary approach that associates research in cognitive psychology and human engineering, we bring these 4 basic elements together in a methodology for designing Human-Machine cooperative systems. This methodology is the result of more than twelve years of experiments at LAMIH in several fields of application, mainly Air Traffic Control and Telecommunication networks.

Keywords: Human Machine cooperation, cooperative decision support system, Common Frame of Reference, Design of human-machine systems, cooperation forms.

1. INTRODUCTION

The domains of application for this research include large industrial plants or transportation networks in which human activities mainly involve decision-making: monitoring and fault detection, fault anticipation, diagnosis and prognosis, as well as fault prevention and recovery. The objectives encompass both human-machine system performances (production quantity and quality) and global system safety. We apply a human-centered approach to the design of dedicated assistance tools for human operators and their integration into human activities, based on a cognitive analysis of the human activities in order to evaluate the need for such tools and their use.

2. HUMAN MACHINE TASK SHARING

The methodology starts by defining the tasks to be performed. To this end, the technical constraints (e.g., dynamics, safety) for the different predictable system operation modes need to be extracted. Then, functional/dysfunctional system analysis methods (Fadier et al 94; Vanderhaegen 99) can be used to deduce (or induce) the trouble shooting tasks needed for system recovery. These trouble shooting tasks must first be specified in terms of their objectives, allowed means (e.g., sensors, actuators) and functions, and then distributed between the operators and the machine according to two criteria: technical feasibility and ergonomic feasibility:

- The technical feasibility criterion divides the initial task set into two classes, fig 1:
  - TA tasks that can technically be performed automatically, and
  - TH tasks that cannot be performed automatically, due to lack of information and/or technical or even theoretical reasons and thus must be allocated to human operators.
- The ergonomic feasibility criterion is then applied on both subsets TA and TH to evaluate those tasks that can be accomplished by human in order to enhance the global system safety:
  - subset TA: some tasks TA can also be performed by humans, and allocating them to human operators can allow these operators to better supervise and better understand the global technical system and the automated devices; the subset TA is the set of the shareable tasks used in a form of human machine cooperation called augmentative that will be discussed further below.
  - subset TH: some subtasks TH are very complex or their complexity may be increased by very short response times and thus could be facilitated by a Decision Support System (DSS) or a Control Support System; the subset TH can be performed through another form of cooperation called integrative.

The ergonomic criterion is based on human operator models that define the allowable cognitive resources and limits as well as the operator’s intrinsic limits: perceptual
and/or physical limits for performing the related actions (Hollnagel 00). The cognitive resources are identified according to the application context. The human physical resources are determined through ergonomic guidelines.

Once the organization of the task sharing is determined, the type of human machine cooperation can be defined and a framework for implementation can be proposed.

3. DEFINING HUMAN-MACHINE COOPERATION

3.1 Defining an agent

The DSS is designed to assist Human Operators in order to facilitate their tasks and avoid faulty performances. Both the DSS and the Human Operators are called agents. Agents (be they human or machine) can be modelled with 3 classes of capabilities: 1) the Know How (KH) for solving problems and performing tasks autonomously, including problem solving capabilities (knowledge, processing abilities) and communication capabilities for sharing information with the environment and other agents through sensors and control devices.

2) the Know-How-to-Cooperate (KHC) needed for Managing Interference (MI) between goals and for facilitating other agents' goals (FG) according to the definition of cooperation definition given in the next subsection (Millot, Hoc 97).

3) a Need-to-Cooperate (NC) including:

a) the adequacy of the agent’s personal KH (in terms of knowledge and processing abilities) for the constraints required by the task.

b) the abilities to perform the task (the human agent’s workload WL produced by the task, perceptual abilities, control capacities).

c) the Motivation-to-Cooperate including the motivation to achieve the task, self-confidence, trust (Moray et al. 95) and the confidence in the cooperation (Rajaonah et al. 06).

3.2 Defining Know-How-to-Cooperate

In the field of cognitive psychology, Hoc (96) and Millot & Hoc (97) propose the following definition: “Two agents are cooperating if 1) each one strives towards goals and can interfere with the other, and 2) each agent tries to detect and process such interference to make the other's activities easier.” From this definition, two classes of cooperation activities which constitute know-how-to-cooperate (KHC) can be derived (Millot, Lemoine 98):

- The first activity requires the ability to detect and manage interference between goals (MI): this interference can be positive (common goal, sub-goal ...) or negative (conflicts between goals, sub-goals ... or common resources to be shared).

- The second activity requires the ability to facilitate the goals of the other agents (FG).

Therefore MI involves coordination ability, while FG involves generous agent behavior. Before giving the specific elements of MI and FG the organizational aspects of the cooperation must be considered.

3.3 Structures for Cooperation

In an organization an agent performs tasks encompassing the different activities needed for acquiring and processing information and for making decisions which may or not result in actions. Defining the organization is one way to prevent or solve decisional conflicts between the agents, especially in human engineering where agents can be either humans or artificial DSS. This organizational aspect has also been studied in Distributed Artificial Intelligence, and two generic structures of purely structural organization exist, called respectively vertical (ie: hierarchical) and horizontal (ie: heterarchical) (Millot, Taborin et al 89, Grislin-Le Strugeon E., Millot P.99).

- In the vertical structure the agent AG1 is at the upper level of the hierarchy and is responsible of all the decisions. If necessary it can call upon the agent AG2 which will give advice. In the case fig 2, AG1 is a human operator and AG2 is a DSS.
- In the horizontal structure both agents are at the same hierarchical level and can behave independently if their respective tasks are independent. Otherwise, they must manage the interference between their goals using their MI and FG capabilities. In fig 3 AG1 is a human operator and AG2 is a DSS. The MI activities are performed by a coordinator at the upper level.

Several combinations of these two structures are possible by breaking the task down into different abstraction levels (Rasmussen, 91) and assigning a dedicated structure to each of these levels. An example will be given in the section 4.

3.4 Cooperative forms and know-how-to-cooperate

Consider an agent AGx that has know-how KHx, and know-how-to-cooperate KHCx, and is within a structure. KHCx can be specified using MIx and FGx in the different cooperative situations that may be encountered (or built). To this end, we use the generic typology of cooperative forms proposed by K. Schmidt (91): augmentative, debative, integrative. Then we simulate the activities of the agents in order to define the primitives of their KHC.

3.4.1. Augmentative cooperation

Cooperation is augmentative when agents have a similar know-how, but must be multiplied to perform a task that is too demanding for only one agent; the task T is then shared into similar subtasks STi. Interferences between the agents' activities can result from the need to share common resources, but also from conflicts between the goals or sub-goals of their individual STi. KHC must involve abilities 1) to decompose the task T into independent STi before it be performed, in order to prevent these conflicts, 2) to manage the residual conflicts stemming for instance from sharing common resources while executing STi and 3) to recompose the results afterwards if the results of the STi were not an action, or otherwise rebuild the task context. These activities can be performed by an agent called a coordinator which can be a third agent, either AGx or AGy, which then plays the dual role of coordinator and actor.

The coordinator's KH includes capabilities for acquiring the task context, for building a global task plan and for decomposing it into STi (sub-plans). The coordinator's KH includes capabilities for 1) acquiring other agents' KH for testing the agent's adequacy for the task (or inferring the agent KH through modelling), 2) acquiring other agents' workload in order to test the agent's abilities and/or resources for the sub-tasks to allocate, 3) controlling and recomposing the results or the contexts after each STi has been performed and 4) managing conflicts about common resources. All coordinator KH involves MI while the KHC of general agents involve at least FG for answering to the coordinator requests.

3.4.2. Debative cooperation

Cooperation is debative when agents have a similar know-how and are face with a single task T (non-divided into STi). Each agent performs the task and then discusses the results (or partial results) with the other. Conflicts can appear, and the KHC is then applied to solve these conflicts through explanations based for instance on previous partial results in the problem solving process and on a common frame of reference (see below and Millot, Hoc, 97). Before executing the task, each agent KH involves the ability to acquire the task context, and to build a plan (goal, sub-goal ... means). Each agent KHC involves acquiring the other agent KH either by inferring a model of the other agent, or by asking the other agent directly. This indicates MI capability, but the other agent's answer involves FG.

After task execution (or partial execution) each agent transmits its own results to the other, receives the other's results and compare those results with its own. In addition to MI capabilities (ie: asking others for results) and its FG capabilities (ie: transmitting its own results), specific competences are needed to understand the other's results, to compare them with its own, and to decide if it agrees or not. All these competences are MI.

In the case of conflict each agent must be able to ask for explanation (eg: the other agent's view of the task context, its partial results, its goal or sub-goals) and compare these explanations with its own point of view in order to decide if the conflict continues or not. In addition, each agent must be able to accept its own errors and learn from them. This last capability can have important consequences on the agent KH, especially with respect to learning new knowledge.

3.4.3. Integrative cooperation

Cooperation is integrative when agents have different and complementary know-how and the task T can be divided into complementary sub-tasks STi with respect to each agent's KH. As in augmentative form, an agent plays the role of coordinator. This role could be performed by AGx or AGy or by a third agent. The coordinator's KHC must be able to 1) elaborate a common plan (goal, means) and break it down into complementary sub-plans (STi, sub-goals) related each to the respective agents' KH, 2) control the partial results or the evolution of the context throughout the agent's execution of the STi, and 3) if the results of the STi were not an action, recombine the results afterwards, or rebuild the task context. This form of cooperation is similar to the augmentative form excepted during the STi executions, due to the possible interactions between the agents, which requires the ability to verify each partial result and to order corrections, if necessary.

A more general and complex case, in which both agents AGx and AGy must cooperate in order to build the shared common plan together, can be imagined. In this case, studied by the field of Distributed Artificial Intelligence, each agent plays a coordinator role. It must first elaborate a common frame of references for the task context, and for their own KH (Millot, Hoc 97) and then it can elaborate its own global common plan and compare it with the others in debative cooperation. Examples of this situation can be found in the Human-Human cooperation practiced in multidisciplinary research, for instance.

3.4.4. Genericity of the 3 cooperative forms

An example of the augmentative form can be observed at the bank office, when the queue of customers in front of the window is too long, a second window is opened to split the queue and to reduce the first operator's workload. An example of the debative form could be the mutual control between the flying pilot and non-flying pilot in the plane cockpit. An example of the integrative form can be seen in the coordination of the different tasks required when building a house.

These 3 forms already exist in human-human organizations and are sometimes naturally combined. The
innovation of our methodology lies in implementing these forms of cooperation between a human being and a machine. Fig 4 shows that the 3 forms are generic for all kind of cooperation. Therefore to be cooperative in general cases a system must combine in its KH, the union of the primitives with compose the KHCj of each generic form augmentative, debative, integrative:

\[ \text{KHC} = \text{KHC}_a \cup \text{KHC}_d \cup \text{KHC}_i \]  

(1)

<table>
<thead>
<tr>
<th>Adequacy of</th>
<th>Different KHi</th>
<th>Similar KHi</th>
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<td>Task</td>
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<td>Similar STj</td>
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<td>Different STj</td>
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<td>Integrative</td>
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<td>Non-shareable Tasks</td>
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<td>Debative</td>
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Fig 4: Genericty of the 3 forms of cooperation

3.5 Architecture of human machine cooperation & COFOR

Human agents plan their own activities in order to manage their internal resources according to the time pressure and the stress to which they are subjected. To manage situations, human agents build a frame of reference that contains different attributes: information (stemming from identification elaboration activities); problems (stemming from identification activities); strategies (stemming from schematic decision making activities); solutions (stemming from precise decision making activities); and commands (stemming from solution implementing activities).

When several human operators supervise and control the same process, they develop and maintain a common frame of reference which is a common representation of the environment and the team resources. This Common Frame Of Reference (COFOR) involves common goals, common plans, role allocation, representations of the process, for example (Loiselet, Hoc, 01). In order to prepare to cooperate, human agents exchange such elements as information, problems and strategies in order to share their own frame of reference, thus building a virtual COFOR. In the case of Human-Machine Cooperation, a Common Work Space (CWS) can be the realisation of the COFOR and become a support for the cooperation between the human agents and the artificial agents. But it is necessary to define which activities/functions will be performed by the different agents and which form(s) of cooperation (augmentative, integrative and debative) must be implemented, (Riera, Debernard, 03).

4. COOPERATIVE FORMS, STRUCTURES & CWS

4.1 Debative form and structure

Both agents have a similar KH and are faced with a single non-shareable task T. After the task has been performed by each of the agents, they compare the results (total or partial) and in case of conflict they debate.

If both agents have all the needed KH and KHC capabilities a purely horizontal structure could be developed. The ability to recognize and correct errors may then depend on trust and self-confidence (Moray et al 95). With a hierarchical structure, the conflict resolution process can be helped by the hierarchy. If only one agent has full KHC capacities, a de facto hierarchy exists, which is a fairly realistic situation in human-machine cooperation, where the machine capabilities may be reduced to FG ability. In this case the machine’s designer should have simulated the conflict resolution process of the human user, in such a way the machine can help the human to cooperate with it.

Fig 5: Synthesis of the decisional conflict solving pathway in a debative form

For instance, we designed a graphical justification interface to integrate a DSS in the supervision loop of a continuous production process (Millot, Taborin 89). It was a first kind of CWS. In that study the conflict resolution process was simulated by placing both decisional processes (human and DSS) in parallel; each of the processes was inspired from Rasmussen (83). Conflict resolution consists of searching for "consensus points" in the common deductions of each decision-maker, fig 5. If the conflict results from differences in the procedures of each decision-maker, the first consensus-point is the previous common deduction: each diagnosis. A second consensus point is the set of variables used by each decision-maker when making the diagnosis.

4.2 Integrative form and structure, an example of a diagnosis task for a telecommunication network

Both agents have different and complementary KH and each performs a subtask STi resulting from dividing T into complementary subtasks. Task decomposition and management can be done by a coordinator provided with all KHC capabilities, either a third agent or one of the two agents.
As for the other cooperative forms, when each agent is provided with all KHC capabilities a horizontal structure can be predicted, as is generally the case in Human-Human cooperation for instance between the pilot and the copilot in the plane cockpit. When the KHC capabilities of one agent are only partial, as generally in Human-Machine cooperation, a de facto hierarchy does exist and the chosen structure must respect it.

Let us see an application to the diagnosis. Two main tasks are essential in order to quickly focus on the failures affecting the supervised process:

1) Interpretation of the data collected about the process and generation of a set of failure hypotheses, which are then crossed to rapidly determine a minimal set of failures explaining the observed effects.

2) Verification of the consistency of the hypotheses at each step in the reasoning process according to a model of the system to diagnose.

The first task requires a global and flexible view of the system in order to quickly generate consistent failure hypotheses. This Know-How is close to human abilities and is thus allocated to the human operator. The second task requires calculation power in order to verify consistency and allow multiple alternatives to be considered quickly; thus, it is close to machine abilities and is allocated to the DSS.

After the task has been allocated, the main problem is to define the means for coordinating both decision-makers activities during the diagnosis process. Partial results must be aggregated and as the tasks are shared, the decision-makers have to exchange and interpret the data. The decision-makers must share their knowledge about the process (eg: external data) and a common workspace must be created for coordinating the human and machine reasoning processes. The common knowledge may be, for instance, a causal network of the links between symptoms and failures causes.

An example of a diagnosis for a domestic phone network was studied (Jouglet, Millot 01). When customers have difficulties with their phone they call a “hot line” service in order to diagnose the trouble. The “hotline” operator has less than 3 minutes to find one diagnosis among 49 possibilities knowing the symptoms among 150 possible ones. The operator collects the symptoms through direct dialogue with the customer and through test devices. We have built a DSS for this “hotline” operator and tested experimentally the global cooperative system. These experiments showed that the DSS used in integrative cooperative form, the average performance of good diagnosis has increased from 64% to 82%.

4.3 Augmentative form and structure, an example from Air Traffic Control

Both agents have a similar KH and each performs a subtask STi resulting from dividing task T into similar subtasks. In order to prevent conflicts between the agents, the coordinator must break down T into independent subtasks.

An example in the field of Air Traffic Control (ATC) was studied. The ATC objectives include monitoring and controlling the traffic in such a way that the aircraft cross the air space with a maximum level of safety. The air space is divided into geographical sectors, each of them being controlled by two controllers. The first one is a tactical controller, called a “radar controller” (RC) who supervises the traffic using a radar screen and dialogues with the aircraft pilots. This supervision involves detecting conflicts (risks of collision) between planes and then in solving them by ordering one pilot to modify his/her flight level, heading, or speed.

The second controller called a “planning controller” (PC) has a strategic role. First, he/she coordinates the activity in his/her sector with those in the other sectors in order to avoid unresolvable conflicts at the sector borders. Second, he/she is supposed to anticipate traffic density and regulate the radar controller’s workload. To supporting the RC we built a dedicated DSS called SAINTEX. In this system each agent—i.e., the RC and SAINTEX—are allowed to act on the traffic and the tasks were distributed dynamically between them according to performance and workload criteria.

To this end a task allocation control system was introduced at the strategic level of the organization, to play the role of coordinator. This role can be i) implicit i.e. controlled by a dedicated artificial decisional stage which requires the ability to assess human workload and performance, ii) explicit i.e. controlled by the RC himself who plays a second role involving strategic and organizational tasks (Vanderhaegen et al 94). These two principles were implemented and evaluated experimentally on a realistic ATC simulator with professional Air Traffic Controllers. In these experiments, a better performance in terms of safety and global kerosene consumption, and a better regulation of the human workload was obtained in the implicit allocation mode than in the explicit mode. Nevertheless, questionnaires showed that the professional Air Traffic Controllers would not easily accept the implicit allocation in a real situation, because 1) the different tasks were not completely independent, and 2) they lost control of a part of the traffic (tasks that had been allocated to SAINTEX) while still remaining responsible for all the traffic tasks. These results demonstrate the importance of the motivation-to-cooperate. Moreover no COFOR had been provided for supporting the cooperation.

In terms of structure, if AGx and AGy are both provided with all the KH and KHC capabilities of an agent coordinator, a purely horizontal structure will appear as is the case in Distributed Artificial Intelligence. However, if only one agent—for instance AGx—is provided with the capabilities needed to be a coordinator, a de facto hierarchy will be established, in which AGx will manage the cooperation, while AGy, with its FG capabilities, will simply facilitate the cooperation. The ATC experiment instituted such a de facto hierarchy, but the implicit task allocation mode did not respect it, which could explain why the RC rejected this kind of organization.

4.4 Real case, a second example from Air Traffic Control

In real situations, pure cooperative forms are rare; as a general rule the three forms are combined. This is the case in the field of ATC in which a new version of cooperation between Human Controllers and a new tool called STAR has been studied as part of the AMANDA project (Automation and MAN-machine Delegation of Action). The cooperation between STAR and the human controller can take the 3 forms: a) debative, b) integrative, c) augmentative. The project’s objective is to identify a COFOR and to build a Common Work Space (CWS) between STAR and the human controllers, which takes controller strategies into account in order to calculate precise solutions and
then transmits the corresponding command to the plane’s pilot (Debernard et al., 02). In an initial experiment, the air-traffic controllers frame of references were identified by coding the cognitive activities of the controllers (Guiost et al., 2003). The CWS plays a role similar to a black-board displaying the problems to be solved cooperatively, as each agent brings peaces of the solutions the CWS displays the evolution of the solution in real time. This CWS has been implemented on a graphical interface of the AMANDA platform (Guiost et al., 07).

![Diagram of cooperative forms in ATC](image)

Figure 6: Complementary cooperative forms in ATC

The experimental evaluation shows that this cooperative organization allows controllers to better anticipate air traffic conflicts, thus increasing the level of safety. In addition the CWS seems to represent air traffic conflicts well and thus is a good tool for conflict resolution. Furthermore the organization offers the best task sharing between both controllers, which results in a better regulated workload.

5. CONCLUSION

In this paper, a framework for integrating human machine cooperation has been presented. According to this framework, in order to implement effective Human-Machine cooperation, the KH of the different agents (either human or machine) must be dealt with, as well as their respective KHC, and the appropriate cooperative structure must be chosen. Several examples have been given and some problems mentioned.

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