Towards human-based industrial cyber-physical systems

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Marie-Pierre Pacaux-Lemoine, Quentin Berdal, Simon Enjalbert, Damien Trentesaux
Univ. Valenciennes, CNRS UMR 8201- LAMIH, F-59313 Valenciennes, France
Email: {marie-pierre.lemoine; quentin.berdal; simon.enjalbert; damien.trentesaux}@univ-valenciennes.fr

***Abstract*— The constant advances in sciences and technologies encourage industrialist and researchers in manufacturing, to address new challenges relevant to industrial Cyber-Physical Systems (CPS). Human aspects, among others, are of importance and researchers try to take them into account, but they remain to be efficiently dealt with during the design of industrial CPS. The goal of this paper is to highlight how it is possible to integrate “human-in-the-loop” inside the process control of industrial CPS. For that purpose, relevant studies already done in industrial engineering and Human-Machine Systems are presented, completed by an overview of the main cognitive dimensions industrial designers have to integrate in assistance systems definition, in order to benefit from human competencies and capacities while respecting human limits. The main idea is to balance Human and technology involvement, taking advantage of industrial CPS advances and Human capabilities identified and implemented through Human-Machine Cooperation principles. The project HUMANISM, which is presented, aims to specify and experiment such principles.**

***Keywords*—human-machine cooperation; adaptive level of automation; collaborative robotics; intelligent manufacturing systems; multi-agent systems; cyber-physical systems**

I. Introduction

The constant advances in sciences and technologies encourage industrialist and researchers in manufacturing, to address new challenges relevant to industrial Cyber-Physical Systems (CPS). Human aspects, among others, are of importance and researchers try to take them into account. For example, Human Cyber-Physical systems have been defined as well as the notion of Operator 4.0 [1]. Control 5.0 has been also introduced, bringing together Control 1.0 to Control 4.0 in the artificial world, supporting the virtual-real duality as well as the Cyber-Social-Physical Spaces notion [2]. Most of the time, the design of an industrial CPS is mainly focused on how providing information to Human operators [3]. More, human aspects are often taken into consideration only at the end of the design process, that is once the control system has been fully designed. In fact, researchers in manufacturing mainly adopt a techno-centered approach, favoring in priority the definition and allocation of tasks to automated intelligent systems while considering at the same time that humans, being operators or supervisors, will be there only to handle any unexpected situations efficiently.

Human aspects remain to be efficiently dealt with during the design of industrial CPS: in normal conditions, human operators or supervisors are assumed to decide and inform perfectly within due dates, with no stress or mental overload. They are called when a problem appears. They have to make quick and efficient decisions while they are facing complex systems composed by autonomous entities connected each other, with possible emergent behavior. Human operators thus face difficult tasks without being aware of process design or current state [18]. Consequently, in a single word, these humans are assumed by designers to behave like “magic humans” [4], which is neither realistic nor sustainable in the context of the future industrial CPS interoperating with humans.

The goal of this paper is to highlight how it is possible to integrate “human-in-the-loop” inside the process control of industrial CPS. For that purpose, relevant studies already done in industrial engineering are presented in the next part, completed by an overview of the main cognitive dimensions industrial designers have to integrate in assistance systems definition, in order to benefit from human competencies and capacities while respecting human limits. The third section presents the Human-Machine System (HMS) approach, which deals with the support of the cooperation between human operators and assistance systems. An example of the use of HMS in the robotics field is detailed not only to illustrate this approach but also to identify its possible benefits in the context of human-based industrial CPS. To illustrate how human-based industrial CPS can be designed, the fourth section presents the project HUMANISM, which aims at implementing HMS approach to three types of CPS taking part in a Flexible Manufacturing System (FMS).

II. Issues relevant to human aspect in industrial CPS

A growing number of researchers, especially in ergonomics and human-engineering, have already addressed the domain of industrial engineering to ensure more human-centered designs of manufacturing control systems. As a prerequisite, they have worked on Levels of Automation (LoA) and Human-Automation Symbiosis [5][6]. They propose methods and associated assistance systems in order to identify and design appropriate LoA, regarding human competences and needs [7][8], as well as industrial system goals. Targeted industrial studies involving human aspects aim at providing cost-efficient solutions based on flexibility and functionality of proactive assembly systems [9], agile and adaptive manufacturing control architecture [10], and they aim at integrated physical/mechanical and cognitive/information-related variables [11]. Other interesting studies have been conducted focusing on human-machine interface like augmented reality technics [12], or monitoring for maintenance [13], or are focusing on emerging technologies such as cobots [14]. Applications to manufacturing cells are also found [15][16].

Industrial CPSs are dynamic systems regarding the different constraints they have to respect and especially temporal pressure, reaction time lags and numerous variables that could lead to unstable behaviors. The use of an HMS tools and approaches may then counter-balance the techno-centered design way followed by industrial CPS engineers. Among these tools and approaches, a first interesting one is the use of the five cognitive dimensions influencing human operator in the control and the supervision of dynamic situations [19]. These dimensions are the supervisory span, the control directness, the process information accessibility, process speed and continuity.

The first dimension relates to the supervisory span. It concerns the ability for human to access to process variables due to temporal, causal or spatial restriction or excess and their combination. A restricted supervisory span may result in the difficulty to anticipate process states regarding the speed of action feedbacks. An example of a dynamic situation presenting this characteristic is the control of heavy and long ship. A ship needs time to reach the direction or the speed defined by the pilot, and external unpredictable events like waves, winds and sea currents disturb its trajectory. Assistance systems provide useful support for anticipating disturbances using simulation tools. On the opposite, large supervisory span may lead to difficulty to identify process, to build a model and to make decision at the right time before decision begins to be obsolete. Typical example is fighter aircraft piloting. During certain phases of the flight, a pilot is unable to make a decision due to the quickness of the aircraft and the quick sequences of actions. All actions must be planned before the flight and updated during the flight. Recent fighter aircrafts are now equipped with assistance systems aiming at supporting task plan update on the tactical situation (SITAC display). This dimension deals with system complexity regarding the difficulty to identify causal relationship between variables. Industrial CPS and especially Intelligent Manufacturing Systems integrating smart products would present such a large supervisory span. Indeed, smart products have a quick and reactive behavior that impede human operator to intervene correctly for updating parameters. Assistance system based on simulation allows the test of commands regarding the current state of the smart products, and/or can provide a selection of possible commands to the human operators [18]. Another type of example is the lack of process awareness, when different staffs, like maintenance, designer and production staffs, modify the system regarding different and conflicting objectives. In that case, process may have an unexpected behavior because the model used by the human operator is not the good one anymore. Supports about the situation awareness using collaborative tools may mitigate such risks [21].

The second dimension relates to the control directness. It deals with the length of causal chains and the impact of intermediate variables, not fully controlled or predicted. Control directness affects system controllability, mainly due to a large number of variables. A large control directness, with too long casual chains, may prevent human operators from anticipating what could be the impact of their actions. A process with restricted control is more robust because disturbances have less chance to appear. Control directness relates then to complicated and dynamic systems. Industrial CPSs can be regarded as these kind of systems since they are concerned with numerous intermediate variables, with several communications between entities with sometimes hidden connections or connections unknown by human operators. Planes, trains, plants present large control directness, and more and more assistance systems have to be designed in order to restrain this dimension to allow human operator to grasp global process through its sub-parts. HMS provides tools to make shorter causal chains with assistance systems like information screening, prediction and simulation supports.

The third dimension concerns the process information accessibility. This dimension also concerns accessibility of process variables but it deals with the absence of the variable that must be calculated or assessed in the base of “surface” variables. System observability is relevant to this dimension. A variable, which is not accessible, implies that the human operator has to make inferences and hypotheses. It could also be a problem of delay. Indeed, a variable can be accessible but too late to diagnose process and make decision. In this case, predictions based on model have to be done. One of the advantages of industrial CPS concerns the potential access and use of large amount of raw data provided by sensors connected to physical components of the process (big-data). This implies then that diagnosis assistance systems are provided to support maintenance and supervision decisions.

The fourth dimension relates to process speed. It concerns typically sampling frequency and the time human operator has to monitor processes to be sure not to miss an important information. This dimension also deals with the human operator’s ability to plan during control task if the process is slow, e.g. blast furnace, or fast like in highly automated systems. In the first case, simulators provide useful tools to allow human operator to build a representation of the process according to a specific time. In the second case, assistance systems like autopilot replaces human operator’s skills and reduces his/her workload due to time pressure induced by process speed.

The last dimension concerns process continuity that is the evolution of the process and the ability for human operator to determine significant variations. Assistance systems aim at highlighting important information stemming from data analysis, especially regarding sampling.

Human operators feel these five dimensions differently according to their own expertise, experiences and capacity, and this last ability can evolve very quickly according to the difficulty of the tasks.

Human-Machine Systems approach uses these five dimensions in order to design assistance systems adapted to process characteristics and human operators’ needs. Such an approach would be very useful in the design of Human based industrial CPS. A detailed presentation of this approach is now provided in the next section.

III. THE HUMAN-MACHINE SYSTEMS APPROACH

Industrial systems designers have now to work with computer sciences and psychological designers, and they are at the first steps of identifying their common objectives, their sharing languages and models. The construction of cooperation between researchers who belong from different fields is a long way which have already been followed by the Human-Machine

Systems (HMS) domain. HMS approach aims at considering Human operator and assistance system in the same way, each one having own competences and capacities which have to be update if necessary to enable fruitful cooperation. HMS first principles have been proposed in 1975 by Thomas Sheridan who described models of human performance concerning information, control and decision [17]. Such principles have the objectives to adopt a Human-Centered design approach, considering the current and future activity of Human operator at the first steps of the HMS design. Human-Machine Cooperation focuses on cooperative goals and aims at taking into account objectives, competences and characteristics of each agent, human and artificial ones, to find the best organization regarding the situation to control [19].

A. *Human-Machine Cooperation principles*

The principles of Human-Machine Cooperation have been defined more than thirty years ago [20] and been used in different domains like nuclear plant, air traffic control, car driving, military robotics and aviation [21][22]. The general purpose is to propose a generic method to assist human designers in identifying how the human operator and machine may interact with suitable adaptive levels of automation while guaranteeing their performance, safety and security [23]. Human-Machine Cooperation studies led first to define a model of a cooperative "agent", a human being or an artificial entity, with two main dimensions: — the agent's ability to control the process, also called the Know-How (KH), and — the agent's ability to cooperate with other agents involved in the process control, also called the Know-How-to-Cooperate (KHC).

The Know-How of an agent only concerns the control of the process, the achievement of individual tasks without taking into account potential interaction with other agents. The KH is split up into two parts, one is called the internal KH, the other the external KH. The internal KH relates agents' competences and capacity to control the process. The competence of a Human agent is mainly composed by knowledge, rules and skills to control the process [24]. It is linked to expertise, experience and practices of agents. Similarly, the competence of an artificial agent is mainly related to its ability to acquire knowledge (like with machine learning), to follow rules (like expert systems) and to apply predefined commands (like with PLC, Petri net). The capacity of a Human agent is mainly related to workload, fatigue and attention, while an artificial agent is constrained by energy, memory and processor capacity. The external KH deals with the ability to get information from the process and the ability to act on the process. Therefore, the internal KH seems to be close to the cyber part of an industrial CPS and the external part seems to be close to the physical part of the industrial CPS. For implementation purpose, the KH has been summed up in four functions: information gathering, information analysis, decision making and action [25], and these functions only concern the process and not how the activity of other agents involved in the process control can be considered. The KHC is dedicated to this special task.

The Know-How-to-Cooperate is also split up into two parts. The external KHC is the ability of an agent to have information about other agents and to provide information to other agents. The support of the external KHC is called the Common Work Space. It supports the situation awareness dedicated to process state and environment, but it is enriched by the team situation awareness dealing with past, current and future activity of all agents [21]. The internal KHC allows agents to build up a model of others in order to make easier the cooperation with them. It is built up and updated by learning, training and exchanging with agents. Agents gather and analyze information about others in order to infer their KH and KHC. This notion seems to be inexistent in industrial CPS where other artificial agents are most of time considered as part of the process or they have myopic behavior combined to a reactive behavior that impedes Human operators to have deep exchanges with them.

KH and KHC can be understood as two parallel functions described each one by different sub-functions. Fig. 1 contains an illustration of this articulation. In this figure, the cooperative agent model is used to highlight interaction between Human and machine [26]. KH functions of agents are in interaction by the means of a Common Work Space represented by the blue area in the middle of the figure. KHC functions of agents use information provided by the Common Work Space in order to build up a model of the other agent and to evaluate this agent's involvement in the process control. The results of the evaluation compared to the own involvement and model of oneself (interference detection and management) have to lead to the adjustment of the position of the four sliders that describe the functions allocation (scales represented in the Common Work Space). A scale is associated to each KH functions. The position of the slider on the scale defines the degree or the percentage of sharing between Human and machine activity. Some functions can be completely allocated to machine or to human regarding their competency and capacity, but also regarding how they can take into account the activity of the other. The function allocation can be predefined and updated according to the information on the current situation.

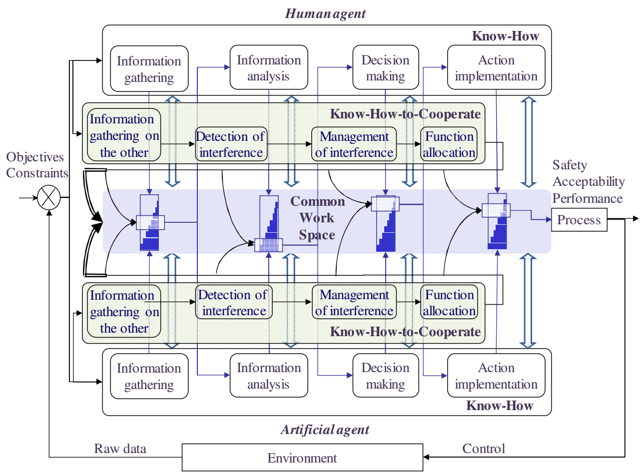

Fig. 1. Model of cooperative activities (adpated from [26]).

The model is also able to encompass existing definitions of levels of automation (LoA) and to propose new ones [30]. It is generic enough to be used on different types of levels of activity, also called layers [28]. Layers are most of the time used at operational, tactical and strategic levels. Industrial CPS are usually more concerned by layers close to command/control of process, than higher decisional layers close to the strategic level, where decision making is more and more distant from the physical part of the process.

B. An illustrative example

To illustrate these principles and to visualize their potential benefits to design industrial CPS that integrates efficiently the human operator or supervisor, an application dealing with crisis management and cooperation between a supervisor and robots is presented. This application, designed and realized in authors' lab, presents some similarities with the context of industrial CPS and research results can thus be extrapolated. For example, in industrial CPS, one can easily imagine that several human operators augmented with information capabilities (smart glasses, smart garment) share spaces and activities with mobile autonomous robots or intelligent products. In this context, crisis could concern hazardous situation, critical machine breakdown management, threat or unexpected process states that appear.

In this study, three types of agents take place in the scenario: a human supervisor (equipped with EEG and a brain computer interface BCI), operators (equipped with smart garment) and robots [29]. At the operational level, robots and operators have to be cooperative with each other and with the human supervisor in order to achieve a given common goal (solving the crisis or limiting its impact). The human supervisor is at the tactical level; he/she can observe the situation, make decision about the process and send instructions to the robots using a visual support presenting large amounts of information [30]. The model of cooperative activities helps agents to better organize their actions. Fig. 2 proposes an example of the use of the model of cooperation for identifying and selecting shared control functions and common work space in order to support cooperation between the supervisor and one robot in the field [31]. Four LoA have been identified according to KH and KHC of each agent (cf. Fig. 2). The human KH is violet, the robot KH is blue, the human KHC is light pink and the robot KHC is light blue. If the agent has the ability to perform one of the KH or KHC functions presented in the model (cf. Fig. 1), "1" is written in the rectangle. A new concept, the "emulated shared control" has been proposed to improve the robot KHC. This new concept has been defined with the same idea as the haptic control used in robotics and aeronautics (force feedback in the joystick) and in car driving (force feedback in the steering wheel) [32]. In the case of a command sent via the BCI, there is no real haptic feedback because no muscles are involved in the control to oppose or to follow the direction provided by the system. But the idea is to emulate this haptic behavior with a visual display. Depending on where obstacles are detected, the robot/BCI system makes it easier or more difficult—in terms of (mental) effort—for the human to deliver a command (cf. Fig. 2 where blue and red arrows give the left or right direction to the robot). The common work space focuses on this visual feedback and contains a live video stream of the environment from the robot's perspective. Red rectangles highlight the differences between each LoA regarding the layer, operational or tactical. A command is associated to each "1" function. Model predictive control approach (MPC) has been used to combine the different functions and their priority [30]. Each LoA has been evaluated within the framework of an experiment conducted up to now with only one participant and one robot. Comparison between results recorded for each LoA highlights the interest of the LoA defined by "With Emulated Haptic Feedback" and "Without Obstacle Avoidance". Precise analysis of agents KH and KHC during each step of the experiment underlines lack of situation awareness regarding obstacle detection and avoidance. This result leads to improve agents KHC to share their situation awareness.

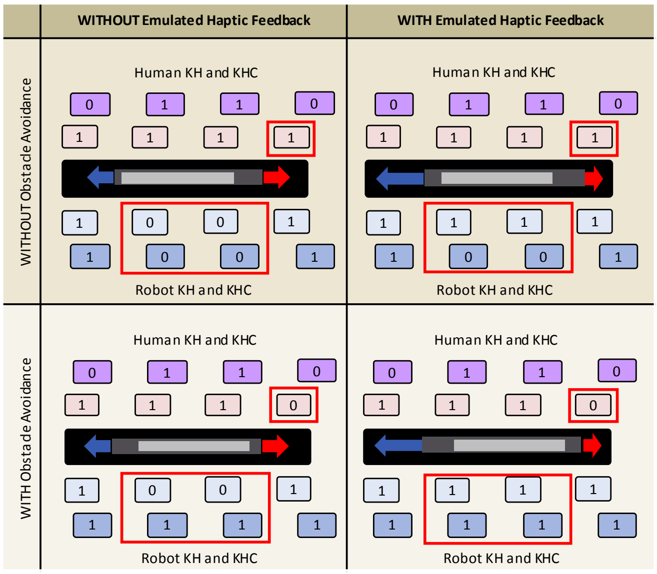

Fig. 2. Shared control and common work space (adapted from [31])

The robot used in this experiment owns very simple KH functions, and difficulty holds here in the interaction process and the design of its KHC. Obviously, the control of a swarm of artificial agents increase considerably operator's and supervisor's tasks. From the knowledge drawn from these experimentations, we concluded that the complexity to elaborate efficient and effective human-based industrial CPS will mainly come from the number and the variety of artificial agents involved. Indeed, in the context of industrial CPS, smart products, smart machines, smart inventories, smart tools, etc. would compose such artificial agents. From our perspective, the complexity of the HMS will be brought by the complexity of human tasks (e.g. supervision and control of a swarm of smart entities), by the inherent complexity of each of these smart entities (e.g. issuing their specific supervision) and complexity in the interaction between human and all the set of these artificial agents (e.g. occurrence of emerging behaviors and self-organization).

To study some aspects relevant to these kinds of complexity is the topic of the French ANR granted project HUMANISM, which is presented in the following section.

IV. THE HUMANISM PROJECT

The objective of the HUMANISM project, newly launched in October 2017, is to study, improve and experiment innovative and cooperative systems involving production and supervisory human operators, diagnostic systems and control systems of intelligent Flexible Manufacturing Systems (FMS) within the context of industrial CPS. Two complementary contributions are proposed and concerned operational and tactical levels. The first one deals with the design of a method to control the intelligent FMS assuming that it is composed of autonomous artificial agents (which are known to provide adaptation capacity and robustness [33]) through a better integration of the Human operator. Complementary and new approaches have to be proposed and developed to enable the cooperative diagnostic of technical incidents and the control of emergent behaviors of such systems. The second contribution focuses on the identification of the pertinent information set that allows the design of monitoring and control systems enabling to maintain human operator's situation awareness in order to help him/her to take (near)optimal decisions, and to define and select LoA that takes into account competences and capacities of each agent involved in the global system, being human or artificial.

The cooperation models and methodology presented in the previous section will be used, as well as an approach called the Cognitive Work Analysis (CWA). CWA is a method to support the analysis of decision-making process and of the evaluation of situation awareness, workload and modes of cognitive control in dynamic situations [34]. To ensure the genericity of our theoretical developments, HUMANISM will be applied on three different kinds of autonomous systems, called Artificial Self-Organized systems (ASO), with a focus on their ability to contribute to a controlled and efficient intelligent FMS: a cobot system, a swarm of intelligent products, and a swarm of mobile robots (cf. Fig. 3). They present different adaptable or adaptive LoA. They differ each other in the kind of interaction they have with the Human (close vs. distant), and in their behavior (predictive or reactive, with or without communication abilities and accessible data).

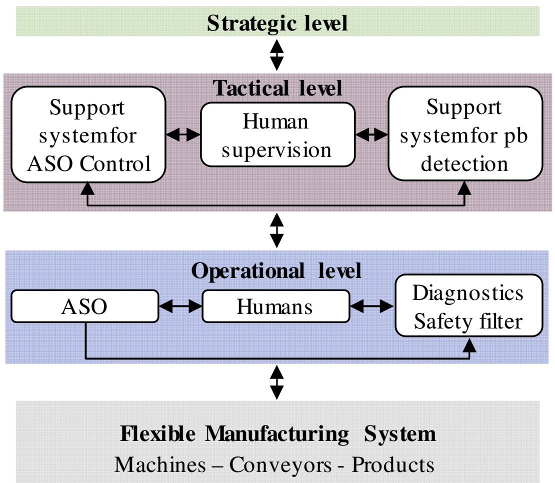

Fig. 3. Multi-level cooperation between Humans and innovative autonomous systems

From a theoretical point of view, HUMANISM will give the opportunity to observe and to analyze the propagations of constraints between the operational level and the tactical level of an intelligent socio-technical system as well as their impact on operators' activities.

Experiments will be conducted with several participants on the three ASOs combined to the support systems of the tactical level. Of course, experiments will be counter-balanced regarding learning and order effects. Subjective data will be stemmed from questionnaires, interviews and video records in order to analyze participants' activity. Objective data (duration of operation, number of interferences between human and ASOs, number of mistakes...) will reinforce the results in terms of situation awareness, acceptability, performance, safety.

V. Conclusion

In this paper, authors fostered the idea to integrate the principles of Human-machines systems to improve the effectiveness of the cooperation between Human, being operators or supervisors, and industrial Cyber Physical Systems composed of autonomous artificial agents. Pending issues concerning integration of Human in industrial Cyber Physical Systems and associated cognitive dimensions have been discussed. The lack of tools facilitating this integration and especially the lack of principal axes [37], leads us to investigate principles of cooperation in Human Machine Systems.

An illustrative and concrete example helped us to identify the different kinds of complexity that may make it difficult to design human-based industrial Cyber-Physical Systems that will be studied within the context of the HUMANISM project. Both approaches from Human-Machine Systems and industrial Cyber Physical Systems will be mixed and should be evaluated to assess performance of human-based industrial CPS.

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